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(54) **ULTRASONIC CAVITATION SENSOR**

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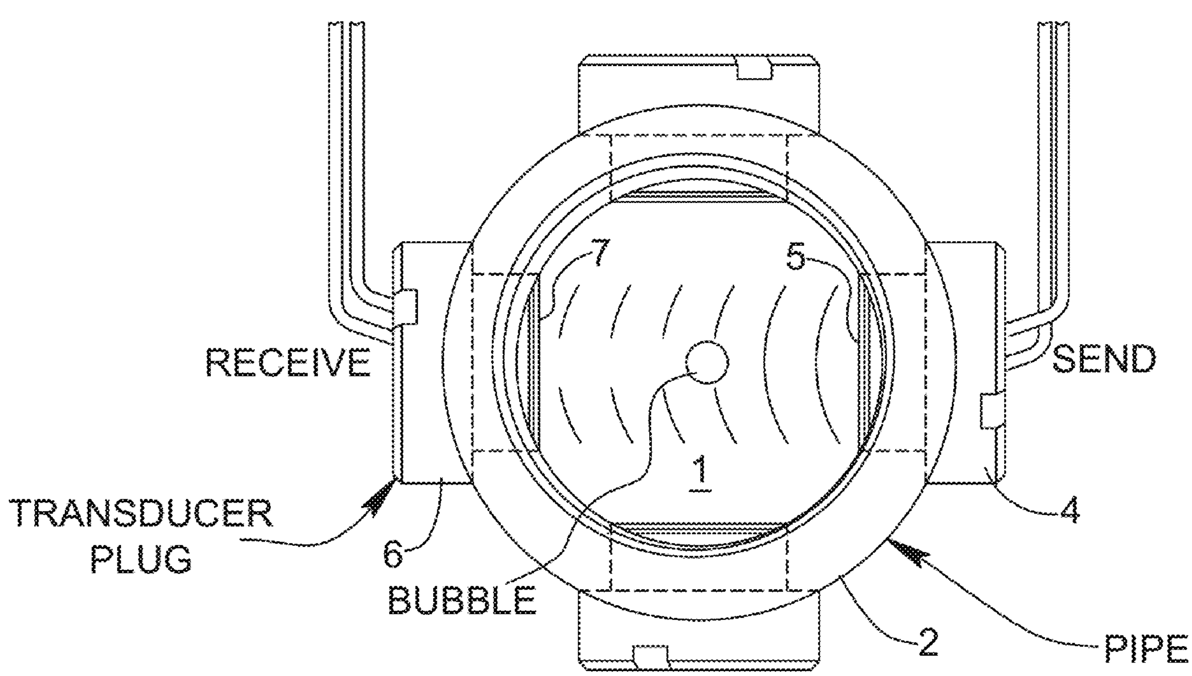
(57) **ABSTRACT**

An apparatus for sensing cavitation in liquid flowing through a conduit in a housing includes an ultrasonic transducer system having one or more ultrasonic transducers attached to the housing and arranged in acoustic communication with the liquid, and control electronics connected to the ultrasonic transducer system. The control electronics is configured to drive the transducer system to send an ultrasonic signal through the flowing liquid, wherein the transducer system receives the ultrasonic signal and generates an electronic cavitation detection signal representing a strength of the received ultrasonic signal. The control electronics is further configured to process the cavitation detection signal to provide a cavitation measurement signal indicative of whether or not the ultrasonic signal interacted with one or more cavitation bubbles, evaluate the cavitation measurement signal to determine if one or more alarm conditions is met, and output an alarm signal when each of the cavitation alarm condition(s) is met.

CAVITATION BUBBLE



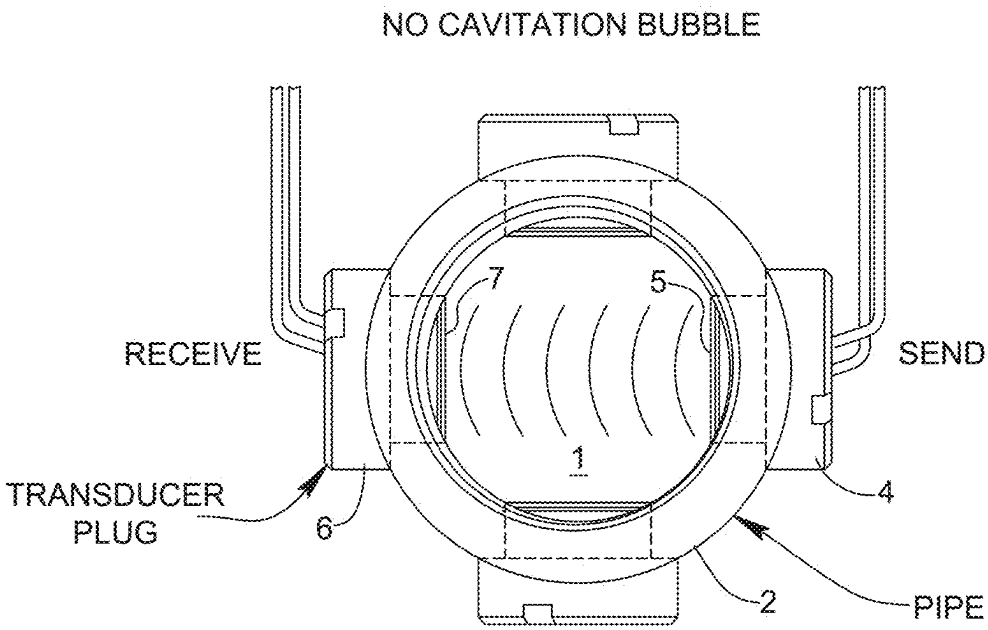

NO CAVITATION BUBBLE
RECEIVE
SEND
7
5
1
TRANSDUCER PLUG
6
4
2
PIPE

FIG. 1A

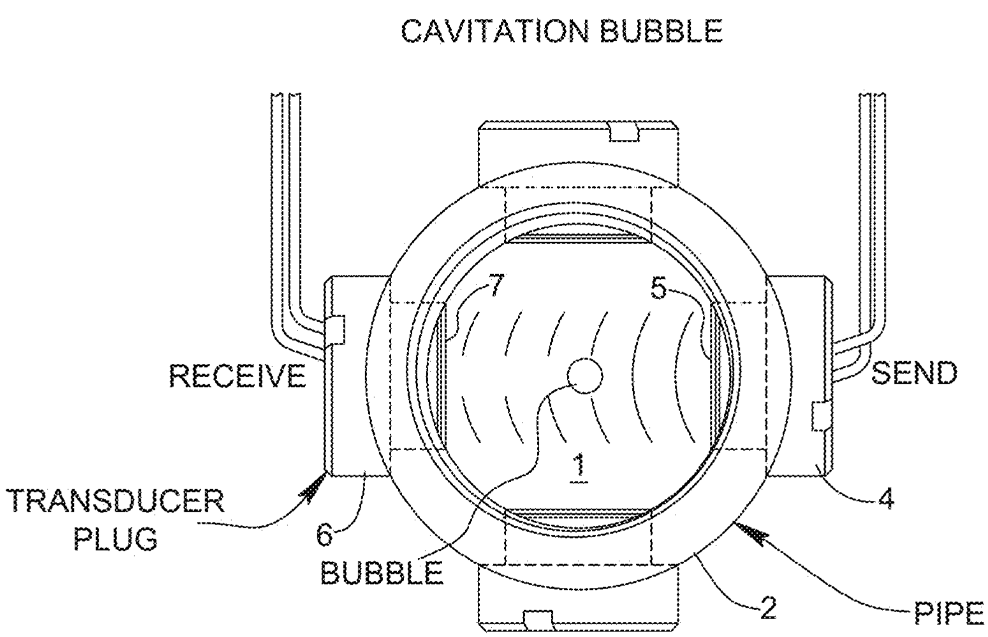

CAVITATION BUBBLE
RECEIVE
SEND
7
5
1
TRANSDUCER PLUG
6
BUBBLE
4
2
PIPE

FIG. 1B

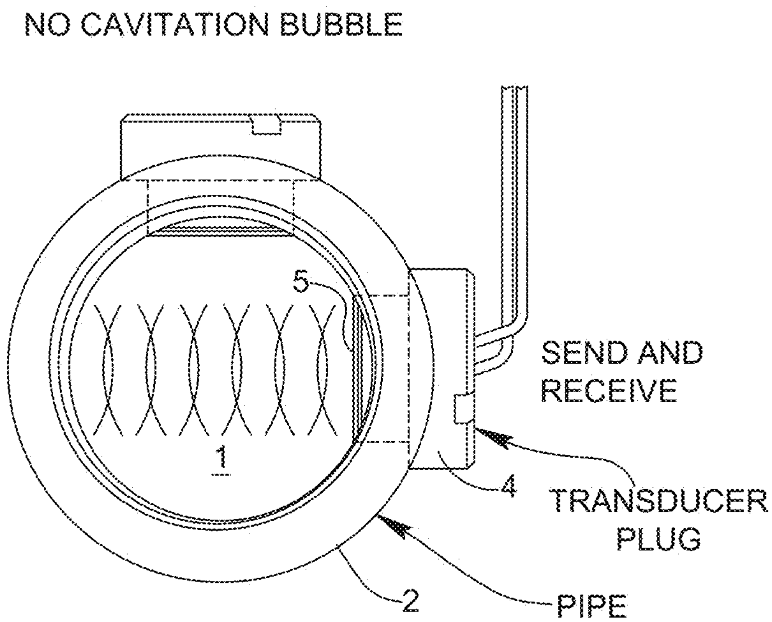

NO CAVITATION BUBBLE
5
SEND AND
RECEIVE
1
4
TRANSDUCER
PLUG
2
PIPE

FIG. 1C

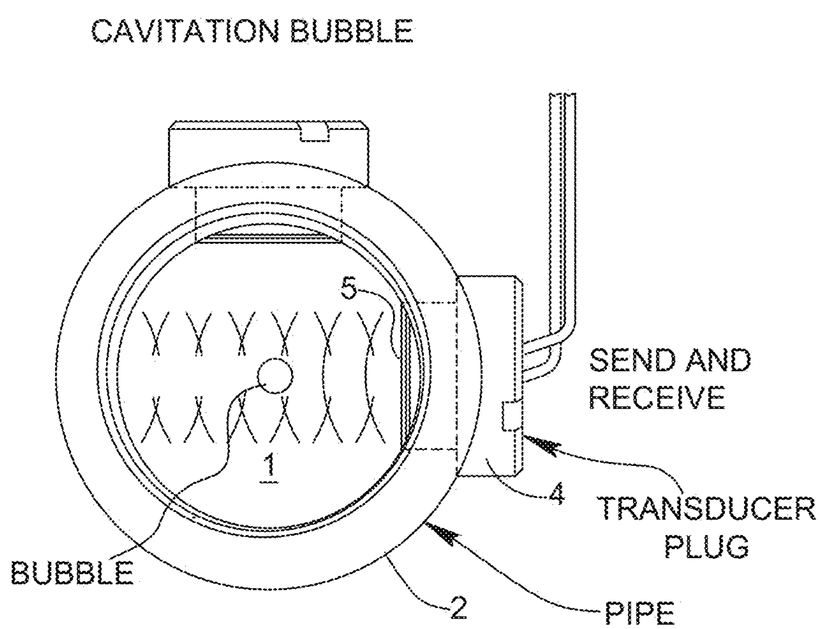

CAVITATION BUBBLE
5
SEND AND
RECEIVE
1
4
TRANSDUCER
PLUG
BUBBLE
2
PIPE

FIG. 1D

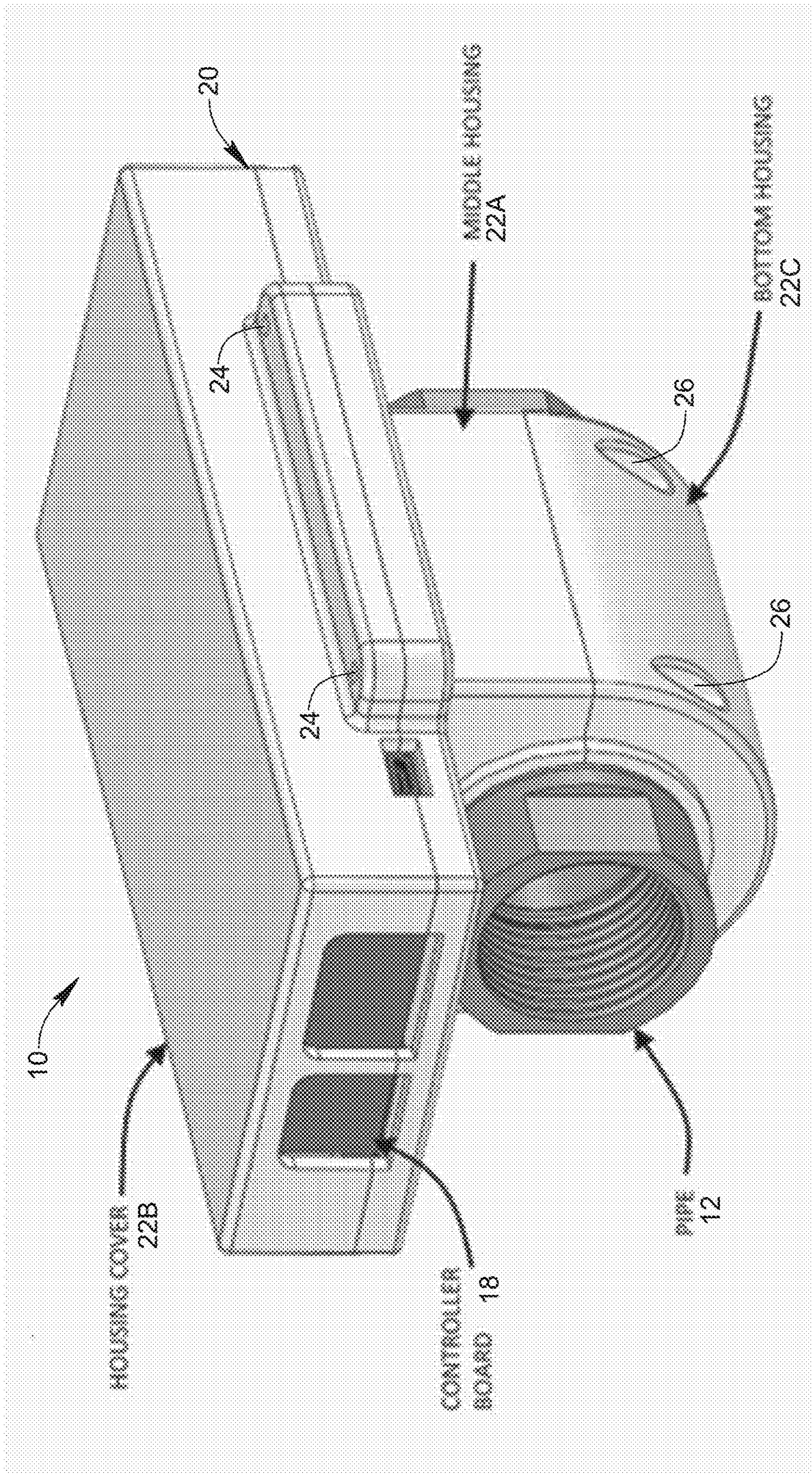

20
MIDDLE HOUSING
22A
BOTTOM HOUSING
22C
24
24
26
26
10
HOUSING COVER
22B
CONTROLLER
BOARD
18
PIPE
12

FIG. 2

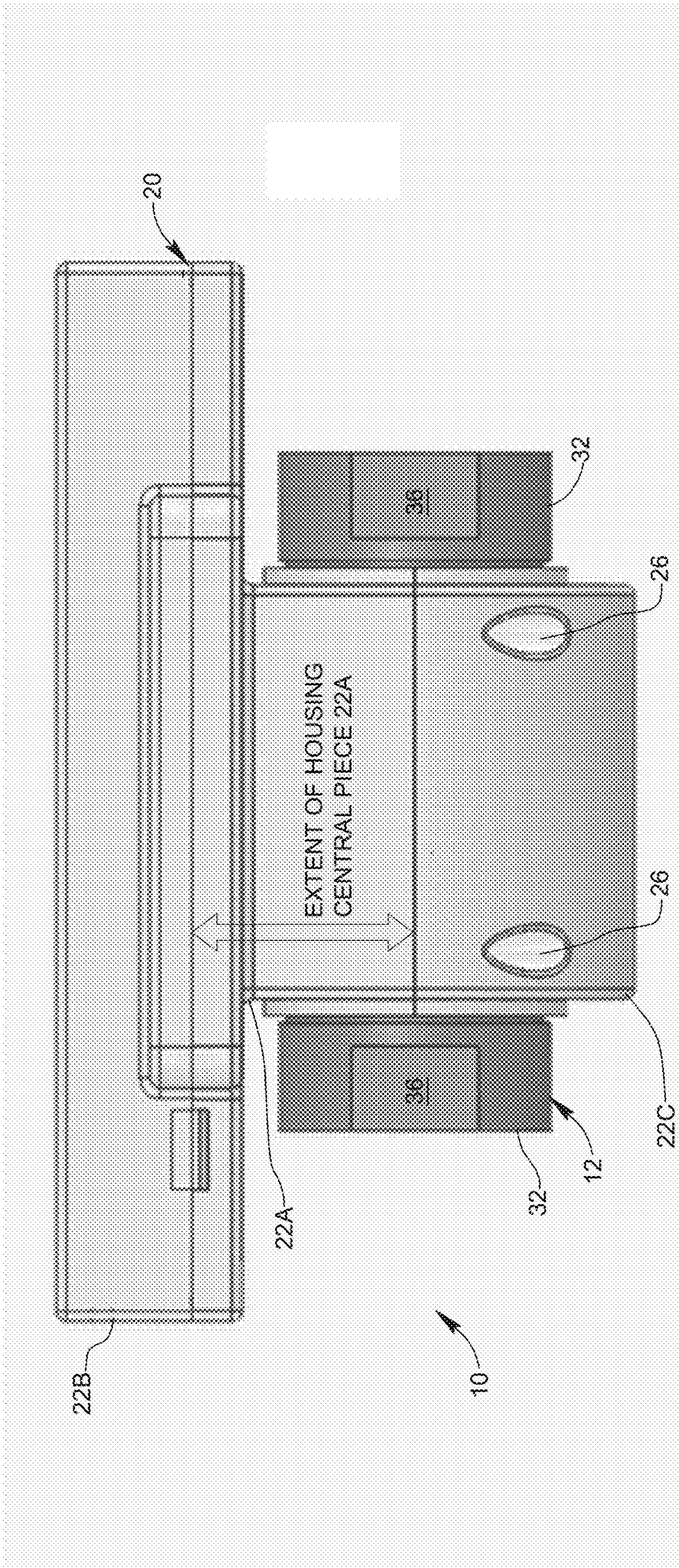

20
32
36
26
EXTENT OF HOUSING
CENTRAL PIECE 22A
26
36
22A
32
12
22C
22B
10

FIG. 3

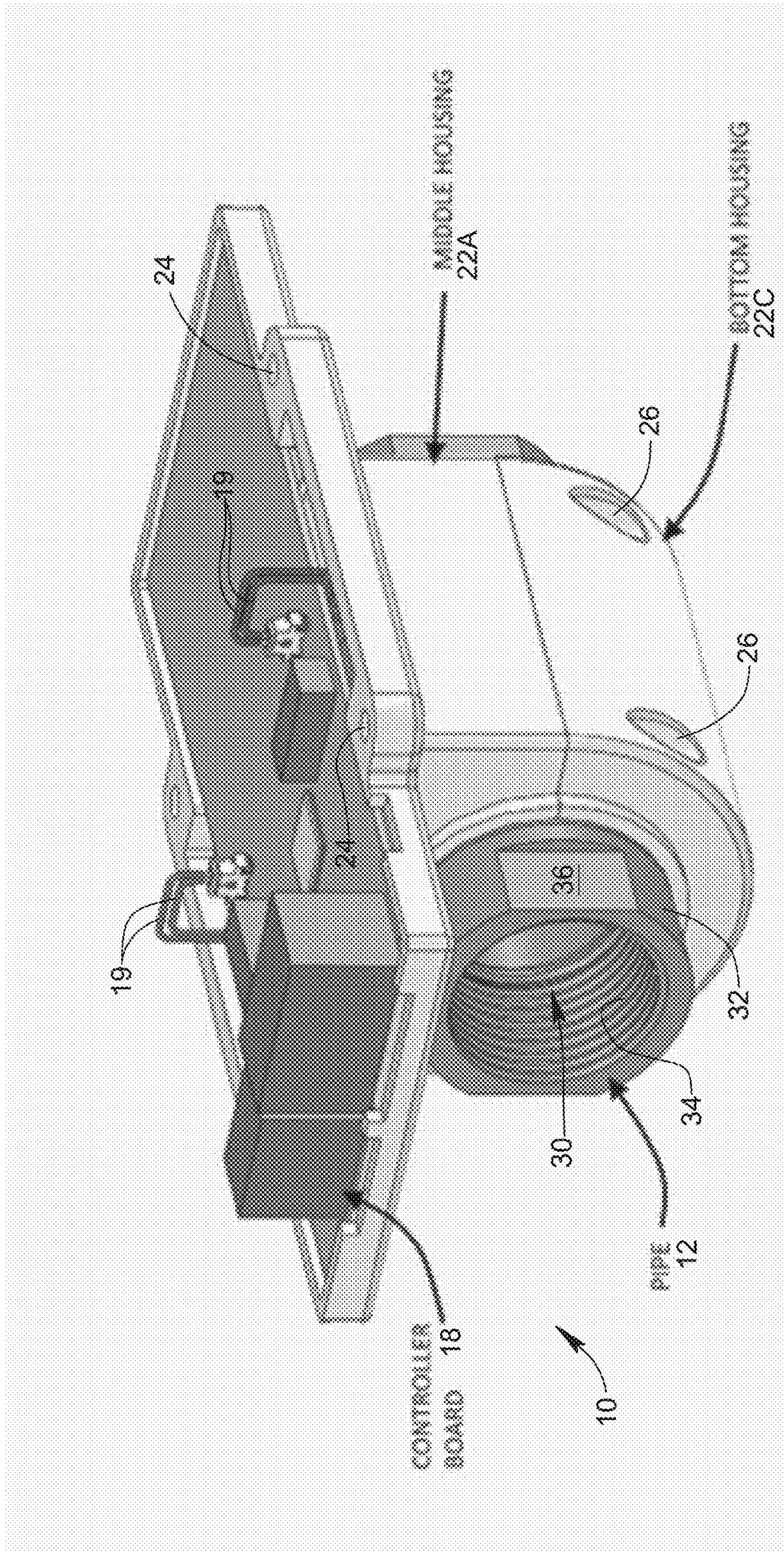

MIDDLE HOUSING
22A
BOTTOM HOUSING
22C
24
24
19
19
26
26
36
32
34
30
PIPE
12
CONTROLLER
BOARD
18
10

FIG. 4

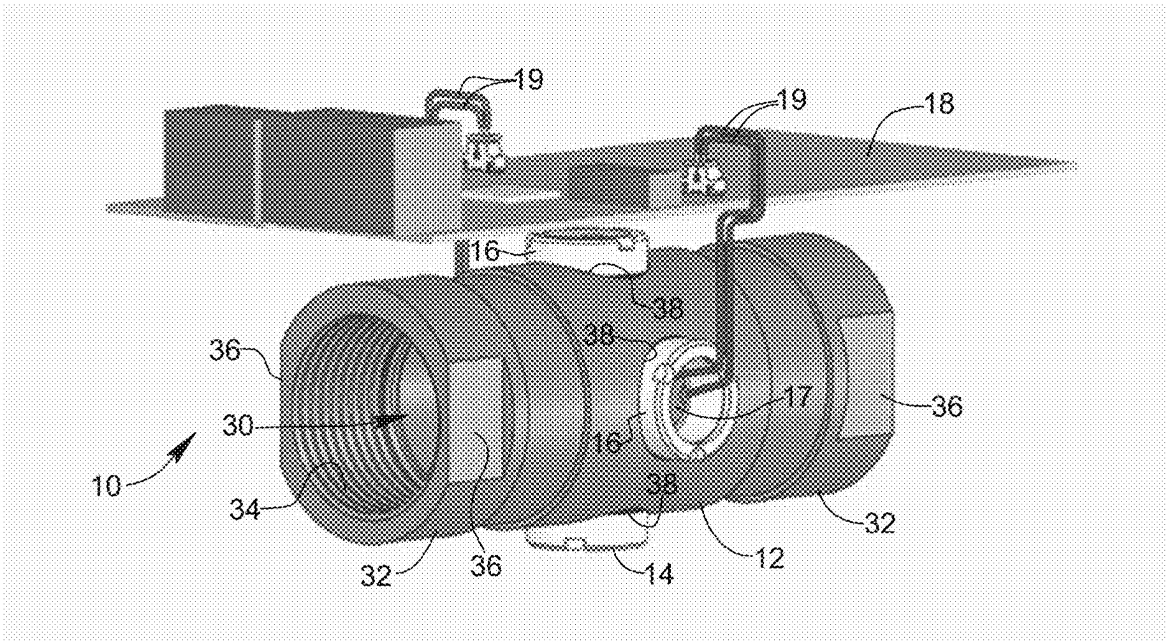

19
19
18
16
38
38
36
30
17
16
36
10
34
38
32
32
36
14
12

FIG. 5

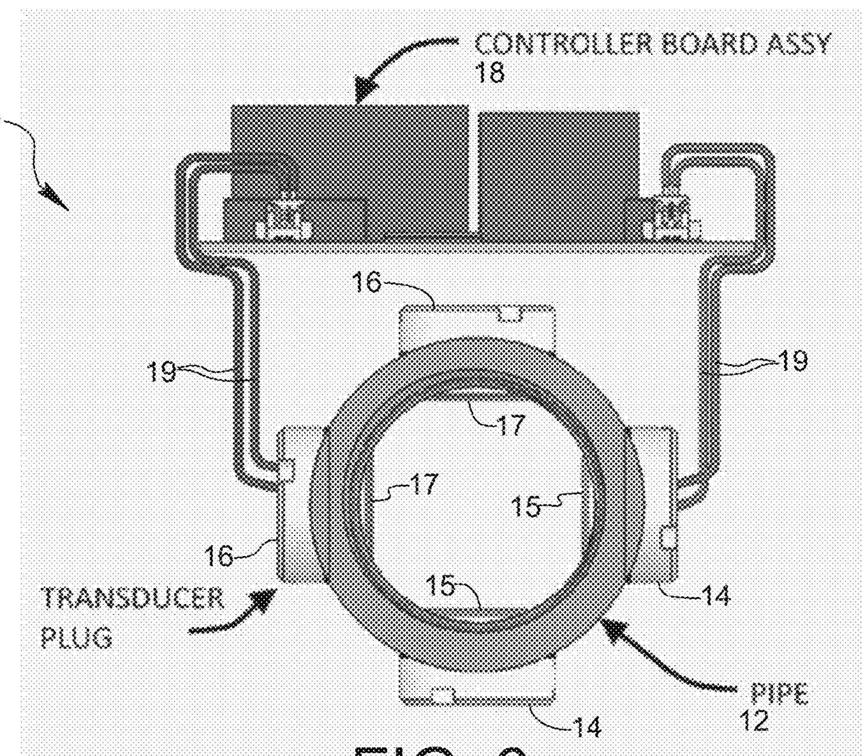

CONTROLLER BOARD ASSY
18
10
16
19
19
17
17
15
16
15
14
TRANSDUCER
PLUG
PIPE
12
14

FIG. 6

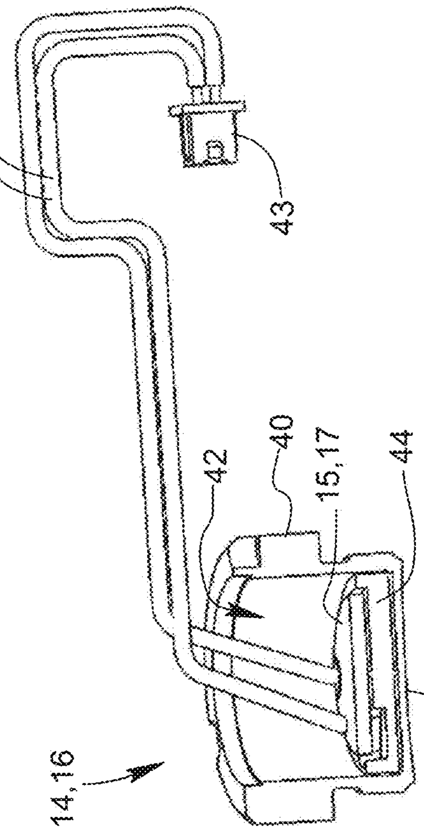


FIG. 8

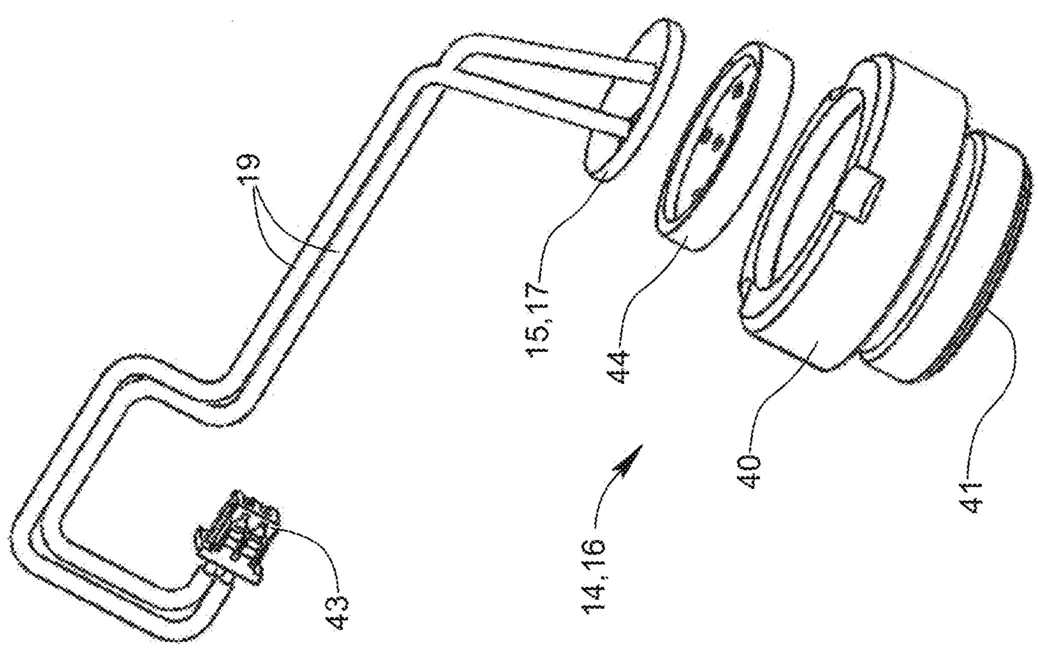


FIG. 7

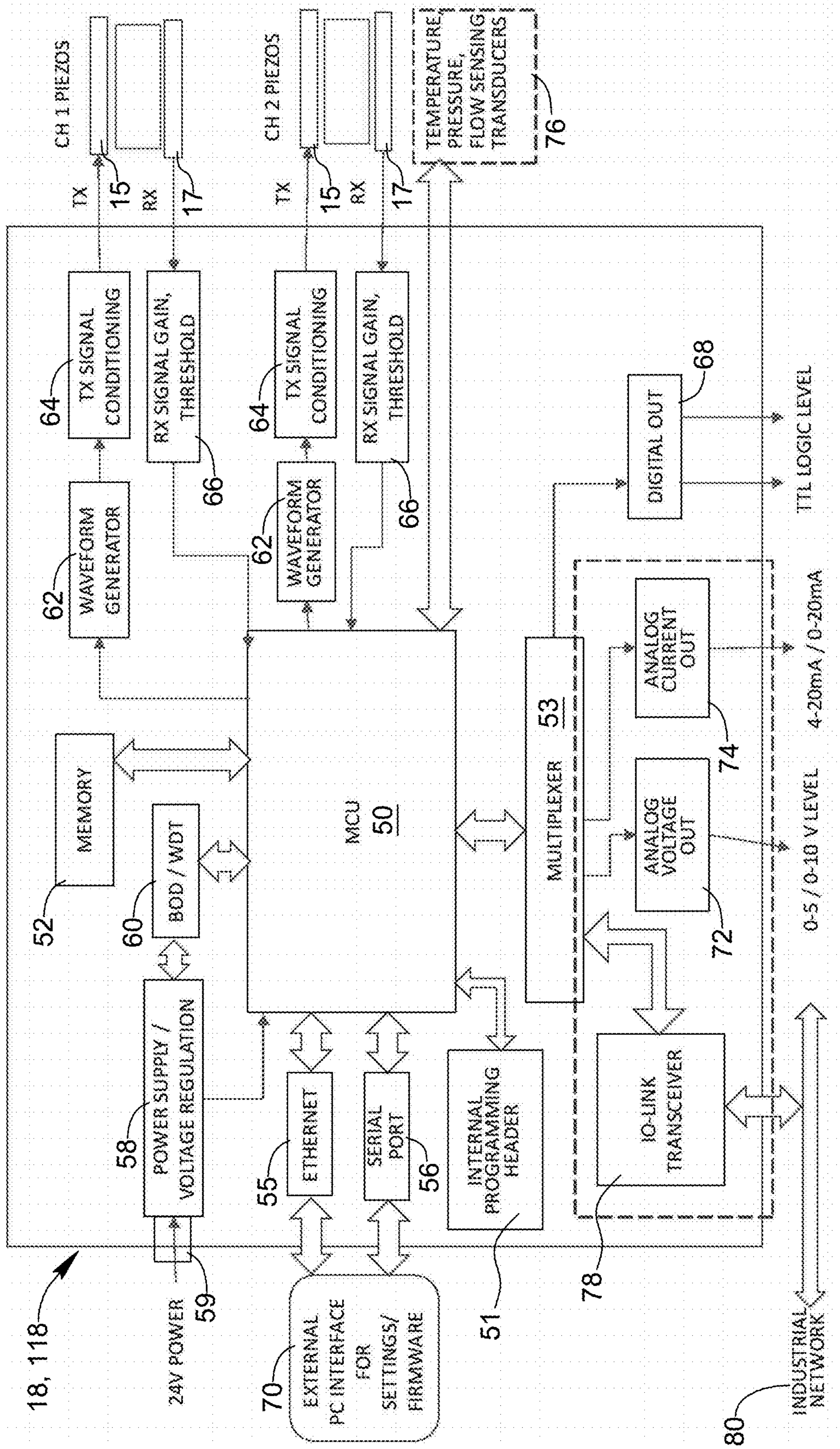

CH 1 PIEZOS
TX
15
RX
17
CH 2 PIEZOS
TX
15
RX
17
TEMPERATURE, PRESSURE, FLOW SENSING TRANSDUCERS
76
TX SIGNAL CONDITIONING
64
RX SIGNAL GAIN, THRESHOLD
66
WAVEFORM GENERATOR
62
MEMORY
52
BOD / WDT
60
MCU
50
POWER SUPPLY / VOLTAGE REGULATION
58
59
24V POWER
ETHERNET
55
SERIAL PORT
56
INTERNAL PROGRAMMING HEADER
51
EXTERNAL PC INTERFACE FOR SETTINGS/ FIRMWARE
70
MULTIPLEXER
53
DIGITAL OUT
68
TTL LOGIC LEVEL
ANALOG CURRENT OUT
74
4-20mA / 0-20mA
ANALOG VOLTAGE OUT
72
0-5 / 0-10 V LEVEL
IO-LINK TRANSCEIVER
78
INDUSTRIAL NETWORK
80
18, 118

FIG. 9

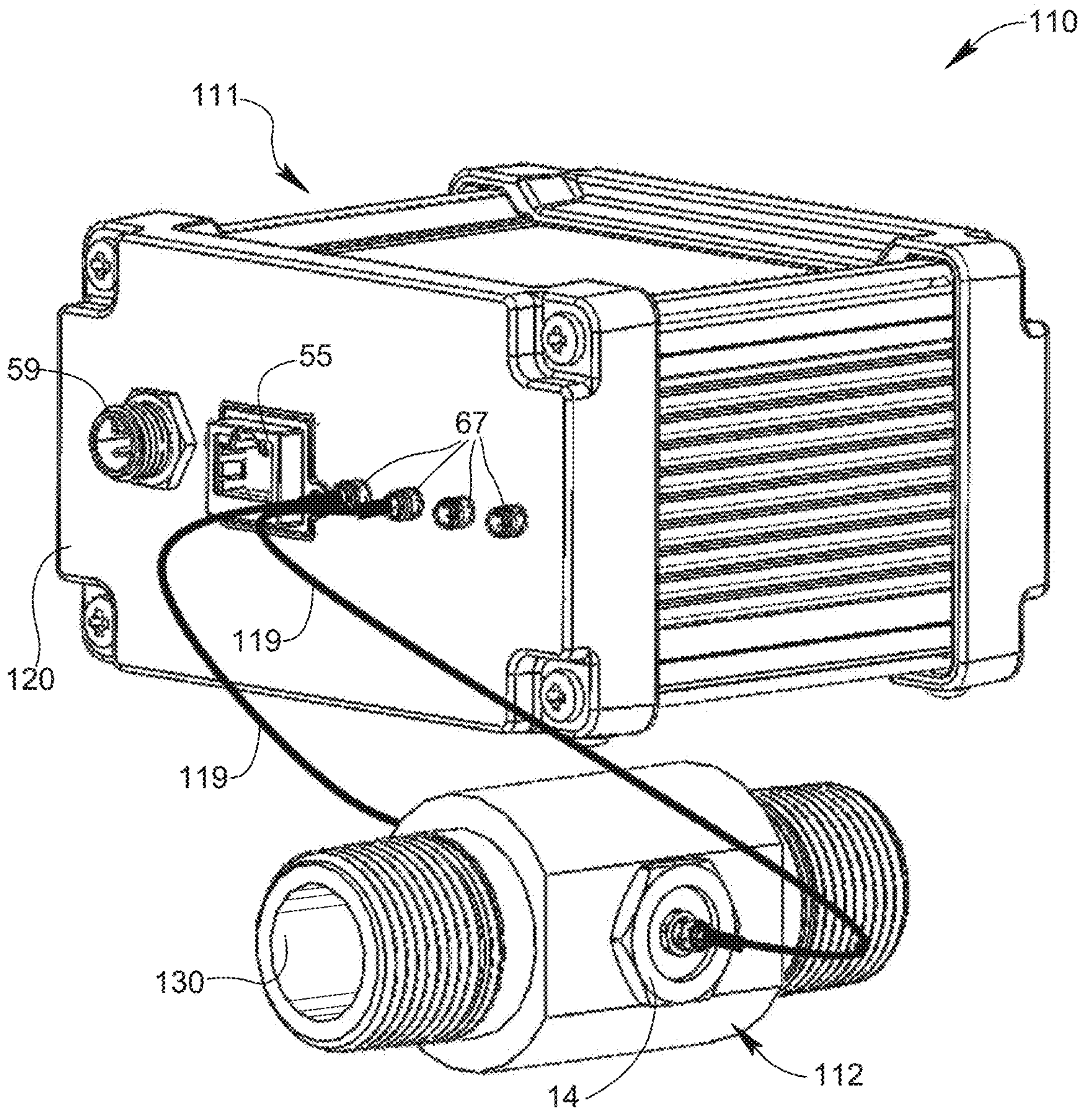


FIG. 10

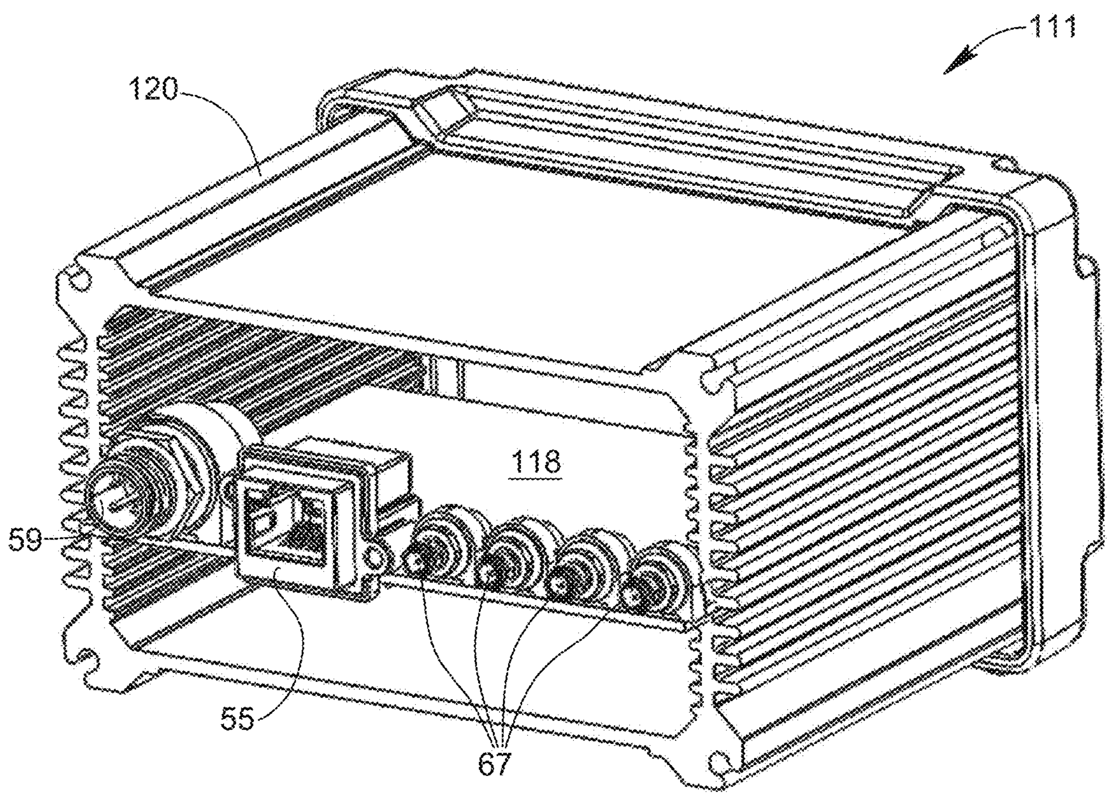


FIG. 11

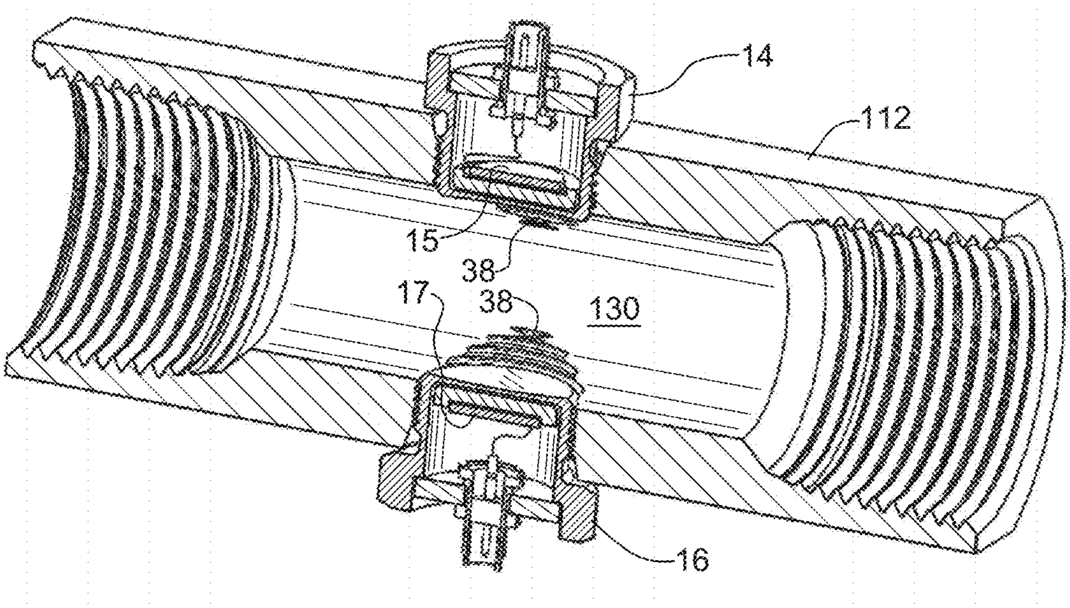


FIG. 12

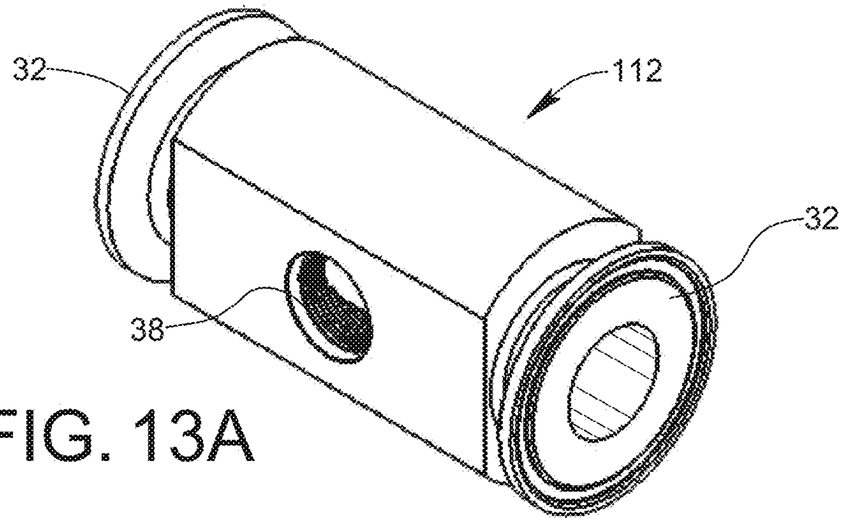


FIG. 13A

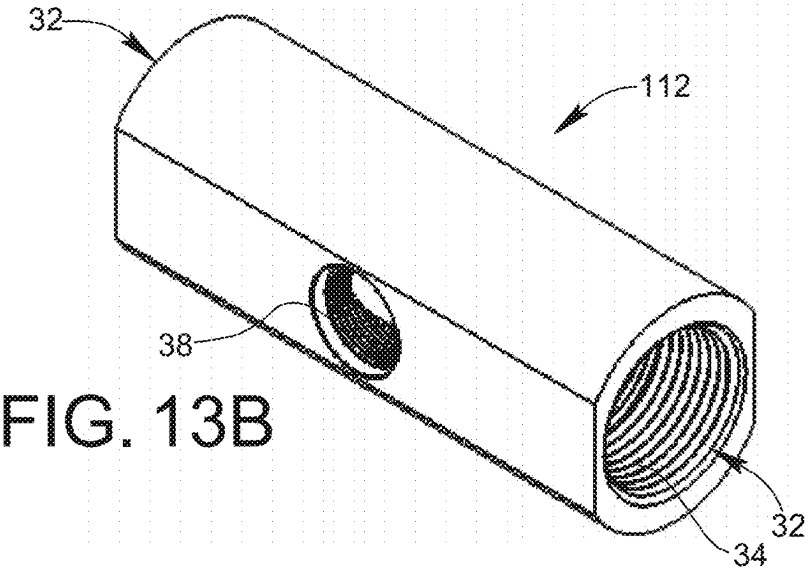


FIG. 13B

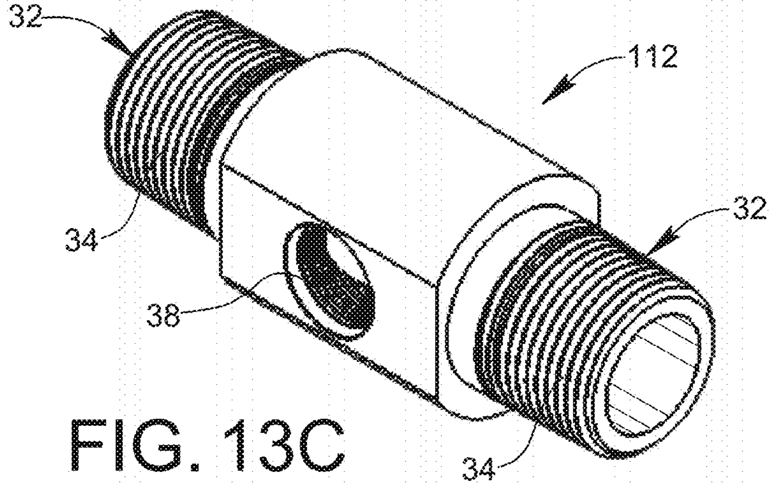


FIG. 13C

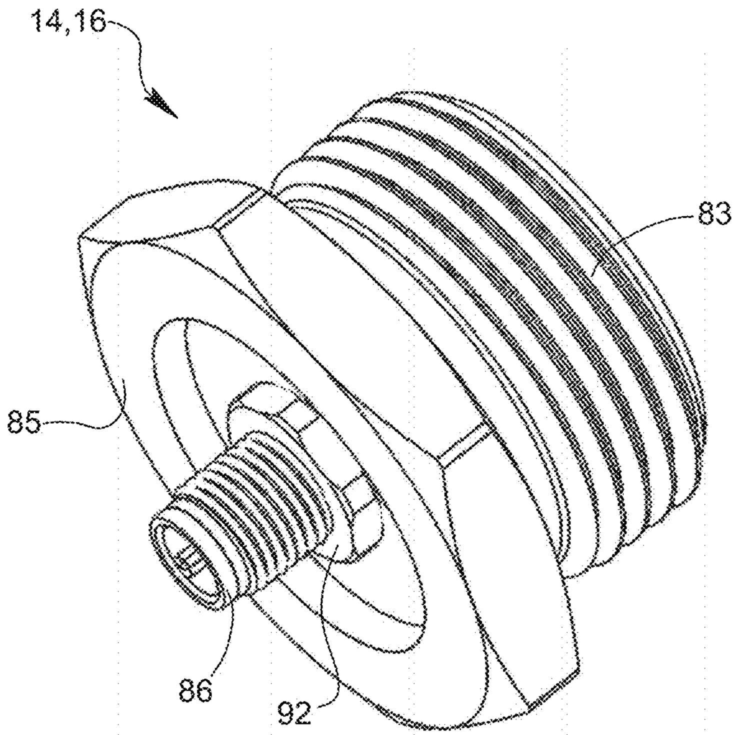


FIG. 14

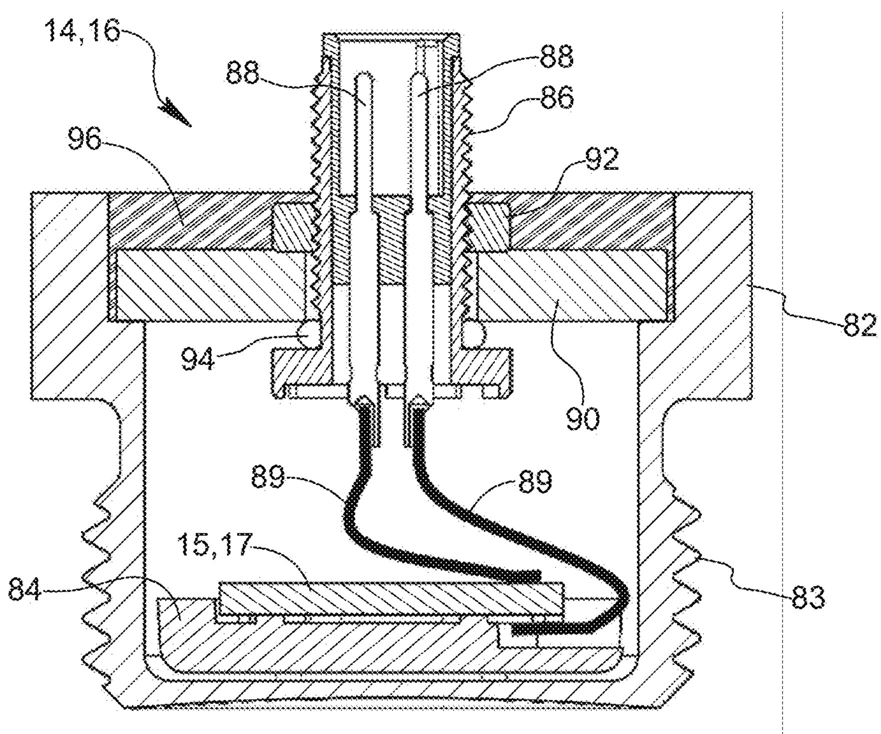


FIG. 15

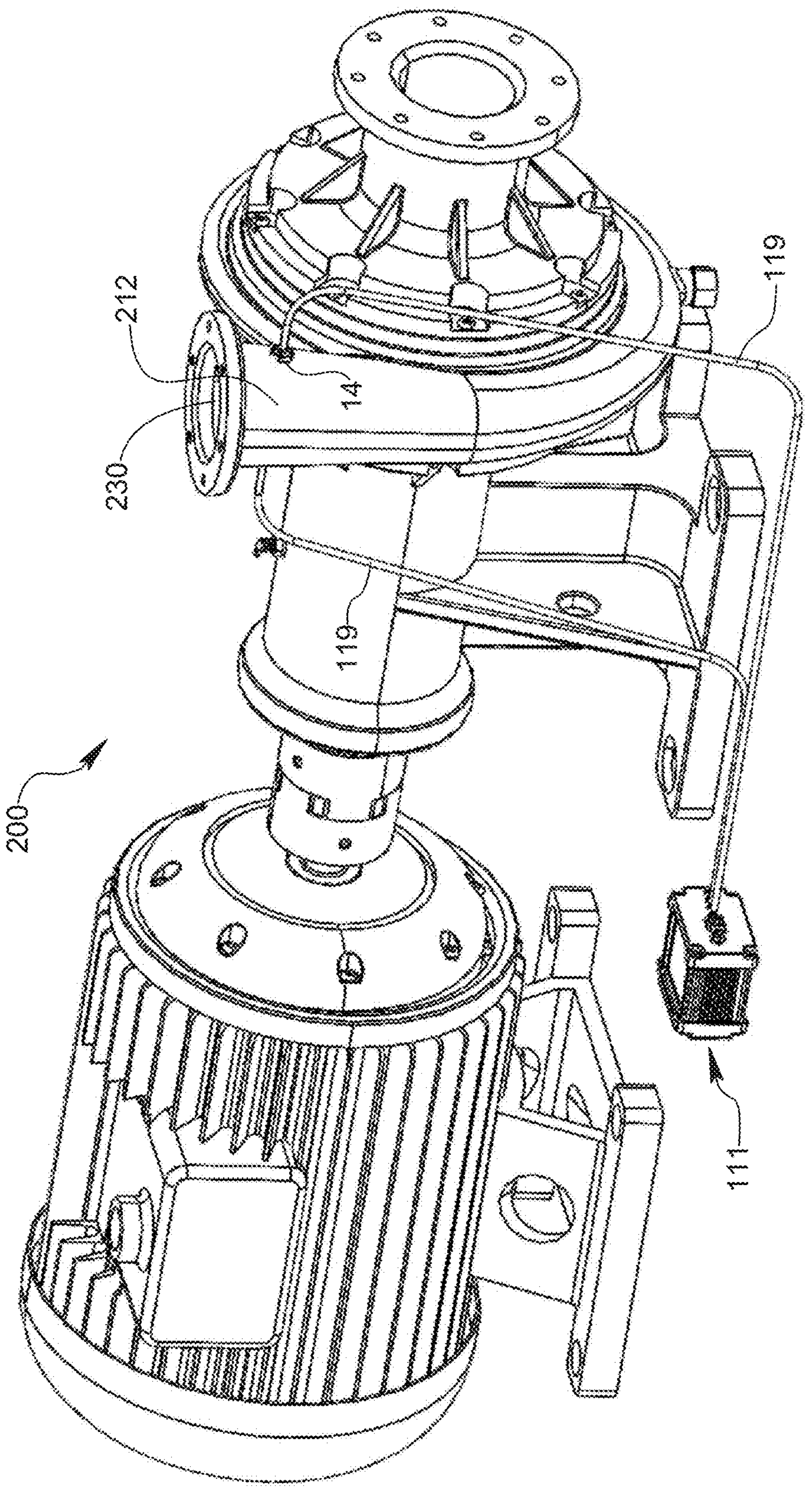


FIG. 16

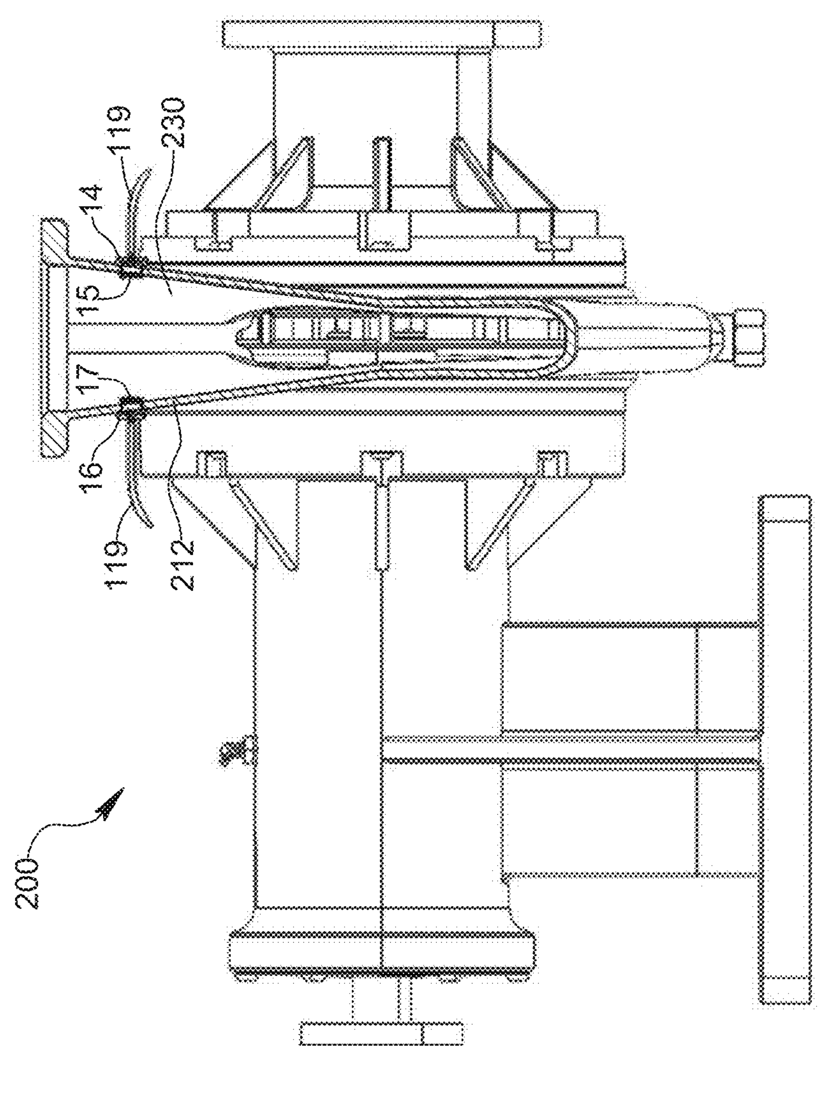


FIG. 17

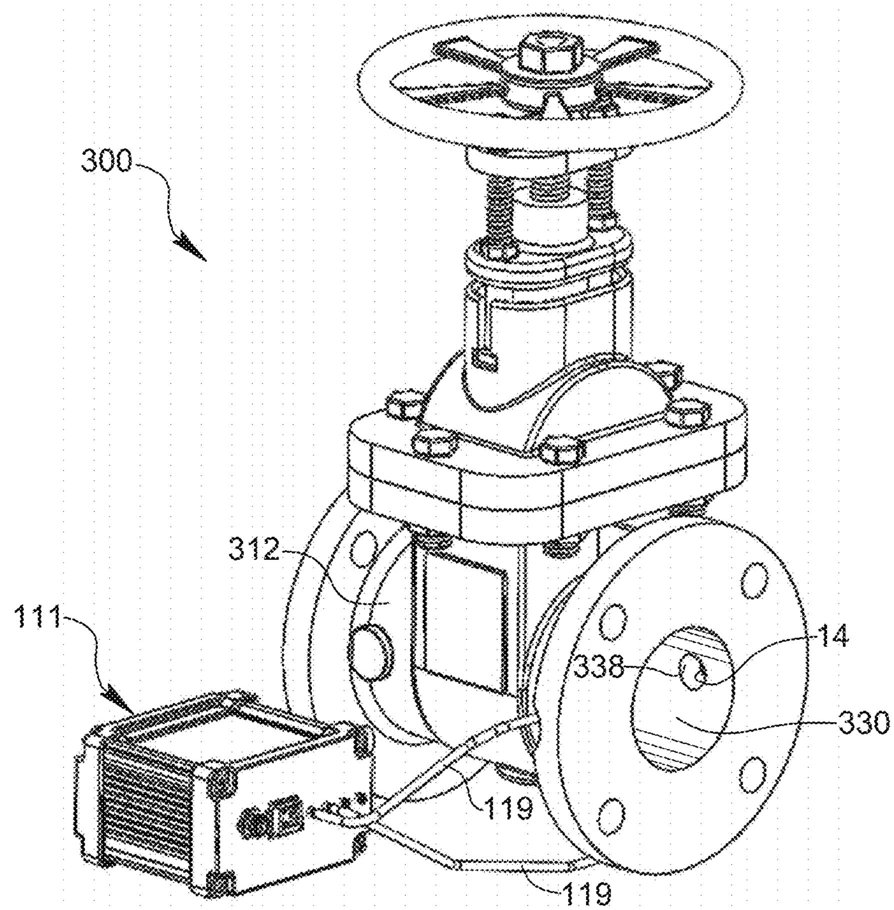

300
312
111
338
14
330
119
119

FIG. 18

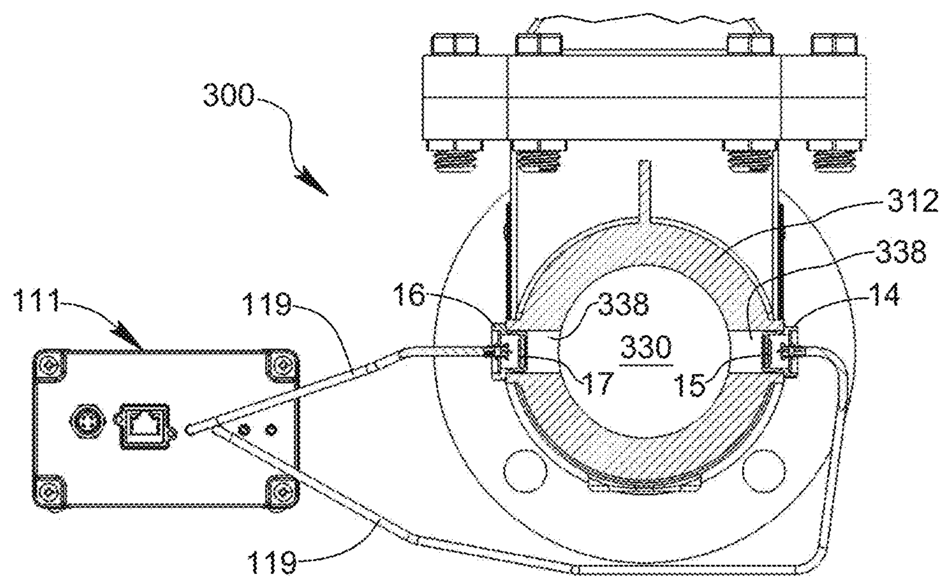

300
312
338
111
119
16
338
330
14
17
15
119

FIG. 19

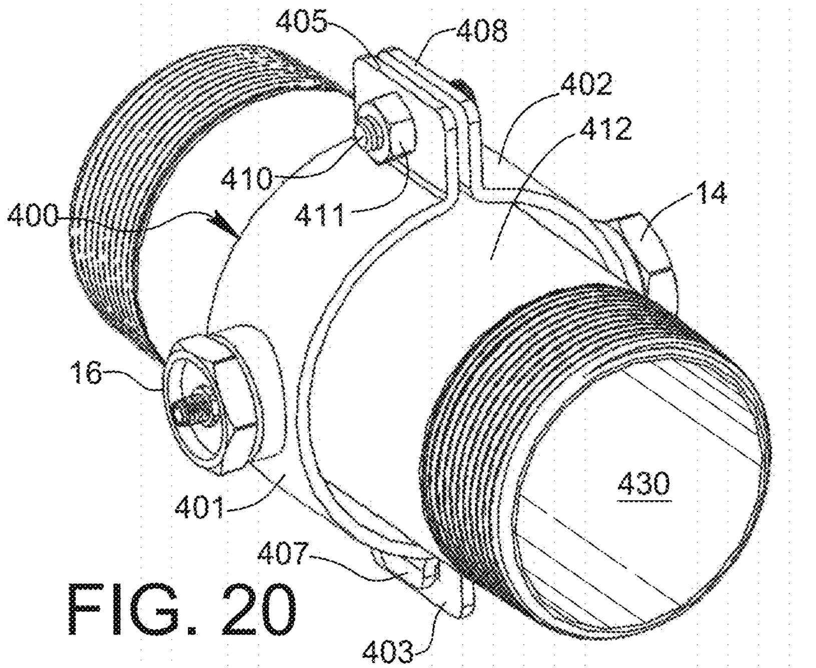


FIG. 20

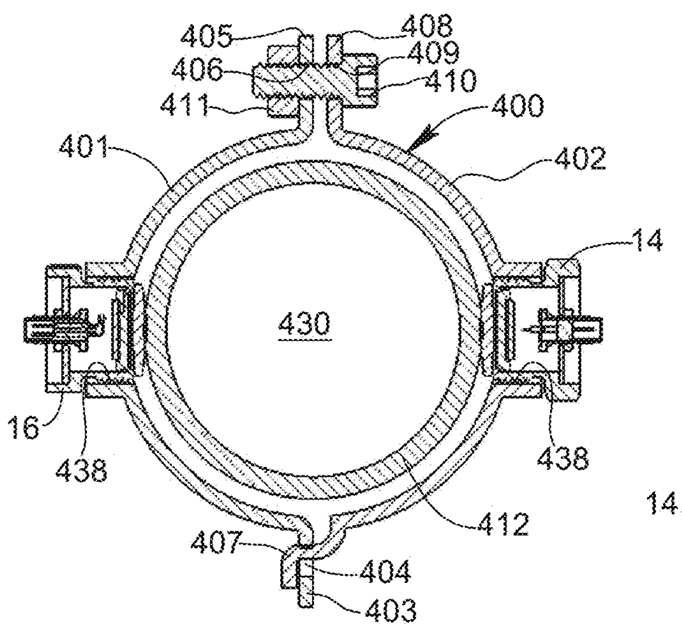


FIG. 21

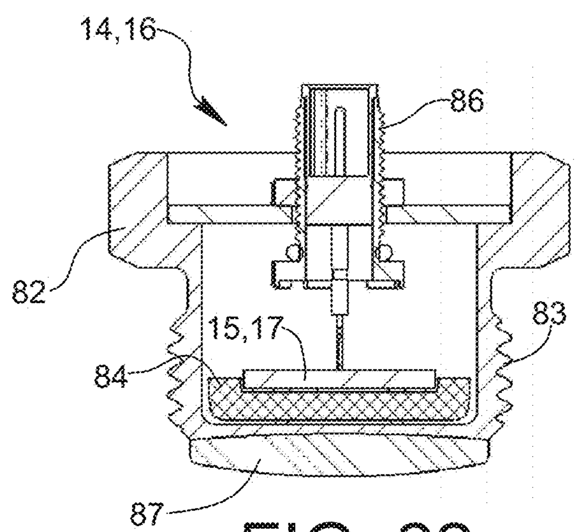


FIG. 22

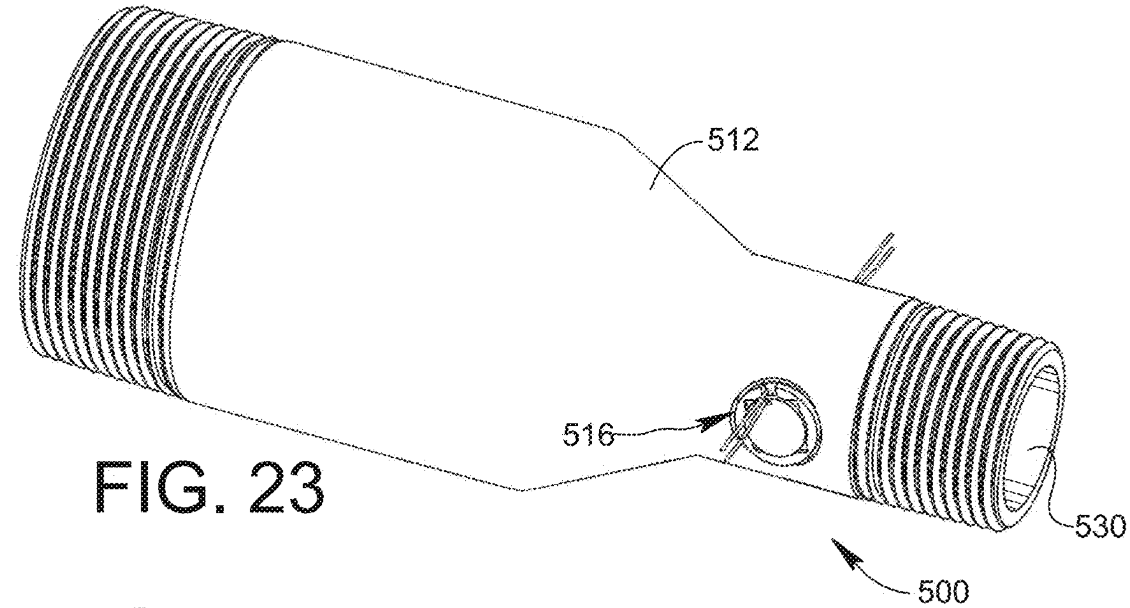


FIG. 23

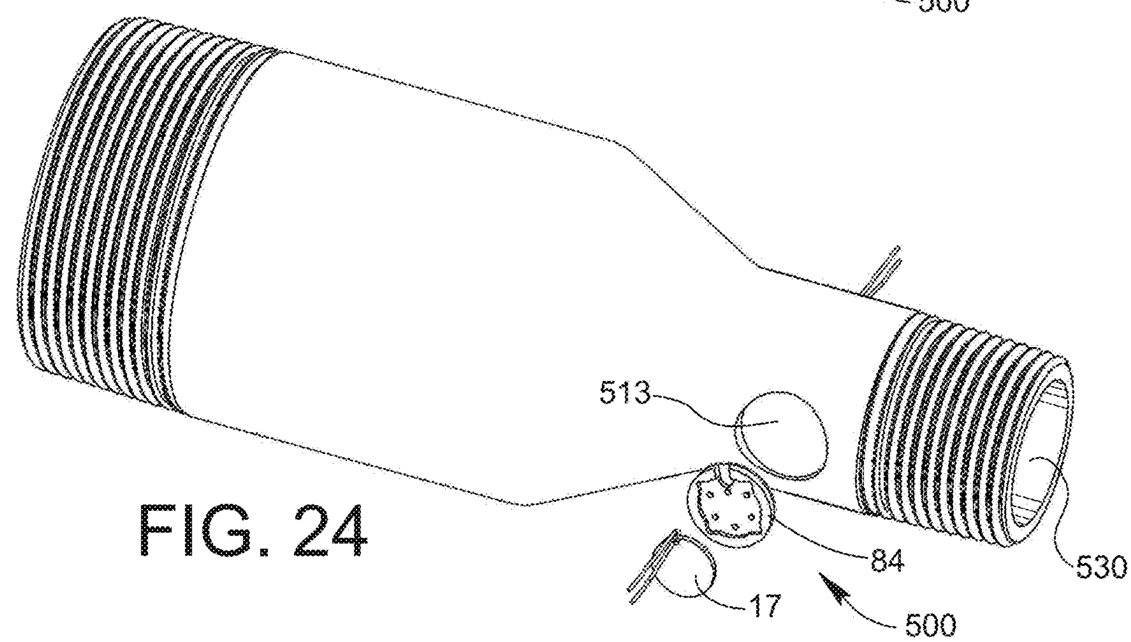


FIG. 24

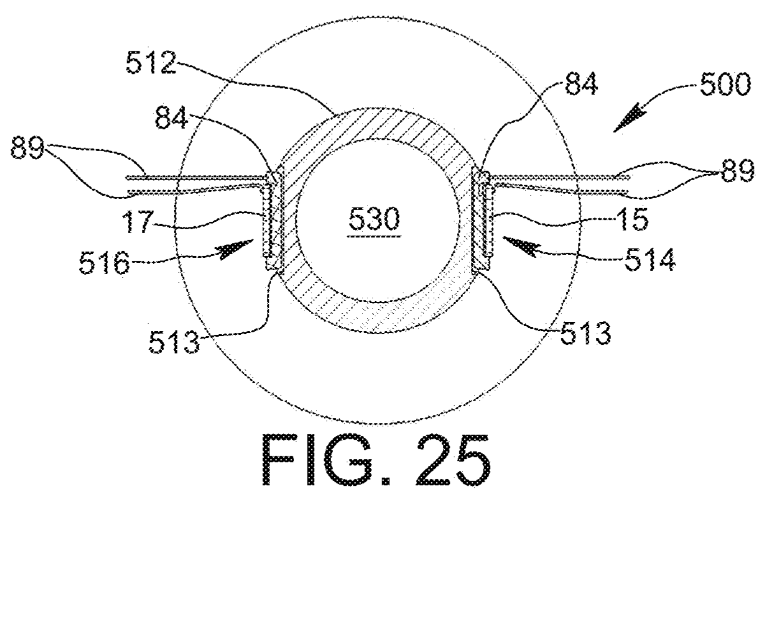


FIG. 25

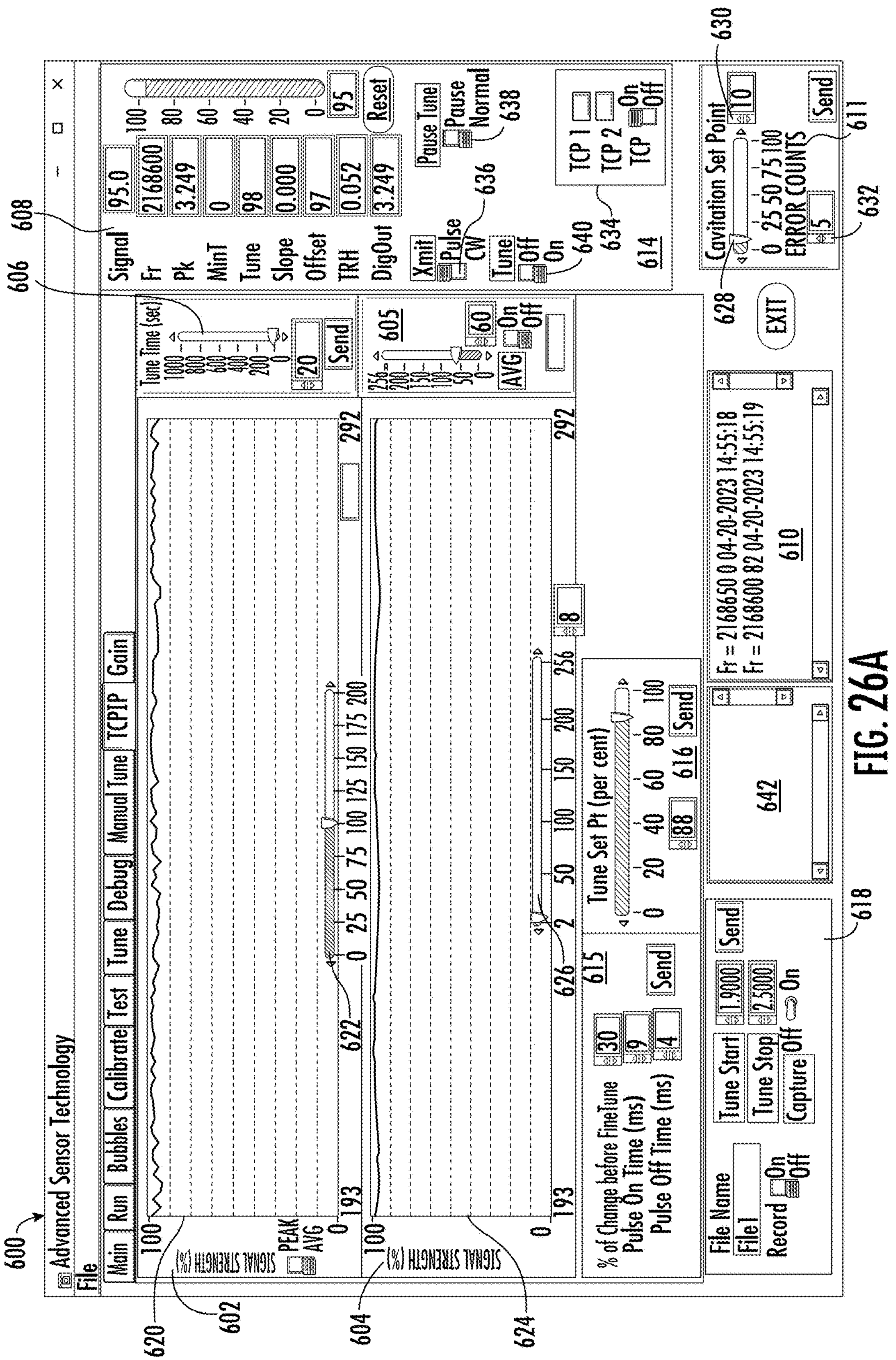

600
Advanced Sensor Technology
File
Main
Run
Bubbles
Calibrate
Test
Tune
Debug
Manual Tune
TCPIP
Gain
SIGNAL STRENGTH (%)
PEAK
AVG
Tune Time (sec)
Send
605
On
Off
Signal
Fr
Pk
MinT
Tune
Slope
Offset
TRH
DigOut
95.0
2168600
3.249
0
98
0.000
97
0.052
3.249
Reset
Pause Tune
Pause
Normal
Xmit
Pulse
CW
TCP 1
TCP 2
TCP
Cavitation Set Point
ERROR COUNTS
% of Change before FineTune
Pulse On Time (ms)
Pulse Off Time (ms)
Tune Set Pt (per cent)
File Name
File1
Record
Tune Start
Tune Stop
Capture
Fr = 2168650 0 04-20-2023 14:55:18
Fr = 2168600 82 04-20-2023 14:55:19
EXIT
602
604
606
608
610
611
614
615
616
618
620
622
624
626
628
630
632
634
636
638
640
642

FIG. 26A

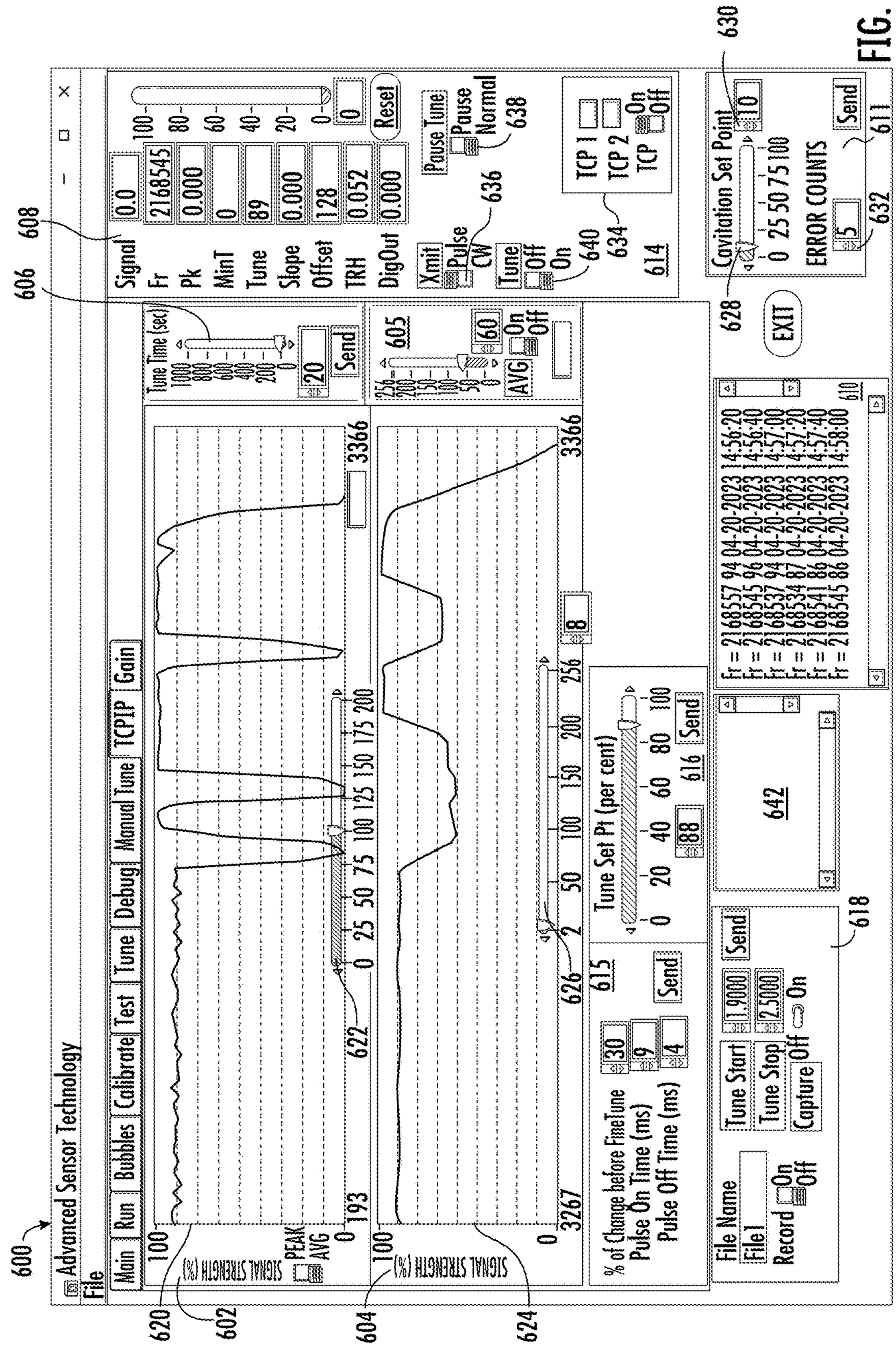

600
Advanced Sensor Technology
File
Main
Run
Bubbles
Calibrate
Test
Tune
Debug
Manual Tune
TCPIP
Gain
SIGNAL STRENGTH (%)
PEAK
AVG
100
0
193
3366
0 25 50 75 100 125 150 175 200
622
2 50 100 150 200 256
3267
626
8
Tune Time (sec)
1000 800 600 400 200 0
20
Send
606
256 200 150 100 50 0
605
60
AVG
On
Off
Signal
Fr
Pk
MinT
Tune
Slope
Offset
TRH
DigOut
0.0
2168545
0.000
0
89
0.000
128
0.052
0.000
608
100 80 60 40 20 0
0
Reset
Pause Tune
Pause
Normal
638
Xmit
Pulse
CW
636
Tune
Off
On
640
TCP 1
TCP 2
TCP
On
Off
634
614
% of Change before FineTune
Pulse On Time (ms)
Pulse Off Time (ms)
30
9
4
615
Send
Tune Set Pt (per cent)
0 20 40 60 80 100
88
616
Send
File Name
File1
Record
On
Off
Tune Start
Tune Stop
Capture
1.9000
2.5000
Off
On
Send
618
642
Fr = 2168557 94 04-20-2023 14:56:20
Fr = 2168545 96 04-20-2023 14:56:40
Fr = 2168537 94 04-20-2023 14:57:00
Fr = 2168534 87 04-20-2023 14:57:20
Fr = 2168541 86 04-20-2023 14:57:40
Fr = 2168545 86 04-20-2023 14:58:00
610
EXIT
Cavitation Set Point
0 25 50 75 100
10
628
630
ERROR COUNTS
5
632
Send
611
620
602
604
624

FIG. 26B

ULTRASONIC CAVITATION SENSOR

CROSS-REFERENCE TO RELATED APPLICATION

[0001] The present application claims priority benefit of U.S. Provisional Patent Application No. 63/356,201 filed Jun. 28, 2022, the entire disclosure of which is incorporated herein by reference.

FIELD OF THE DISCLOSURE

[0002] The present disclosure relates to sensors for detecting cavitation and other properties of flow though liquid pumps and liquid piping systems.

BACKGROUND OF THE DISCLOSURE

[0003] Cavitation is a phenomenon that occurs frequently in liquid pumps and piping systems. It can be caused by restrictions of flow in the pump or piping, or by other conditions which produce a low pressure resulting in the formation of cavitation vapor bubbles. A cavitation bubble differs from an air bubble in that the cavitation bubble or void consists of vapor of the surrounding liquid medium. For example, in a pump and piping system for water, the cavitation bubbles consist of water vapor (i.e., cold steam), not air. Cavitation vapor bubbles may collapse upon surfaces of a pump impeller, valve, or piping and cause surface damage due to the extreme localized pressures involved. Detection of cavitation is important in order to control its occurrence and minimize costly component damage.

[0004] Currently, cavitation is detected by indirect sensing methods. It is known to detect cavitation by means of acoustic sensors listening for sound produced by collapsing cavitation bubbles as they impinge upon surfaces of a pump, valve, pipe, or other component of a liquid flow system. Another known method for indirectly detecting cavitation is to sense vibrations on the pump housing or piping. Still further methods for indirectly detecting cavitation include sensing a significant change in pump impeller speed or current draw, or measuring a significant pressure drop in the liquid flow system. The known methods mentioned above detect an artifact of cavitation (e.g., noise, vibration, pump behavior) as the cavitation vapor bubbles cause damage to system components, and therefore are of limited value in preventing such damage. The use of acoustic sensors is unsuited for noisy environments.

[0005] Cavitation may be directly detected by visual observation, however this requires transparent piping be used in the liquid flow system, and the cavitation vapor bubbles must be large enough to permit visual or optical observation.

[0006] An improved solution for detecting cavitation is needed.

SUMMARY OF THE DISCLOSURE

[0007] The present disclosure provides an apparatus and method for directly sensing cavitation bubbles in liquid flowing through a conduit prior to collapse of the cavitation bubbles on a surface.

[0008] In one embodiment, a cavitation sensor module may comprise a pipe segment adapted for installation in piping of a liquid flow system, one or more first transducer plugs each having a first ultrasonic transducer for sending ultrasonic signals, one or more second transducer plugs each having a second ultrasonic transducer for receiving the ultrasonic signals from a first ultrasonic transducer paired therewith, and a controller circuit board assembly connected to each first ultrasonic transducer and each second ultrasonic transducer. The cavitation sensor module may further comprise an enclosure for protecting the first and second transducer plugs and controller circuit board assembly, and for securing the transducer plugs and controller circuit board assembly to the pipe segment.

[0009] The controller circuit board assembly may include an electronic controller and related circuitry configured to execute stored programming instructions to drive each first ultrasonic transducer and process a cavitation detection signal generated by each second ultrasonic transducer to establish a cavitation measurement signal. The electronic controller may execute stored programming instructions to compare the cavitation measurement signal to a predetermined cavitation threshold value. The controller may be programmed and configured such that when the amplitude of the cavitation measurement signal drops below the cavitation threshold value, an alarm is signaled by the controller. The strength of the ultrasonic signal generated by each first ultrasonic transducer, and a gain applied to the cavitation detection signal generated by each second ultrasonic transducer upon receiving the ultrasonic signal, may be controlled and adjusted by the controller. A count of bubbles and/or an accumulation of cavitation events present in the flowing liquid may be calculated by the controller to provide additional information to a user.

[0010] The enclosure may be a multi-piece enclosure having a plurality of pieces which may be disassembled and assembled for installing the cavitation sensor module in a liquid flow system. In one embodiment, the enclosure includes a central piece dimensioned to receive the controller circuit board assembly and a first radial portion of the pipe segment, a cover piece removably attached to the central piece and dimensioned to cover the controller circuit board assembly, and a securement piece removably attached to the central piece and dimensioned to receive a second radial portion of the pipe segment opposite the first radial portion of the pipe segment to secure the enclosure on the pipe segment.

[0011] In another embodiment, a cavitation sensor apparatus is similar to the sensor module summarized above, except that the control electronics are housed in an enclosed control unit located remote from a housing (e.g., a pipe segment, pump housing, valve housing, fitting, or other housing) where the liquid flow conduit is located.

[0012] In further variants, the cavitation sensor apparatus does not comprise its own housing defining the liquid conduit, and is installed on a housing (e.g., a pipe, a pump housing, a valve housing, a fitting, or another housing) of an existing component in a liquid flow system. The further variants include noninvasive clamp-on and bonded-on variants.

[0013] The cavitation sensing apparatus of the present disclosure may include a user interface, for example an external computing device, connected to the control electronics. The user interface may be configured to display the cavitation measurement signal and/or a value representing an instantaneous strength of the cavitation measurement signal. The user interface may be configured to receive a first variable user input for establishing a cavitation alarm set point. The user interface may also be configured to receive a second variable user input for establishing a cavitation error count setting for reducing nuisance alarms.

BRIEF DESCRIPTION OF THE DRAWING VIEWS

[0014] The nature and mode of operation of the present disclosure will now be more fully described in the following detailed description taken with the accompanying drawing figures, in which:

[0015] FIG. **1**A is a schematic illustration of an ultrasonic cavitation sensor according to an embodiment of the present disclosure, viewed along an axial flow direction of a pipe conduit associated with the cavitation sensor, wherein no cavitation bubble is present in liquid flowing through the pipe;

[0016] FIG. **1**B is a schematic illustration similar to that of FIG. **1**A, wherein a cavitation bubble is present in liquid flowing through the pipe conduit;

[0017] FIG. **1**C is a schematic illustration of an ultrasonic cavitation sensor according to another embodiment of the present disclosure, viewed along an axial flow direction of a pipe conduit associated with the cavitation sensor, wherein no cavitation bubble is present in liquid flowing through the pump conduit;

[0018] FIG. **1**D is a schematic illustration similar to that of FIG. **1**C, wherein a cavitation bubble is present in liquid flowing through the pipe conduit;

[0019] FIG. **2** is a perspective view of an ultrasonic cavitation sensor module according to an embodiment of the present disclosure;

[0020] FIG. **3** is a side view of the cavitation sensor module shown in FIG. **2**;

[0021] FIG. **4** is another perspective view of the cavitation sensor module shown in FIG. **2**, wherein a top cover of an enclosure of the cavitation sensor module is removed;

[0022] FIG. **5** is a further perspective view of the cavitation sensor module shown in FIG. **2**, wherein the entire enclosure of the cavitation sensor module is removed;

[0023] FIG. **6** is a view of the cavitation sensor module shown in FIG. **5** with the cover removed, viewed along an axial flow direction of a pipe segment of the cavitation sensor module;

[0024] FIG. **7** is an exploded perspective view of a transducer plug of the cavitation sensor module shown in FIG. **2**;

[0025] FIG. **8** is a cross-sectioned perspective view of the transducer plug shown in FIG. **7**;

[0026] FIG. **9** is a schematic block diagram of an electronic controller board assembly of the cavitation sensor module shown in FIG. **2**;

[0027] FIG. **10** is a perspective view of an ultrasonic cavitation sensor apparatus according to another embodiment of the present disclosure;

[0028] FIG. **11** is a perspective view of a control unit of the ultrasonic cavitation sensor apparatus shown in FIG. **10**, wherein a front panel of the control unit is removed to reveal internal components of the control unit;

[0029] FIG. **12** is a cross-sectioned perspective view of a pipe segment and ultrasonic transducer system of the ultrasonic cavitation sensor apparatus shown in FIG. **10**;

[0030] FIGS. **13**A through **13**C are perspective views showing various type of pipe segments that may be used in the ultrasonic cavitation sensor apparatus;

[0031] FIG. **14** is a perspective view of an ultrasonic transducer plug of the ultrasonic cavitation sensor apparatus;

[0032] FIG. **15** is a cross-sectional view of the ultrasonic transducer plug shown in FIG. **14**;

[0033] FIG. **16** is a perspective view of a pump formed in accordance with a variant of the present disclosure, wherein an ultrasonic cavitation sensor apparatus of the present disclosure is associated with a housing of the pump;

[0034] FIG. **17** is a partially sectioned side view of the pump and a transducer portion of the ultrasonic cavitation sensor apparatus shown in FIG. **16**;

[0035] FIG. **18** is a perspective view of a valve formed in accordance with a variant of the present disclosure, wherein an ultrasonic cavitation sensor apparatus of the present disclosure is associated with a housing of the valve;

[0036] FIG. **19** is an axial cross-sectional view of the valve and ultrasonic cavitation sensor apparatus shown in FIG. **18**;

[0037] FIG. **20** is a perspective view of a clamp-on ultrasonic cavitation sensor module according to a further embodiment of the present disclosure, connected to a pipe segment;

[0038] FIG. **21** is a cross-sectional view of the clamp-on module and pipe segment shown in FIG. **20**;

[0039] FIG. **22** is a cross-sectional view of an ultrasonic transducer plug of the clamp-on module shown in FIG. **20**;

[0040] FIG. **23** is a perspective view of showing an ultrasonic cavitation sensor arrangement using bonded transducers on a flow reducer fitting according to another embodiment of the present disclosure;

[0041] FIG. **24** is an exploded a perspective view of the ultrasonic cavitation sensor arrangement shown in FIG. **23**;

[0042] FIG. **25** is a cross-sectional view of the ultrasonic cavitation sensor arrangement shown in FIG. **23**;

[0043] FIG. **26**A is view showing a user interface display screen of the ultrasonic cavitation sensor apparatus, wherein no cavitation bubbles are present in liquid monitored by the apparatus; and

[0044] FIG. **26**B is view similar to that of FIG. **26**A, wherein cavitation bubbles are present in liquid monitored by the apparatus.

DETAILED DESCRIPTION

[0045] FIGS. **1**A and **1**B schematically illustrate a configuration for direct ultrasonic detection of cavitation bubbles prior to collapse of the cavitation bubbles on a surface. In both figures, liquid flows through a conduit **1** of a pipe **2** in an axial direction of the pipe conduit, i.e., in a direction normal to the plane of the drawing sheet. Installed on one side of pipe **2** is a first transducer plug **4** extending through a wall of the pipe and having a first ultrasonic transducer **5** in acoustic communication with liquid flowing through the pipe. Installed on an opposite side of pipe **2** is a second transducer plug **6** extending through the pipe wall and having a second ultrasonic transducer **7** in acoustic communication with liquid flowing through the pipe conduit **1**. As may be seen, second ultrasonic transducer **7** faces first ultrasonic transducer **5** along a transverse direction perpendicular to the axial direction of pipe conduit **1** across the liquid flowing through the pipe conduit. First ultrasonic transducer **5** may be driven to send an ultrasonic signal in the form of a series of waves propagating through the liquid flowing in pipe conduit **1** toward second ultrasonic transducer **7**. Second ultrasonic transducer **7** is arranged to receive the ultrasonic signal transmitted by first ultrasonic transducer **5**, and is configured to generate an electronic cavitation detection signal representing a strength of the ultrasonic signal it receives from first ultrasonic transducer **5**. For example, paired first and second ultrasonic transducers **5**, **7** may be piezoelectric transducers operating in an ultrasonic frequency range.

[0046] If the liquid flowing through pipe conduit **1** has no cavitation bubbles to impede the ultrasonic signal as the ultrasonic signal travels across the liquid in the pipe conduit **1**, as illustrated in FIG. **1**A, then the cavitation detection signal generated by second ultrasonic transducer **7** has a relatively high amplitude. However, if one or more cavitation bubbles are present in the flowing liquid, as illustrated in FIG. **1**B, then the ultrasonic signal is attenuated to a greater degree than in FIG. **1**A, less energy is received at second ultrasonic transducer **7**, and the cavitation detection signal generated by second ultrasonic transducer **7** has a reduced amplitude as compared to the cavitation-free condition of FIG. **1**A. The strength of the cavitation detection signal is a relative indicator of the size and/or number of cavitation bubbles present between first ultrasonic transducer **5** and second ultrasonic transducer **7**.

[0047] As described in detail below, an electronic controller and related circuitry connected to ultrasonic transducers **5**, **7** may be configured to execute stored programming instructions to drive first ultrasonic transducer **5** and process the cavitation detection signal generated by second ultrasonic transducer **7** to establish a cavitation measurement signal and compare the cavitation measurement signal to a predetermined cavitation threshold value. The controller may be programmed and configured such that when the amplitude of the cavitation measurement signal drops below the cavitation threshold value, an alarm is signaled by the controller. The strength of the ultrasonic signal generated by first ultrasonic transducer **5**, and a gain applied to the cavitation detection signal generated by second ultrasonic transducer **7** upon receiving the ultrasonic signal, may be controlled and adjusted by the controller. A count of bubbles or an accumulation of cavitation present in the flowing liquid may be calculated by the controller to provide additional information to a user.

[0048] FIGS. **1**C and **1**D schematically illustrate a variant configuration for direct ultrasonic detection of cavitation bubbles prior to collapse of the cavitation bubbles on an internal surface of a liquid conduit **1** which operates using retro-reflection of ultrasonic signals, also referred to as a "pulse-echo" mode of operation. In contrast to the configuration illustrated in FIGS. **1**A and **1**B, the configuration of FIGS. **1**C and **1**D has a single ultrasonic transducer **5** operating as both a transmitter and receiver. Ultrasonic transducer **5** may be driven to send an ultrasonic signal propagating through the liquid flowing in liquid conduit **1** toward an opposing internal wall surface **3** of conduit **1**, and is arranged to receive the ultrasonic signal after it has been retro-reflected by surface **3** back toward ultrasonic transducer **5**. Ultrasonic transducer **5** is configured to generate an electronic cavitation detection signal representing a strength of the received ultrasonic signal. In a "pulse-echo" configuration, the electronic controller and related circuitry may be connected to ultrasonic transducer **5** and configured to execute stored programming instructions to drive the ultrasonic transducer **5**, and to process the cavitation detection signal generated by the ultrasonic transducer **5** in a manner similar to that described above in relation to FIGS. **1**A and **1**B and second ultrasonic transducer **7**.

[0049] FIGS. **2** through **9** illustrate a cavitation sensor module **10** formed in accordance with an exemplary embodiment of the present disclosure. Cavitation sensor module **10** is intended to be installed in a piping system (not shown) for conveying flow of a liquid. For example, cavitation sensor module **10** may be installed in industrial and structural hydraulic systems, liquid cooling systems such as those used at computer server farms, drinking water and wastewater systems, mining and agricultural liquid flow systems, and any liquid pumping systems where the potential for cavitation damage exists.

[0050] Cavitation sensor module **10** may comprise a pipe segment **12**, one or more first transducer plugs **14** each having a first ultrasonic transducer **15**, one or more second transducer plugs **16** each having a second ultrasonic transducer **17** to be paired with a corresponding first ultrasonic transducer **15**, and a controller circuit board assembly **18** connected to each first ultrasonic transducer **15** and each second ultrasonic transducer **17**. In FIGS. **5** and **6**, connection wiring **19** is shown for connecting only one pair of ultrasonic transducers **15**, **17** to controller circuit board assembly **18**, and connection wiring for additional ultrasonic transducers **15**, **17** is not shown for sake of clarity. However, if additional ultrasonic transducers are used by sensor module **10**, the additional ultrasonic transducers are also connected to controller circuit board assembly **18**. Cavitation sensor module **10** may further comprise an enclosure **20** for protecting first and second transducer plugs **14**, **16** and controller circuit board assembly **18**, and for securing the transducer plugs and controller circuit board assembly to pipe segment **12**.

[0051] As best seen in FIG. **5**, pipe segment **12** may be a straight length of metal or plastic pipe defining a liquid flow conduit **30** through which liquid flows. Pipe segment **12** may include couplings **32** at opposite ends thereof for connecting pipe segment **12** to piping of the liquid flow system in which cavitation sensor module **10** is installed. For example, couplings **32** may be standard pipe couplings each having an internally threaded portion **34** for mating with system piping and external flats **36** for facilitating application of torque to pipe segment **12**. The configuration of couplings **32** may be chosen for compatibility with the piping specifications of the liquid flow system in which cavitation sensor module **10** is installed. Pipe segment **12** may further includes a plurality of ports **38** extending through the wall of the pipe segment, for example in a radial direction through the wall of the pipe segment, for receiving and positioning transducer plugs **14** and **16**. Of course, pipe segment **12** may be other than a straight segment, i.e., liquid flow conduit **30** may be bent to change flow direction.

[0052] Specific reference is now made to FIGS. **7** and **8** for description of transducer plugs **14**, **16** according to an embodiment of the disclosure. Each transducer plug **14**, **16** may include a shell **40** dimensioned for slidable fit within a corresponding port **38** in pipe segment **12**. Shell **40** may hold an associated ultrasonic transducer **15** or **17** near an inner end **41** thereof, and defines a passage **42** through which wiring **19** may pass for connecting the ultrasonic transducer to controller circuit board assembly **18** by way of an electrical connector **43**. Shell **40** may be made from metal, for example stainless steel, or from plastic. The ultrasonic transducer **15** or **17** may be fitted into an insulating carrier **44** and mounted within shell **40**. The transducer plug shell **40** and its corresponding port **38** may be cylindrical in shape as shown in the drawing figures, or they may be non-cylindrical in shape. The use of transducer plugs **14**, **16** which slidably fit within a corresponding port **38** in pipe segment **12** facilitates efficient repair or replacement of the associated ultrasonic transducer **15**, **17** in the event the ultrasonic transducer experiences a malfunction.

[0053] Ultrasonic transducers **15**, **17** may be piezoelectronic transducer elements. By way of non-limiting example, ultrasonic transducers **15**, **17** may be made of any of several materials suitable for generating the ultrasonic signal, such as Lead Zirconate Titanate (PZT) or Lead Metaniobate, quartz crystals, or other piezoelectric materials. Ceramic transducer elements made from PZT, supplied by Piezo Kinetics Inc. (PKI) or APC International may be used for practicing the present disclosure. A ceramic transducer element considered suitable in prototypes of cavitation sensor module **10** is a PZT circular disk, 10.2 mm Outer Diameter×1 mm thick, sold by APC International under Part No. 973.) Ultrasonic transducers **15**, **17** may have a circular disk shape as shown in FIGS. **7** and **8**, or a rectangular or square plate shape. Insulating carrier **44** provides electrical isolation between the ultrasonic transducer **15**, **17** and the material of plug shell **40**.

[0054] Transducer plugs **14** and **16** may be manufactured according to identical specifications, incorporating ultrasonic transducers **15** and **17** of the same model or part number, in order to benefit from economies of scale in production. The current embodiment has four ports in the pipe, so two pairs of ultrasonic transducers **15**, **17** may be used to measure cavitation redundantly.

[0055] In a variant of the embodiment described above, a single ultrasonic transducer may be used in place of each ultrasonic transducer pair **15**, **17**. In that case, the single ultrasonic transducer would both transmit and receive the ultrasonic signal in a "pulse-echo" mode of operation. Multiple ultrasonic transducers operating in pulse-echo mode may be used to measure cavitation redundantly.

[0056] FIG. **9** schematically illustrates an embodiment of electronic controller board assembly **18**. Controller board assembly **18** may include a programmable microcontroller **50**, an internal programming header **51** connected to microcontroller **50**, one or more digital memory devices **52** connected to microcontroller **50**, a multiplexer **53** connected to microcontroller **50**, and an Ethernet port **55** and serial port **56** enabling data communication between an external computing device **70** and microcontroller **50**. Internal programming header **51** allows programming of microcontroller **50** in the factory, and is not user accessible.

[0057] Power may be supplied to components of controller board assembly **18** through a power supply/voltage regulator circuit **58** and a brown-out detection/watch dog timer circuit **60** connected to microcontroller **50**.

[0058] Microcontroller **50** may be connected to send drive control signals to each first ultrasonic transducer **15** by way of a waveform generator circuit **62** and a transmission signal conditioning circuit **64**. The strength and timing of the ultrasonic signals generated by each first ultrasonic transducer **15** may be controlled and adjusted by microcontroller **50** in accordance with programming instructions, for example firmware or software, executable by microcontroller **50**. A user interface may be provided to enable users to enter control parameters and settings governing characteristics of the ultrasonic signals generated by each first ultrasonic transducer **15**. External computing device **70**, for example a personal computer, may function as such a user interface. Alternatively, or in addition, a touch-sensitive display panel (not shown) incorporated on enclosure **20** and connected for data communication with microcontroller **50** may function as a user interface.

[0059] The ultrasonic signals sent by each first ultrasonic transducer **15** through liquid in pipe segment **12** may be received by a corresponding second ultrasonic transducer **17**. The cavitation detection signal generated by each second ultrasonic transducer **17** upon receiving an ultrasound signal may be processed by applying a signal gain (i.e., a scaling factor) and signal filtering at circuit **66**. The amount of gain and filtering characteristics applied to the cavitation detection signal from each second ultrasonic transducer **17** may be controlled and adjusted by microcontroller **50** in accordance with programming instructions, for example firmware or software, executable by microcontroller **50**. Users may enter control parameters and settings governing gain and filtering characteristics of the cavitation detection signals generated by each second ultrasonic transducer **17** by means of a user interface (e.g., external computing device **70**) as described above.

[0060] Each circuit **66** provides a cavitation measurement signal to microcontroller **50**. The cavitation measurement signal may be in the form of an analog voltage signal based on the cavitation detection signal from the associated second ultrasonic transducer **17**, wherein signal noise is reduced by filtering and signal strength is increased by gain/scaling. The cavitation measurement signal may be digitized by an analog-to-digital converter which may be provided as part of microcontroller **50**.

[0061] The cavitation measurement signal may be evaluated by microcontroller **50** to determine whether or not cavitation bubbles are present in the liquid between the first ultrasonic transducer **15** and the second ultrasonic transducer **17** paired therewith at a given measurement time. Microcontroller **50** may be configured to execute programming instructions, for example firmware or software stored in memory, causing the microcontroller to evaluate the amplitude of the cavitation measurement signal relative to one or more predetermined threshold values stored in memory **52**. The threshold values may be determined based upon empirical testing. As a non-limiting example for sake of illustration, a liquid in conduit **30** having no cavitation bubbles present between first and second ultrasonic transducers **15**, **17** may generate an output cavitation measurement signal of 3.0 V, and full air in conduit **30** between first and second ultrasonic transducers **15**, **17** may generate an output cavitation measurement signal of 1.0 V. Thus, during operation, a cavitation measurement signal below 3.0 V will indicate the presence of at least one cavitation bubble, and there will be a correlation between the cavitation measurement signal and the extent of cavitation present in the liquid. The nearer the cavitation measurement signal is to 1.0 V, the greater the level of cavitation is in the liquid.

[0062] An alarm threshold value may be assigned corresponding to a level of cavitation bubbles approaching—but not yet reaching—a level of cavitation bubbles known to cause damage to a system surface or component. Microcontroller **50** may be programmed to turn on an alarm if the cavitation measurement signal crosses the alarm threshold. Continuing with the non-limiting example of the preceding paragraph, an alarm threshold such as 2.0 V may be assigned, and if the cavitation measurement signal drops below the alarm threshold, then microcontroller **50** will activate an alarm device (e.g., an audio and/or visual alarm) to indicate potentially harmful cavitation is present so that corrective action may be taken to prevent damage to components or surfaces of the liquid flow system. The corrective action may be manually implemented, or may be automated. For example, a pump flow rate may be reduced manually in response to the audio and/or visual alarm, or automatically in response to an alarm signal from microcontroller **50**.

[0063] As mentioned above, a count of cavitation bubbles or an accumulation of cavitation present in the flowing liquid may be calculated by microcontroller **50** to provide additional information to a user. Microcontroller **50** may be programmed to detect a duration of time that the cavitation measurement signal "goes low" (i.e., dips under a predetermined threshold). If cavitation bubbles are relatively large, the detected duration may be used to estimate the total volume of cavitation bubbles. The detected duration information may also be used by microcontroller **50** to estimate the flow rate of the liquid flowing through pipe segment **12**. Microcontroller **50** may also be programmed to count the number of cavitation bubbles sensed over time.

[0064] The ability to control and adjust characteristics of the ultrasound signals sent through the liquid and the resulting cavitation measurement signals provided to microcontroller **50**, and the ability to assign or set relevant thresholds and ranges used by microcontroller **50** for evaluation of cavitation measurement signals, allows cavitation sensor module **10** to be configured based on specifications of the particular liquid flow system in which the cavitation sensor module is installed. Such specifications may include but are not limited to the type and physical properties of the flowing liquid, and the pumping flow rate or flow rate range.

[0065] As further indicated in FIG. **9**, controller board assembly **18** may include a digital output **68**, an analog voltage output **72**, and an analog current output **74** connected to microcontroller **50**. Additional sensors and transducers, represented at block **76**, may be connected to microcontroller **50** to enhance the functionality of cavitation sensor module **10**. Such additional sensors and transducers may include sensors and transducers for measuring or detecting pressure, temperature, flow rate, occlusions, and foreign debris in flow. For example, optical sensors may be connected to microcontroller **50** for detecting foreign debris in flow or other aspects of the flowing liquid. Controller board assembly **18** may also include an IO-Link transceiver **78** which will allow data and signal communication with an external industrial network **80**.

[0066] Multiplexer **53** may be implemented between microcontroller **50** and the various outputs **68**, **72**, **74**, and **78**. As a result, two pins of a single 4-pin connector provide either (a) up to two digital outputs, or (b) up to two analog outputs, either voltage or current, or (c) an IO-Link output which is a "data" type of output (not just signal). The output type (a, b, or c) may be user-configurable.

[0067] In alternative implementations of the present disclosure, programmable microcontroller **50** may be replaced by a microprocessor, a computer, a field programmable gate array (FPGA), or even hardware-only electronics with no firmware or software involved.

[0068] As shown in FIGS. **2** through **4**, enclosure **20** may be configured to enclose and protect transducer plugs **14**, **16** and controller circuit board assembly **18** from environmental contaminants. For example, enclosure **20** may be sealed to prevent liquid from entering and damaging transducer plugs **14**, **16** and controller circuit board assembly **18**. Enclosure **20** may include a central piece **22**A dimensioned to receive controller circuit board assembly **18** and a first radial portion of pipe segment **12**, a cover piece **22**B removably attached to central piece **22**A and dimensioned to cover controller circuit board assembly **18**, and a securement piece **22**C removably attached to central piece **22**A and dimensioned to receive a second radial portion of pipe segment **12** opposite the first radial portion of pipe segment **12** to secure enclosure **20** on the pipe segment. Cover piece **22**B may be removably attached to central piece **22**A by threaded fasteners (not shown) arranged in a plurality of aligned fastener holes **24** in cover piece **22**B and central piece **22**A. Securement piece **22**C may be removably attached to central piece **22**A by threaded fasteners (not shown) arranged in a plurality of aligned fastener holes **26** in securement piece **22**C and central piece **22**A. As may be seen in the figures, enclosure **20** may be configured such that the enclosure does not enclose couplings **32** of pipe segment **12**, thereby enabling access to the couplings when cavitation sensor module **10** is installed in a piping system.

[0069] As may be understood, the multi-piece configuration of enclosure **20** according to the present disclosure enables pipe segment **12** with transducer plugs **14** and **16** to be installed in a piping system before the other components of cavitation sensor module **10** are installed. After pipe segment **12** with transducer plugs **14** and **16** is installed in the piping system, enclosure **20** containing controller circuit board assembly **18** may be mounted on pipe segment **12** and connection wiring **19** from ultrasonic transducers **15**, **17** may be connected to controller circuit board assembly **18** by plugging electrical connectors **43** into corresponding connection sockets in the controller circuit board assembly. The multi-piece configuration of enclosure **20** also allows the cavitation sensor module **10**, minus pipe segment **12** and transducer plugs **14** and **16**, to be easily removed from a piping system.

[0070] In the embodiments described above, the control electronics is mounted on the housing, for example on pipe segment **12** or on a pump housing. FIGS. **10-17** illustrate an ultrasonic cavitation sensor apparatus **110** according to another embodiment of the present disclosure, wherein the control electronics of the apparatus is located remote from the housing having the liquid flow conduit. Ultrasonic cavitation sensor apparatus **110** may generally comprise a control unit **111**, a housing **112** (e.g., a pipe segment or a pump housing) and one or more first transducer plugs **14** each having a first ultrasonic transducer **15**, one or more second transducer plugs **16** each having a second ultrasonic transducer **17** to be paired with a corresponding first ultrasonic transducer **15**, and a controller circuit board assembly **118** located remote from the housing **112** within an enclosure **120** of control unit **111**. Circuit board assembly **118** may be connected to each first ultrasonic transducer **15** and each second ultrasonic transducer **17** by transducer cables **119**. As may be seen in FIG. **11**, circuit board assembly **118** may include a coaxial power connector **59**, Ethernet port **55**, and a plurality of cable connectors **67** for connecting transducer cables **119** to circuit board assembly **118**.

[0071] FIG. **12** shows housing **112** embodied as a pipe segment having a liquid flow conduit **30** and a pair of female pipe couplings **32** each having an internally threaded portion **34** for mating with system piping. Of course, other types of pipe segments may be used embody housing **112**. For example, in FIG. **10**, housing **112** is embodied by a pipe segment having a pair of couplings **32** having external threads **34**. Examples of common pipe segment configurations useful as housing **112** are illustrated in FIGS. **13**A through **13**C. FIG. **13**A shows a pipe segment having "sanitary flange" connection couplings **32**. FIG. **13**B shows a pipe segment having female NPT couplings **32**, similar to housing **112** in FIG. **12**. FIG. **13**C shows a pipe segment having male NPT couplings **32**, similar to housing **112** in FIG. **10**. Sizing of the pipe segments may be adapted to meet system requirements, and standard sizes may be offered to fit nominal pipe sizes such as 1-inch, 1.5-inch, 2-inch, 2.5-inch, and 3-inch sizes. Of courses, larger or smaller sizes may be developed, and the configuration of couplings **32** is subject to design choice. Threaded ports **38** for receiving transducer plugs **14** and **16** may be drilled and tapped through a wall of housing **112** so that the transducer plugs are arranged coaxially across flow conduit **30** from each other. By using a standardized configuration for transducer plugs **14** and **16** and transducer ports **38**, economies of scale and design simplicities are realized.

[0072] FIGS. **14** and **15** illustrate another embodiment of transducer plugs **14** and **16** according to the present disclosure. Plug **14**, **16** is hermetically sealed and very modular. As may be seen, plug **14**, **16** includes a plug housing **82** which may be machined from either plastic or metal, a carrier plate **84** which may be formed of plastic, a piezoelectronic transducer element **15**, **17** supported by carrier plate **84**, and a sealed connector **86** having a pair of contact members **88** connected to transducer element **15**, **17** by a pair of wires **89**. In the illustrated embodiment, connector **86** is fixed against a circular mounting plate **90** by a nut **92**, and fluid-sealed with an O-ring **94**. Mounting plate **90** may be fixedly held within plug housing **82** by adhesive potting **96**. As may be understood, a transducer cable **119** may be removably connected at one end to connector **86** of transducer plug **14**, **16** and at the opposite end to a cable connector **67** on circuit board assembly **118**. Plug housing **82** includes an externally threaded portion **83** designed to mate with internally threaded ports **38** in housing **112** for easy installation and removal of the transducer plug **14**, **16**.

[0073] As shown in FIGS. **16** and **17**, ultrasonic cavitation sensor apparatus **110** may be modified for installation on a pump housing **212** of a centrifugal pump **200**, wherein the pump housing **212** takes the place of pipe segment **112**. Pump housing **212** includes an outlet liquid conduit **230** and a plurality of ports **238** extending through a wall of the pump housing for receiving and positioning transducer plugs **14** and **16**. Transducer plugs **14**, **16** are threaded and have an O-ring seal for high pressure fluid sealing, so the outlet of pump housing **212** may be drilled and tapped with holes on a common center axis to form ports **238**, and transducer plugs **14**, **16** may be threaded into the ports **238**.

[0074] As shown in FIGS. **18** and **19**, ultrasonic cavitation sensor apparatus **110** may be modified for installation on a valve housing **312** of a liquid flow valve **300**, wherein the valve housing **312** takes the place of pipe segment **112**. Valve housing **312** includes a liquid conduit **330** and a plurality of ports **338** extending through a wall of the valve housing for receiving and positioning transducer plugs **14** and **16**. Transducer plugs **14**, **16** are threaded and have an O-ring seal for high pressure fluid sealing. Valve housing **312** may be drilled and tapped with holes on a common center axis to form ports **338**, and transducer plugs **14**, **16** may be threaded into the ports **338**.

[0075] A "clamp-on" variant of the of the present disclosure is shown in FIGS. **20-22**. In the clamp on variant, ultrasonic transducers **15**, **17** may be installed on a clamp body **400** configured to be clamped onto an existing pipe segment or pipe **412**, or another housing in an existing liquid flow system, having a liquid flow conduit **430**. A clamp-on variant may be used in situations where a non-invasive installation is desired, i.e. in situations where it is not practical, safe, or possible to drill and tap an existing housing to access the liquid flow conduit and install transducer plugs **14**, **16**. The clamp-on variant is non-invasive because the transducer plugs **14**, **16** do not protrude into the liquid conduit **430** through which liquid flows.

[0076] FIGS. **20** and **21** depict a simple example for clamping to cylindrical piping that comprises a clamp body **400** having a pair of arcuate brackets **401** and **402** designed to releasably mate with each other and tighten around cylindrical piping **412** within a range of outer diameters. In the embodiment shown, bracket **401** includes a first flange **403** having an opening **404** therethrough and a second flange **405** having a fastener hole **406** therethrough, and bracket **402** includes a first flange **407** bent to define a clasp sized for removable receipt through opening **404** and a second flange **408** having a fastener hole **409** therethrough. A bolt **410** may be arranged through aligned fastener holes **406**, **409** and secured with a nut **411** to adjustably tighten clamp body **400** onto piping **412**. Each bracket **401**, **402** may include an internally threaded port **38** for respectively receiving and positioning a transducer plug **14**, **16** such that when brackets **401**, **402** are tightened together the corresponding transducers **15**, **17** are axially aligned with one another across liquid conduit **430** of piping **412**. While a simple clamp bracket is shown in FIGS. **20** and **21**, other clamping configurations are of course possible, including but not limited to a linear sliding rail or a spring-loaded transducer housing. Transducer connection cables (not shown) may be provided to connect transducer plugs **14**, **16** to control unit **111** as described above.

[0077] In the clamp-on variant, the ultrasound signal from each first ultrasonic transducer **15** must travel through the wall of housing **412** twice as the signal travels to reach the paired second ultrasonic transducer **17**. Therefore, modifications that minimize the signal attenuation effects of the housing wall may be advantageous. Good coupling of the transducers **15**, **17** to the exterior wall surface of housing **412** is important. For this reason, as best seen in FIG. **22**, each transducer plug **14**, **16** may include a compliant face pad **87** on an end face of plug housing **82**. Compliant face pad **87** may be made of an elastomeric material to conform to the contour of the exterior wall surface of housing **412** when clamp body **400** is tightened onto housing **412**. An ultrasonic coupling containing liquid or gel may be provided in association with each of the transducer plugs **14**, **16** to aid propagation of ultrasonic energy between each ultrasonic transducer **15**, **17** and the existing housing **412** to which the transducers are clamped. The strength of the transmitted ultrasound signals, and the gain applied to the received cavitation detection signals, may be increased to make up for ultrasonic signal attenuation caused by the housing wall.

[0078] A bonded or adhered variant of the present disclosure is shown in FIGS. **23-25**. In many cases, an application has physical space or weight constraints and the use of a transducer plug **14**, **16** is not feasible. Or, in some cases, it may be undesirable to have a transducer plug configuration that is invasive and has a port **38** that may interrupt the otherwise smooth inner surface of a liquid conduit in a pipe, fitting, or other system component housing. In these cases, an ultrasonic transducer system **500** may be bonded to an exterior surface of the housing **512** of the component. For example, in the drawing figures, housing **512** is embodied as a reducer fitting where cavitation may be generated at an inner diameter transition of liquid conduit **530**. The mounting area may be too small for an invasive transducer plug assembly, and if a transducer plug is installed, it may itself cause unwanted cavitation. In the bonded variant, transducer assemblies **514** and **516** may be mounted to the exterior of the fitting **512**. Each transducer assembly **514**, **516** may include a carrier plate **84** which may be formed of plastic, a piezoelectronic transducer element **15**, **17** supported by and bonded to the carrier plate **84**, and a pair of wires **89** connected to transducer element **15**, **17**. A suitable mounting location may prepared by machining a counterbore or flat surface **513** on the exterior surface of fitting **512**. The carrier plate **84** of each transducer assembly **514**, **516** may be bonded to surface **513** using suitable adhesive or bonding agent. As described above, axial alignment of paired transducer elements **15** and **17** is desirable. Wires **89** from each transducer element **15**, **17** may be fed into a connection cable (not shown) that connects to a corresponding cable connector **67** on control unit **111**.

[0079] As may be understood, each embodiment described herein as using paired transducers **15**, **17** may be modified to operate using a single transducer operating in a pulse-echo arrangement.

[0080] Reference is now made to FIGS. **26**A and **26**B for describing an optional user interface display screen **600** of the ultrasonic cavitation sensor apparatus **110**. Screen **600** may be displayed on external computing device **70**, for example a personal computer, and/or on a touch-sensitive display panel connected for data communication with microcontroller **50**. A user interface is not required for use of cavitation sensor apparatus **110**, as the sensor apparatus may operate in a standalone configuration to provide a digital and/or analog output signal to a connected device. However, a user interface may be provided and used for setting sensitivity parameters and general setup parameters of sensor apparatus **110**.

[0081] User interface screen **600** enables a user to monitor functions of sensor apparatus **110** and to set operating parameters of sensor apparatus **110**. FIG. **26**A shows display screen **600** during operation of sensor apparatus **110** when no cavitation bubble is present, whereas FIG. **26**B shows display screen **600** during operation of sensor apparatus **110** when four sets of cavitation bubbles are present. FIGS. **26**A and **26**B represent snapshots of screen **600** during operation of sensor apparatus **110**, and certain portions of display screen **600** are dynamic and change as liquid flow conditions monitored by sensor apparatus **110** change.

[0082] Screen **600** may include a signal strip chart panel **602**, an averaged signal strip chart panel **604**, an averaging slider tool **605**, a tuning slider tool **606**, a signal data panel **608**, a status text box **610**, and a cavitation alarm setup panel **611**. Screen **600** may include further interface items intended for use by factory set-up technicians and service technicians, as opposed to end users of sensor apparatus **110**. These further items of screen **600** may include a communications configuration panel **614**, tuning control panels **615** and **616**, and a record capture panel **618**. It is contemplated to provide a limited version of screen **600** lacking further items **614**, **615**, **616**, and **618** for end user purposes, and an enhanced version of screen **600** including the further items **614**, **615**, **616**, and **618** for factory and service technician purposes.

[0083] Signal strip chart panel **602** has a strip chart recorder **620** showing instantaneous strength of the received ultrasonic signal as a function of time, and may include a slider tool **622** for setting the number of points on the X-axis (time axis) of strip chart recorder **620**. The signal strength range is indicated on the left side of the panel (0 to 100%). If the received signal is at 100%, it indicates that the liquid between the transmitting ultrasonic transducer **15** and the paired receiving ultrasonic transducer **17** has no cavitation bubbles. If the received signal is at 0%, it indicates that there is enough cavitation bubble formation present to block the transmitter-to-receiver path of the ultrasonic signal. A value between 0% and 100% indicates the relative size or volume of cavitation bubbles present in the transmitter-to-receiver path of the ultrasonic signal. Received signal strength is inversely proportional to the size of cavitation bubbles in the transmitter-to-receiver path of the ultrasonic signal.

[0084] Averaged signal strip chart panel **604** is similar to signal strip chart panel **602**. Averaged signal strip chart panel **604** has a strip chart recorder **624** showing a smoothed average of the signal strength as a function of time rather than the instantaneous signal strength as shown in strip chart recorder **620**. This difference is more readily apparent in FIG. **26**B than FIG. **26**A. Averaged signal strip chart panel **604** may include a slider tool **626** for setting the number of points on the X-axis (time axis) of strip chart recorder **624**. Averaging slider tool **605** sets the time interval over which signal strength is averaged in strip chart recorder **624**.

[0085] Tuning slider tool **606** sets a time between tuning events during which a resonant frequency of first ultrasonic transducer **15** is found in order to transmit at maximum signal strength. For example, the tuning event may involve a frequency sweep of first ultrasonic transducer **15** to find the resonant frequency.

[0086] Signal data panel **608** displays instantaneous measurement data of the ultrasonic transducers **15**, **17** such as received signal strength, transmitter frequency, peak voltage of receiving transducer **17**, and other measurement data. The received signal strength indicated in signal data panel **608** is the same as the instantaneous signal strength represented in the strip chart recorder **620** at the right edge (right vertical axis) of strip chart recorder **620**.

[0087] Status text box **610** displays data that is being recorded by sensor apparatus **110**.

[0088] Cavitation alarm setup panel **611** includes interface tools enabling a user to establish one or more alarm conditions for triggering generation of a cavitation alarm signal based on characteristics of the cavitation measurement signal. The alarm conditions may include a cavitation occurrence condition that is met when a strength of the cavitation measurement signal falls below a cavitation alarm set point. For example, if through observation by the user it is determined that system damage potentially occurs when strength of the cavitation measurement signal drops below 10%, then the cavitation alarm set point may be set at 10% as shown in FIGS. **26**A and **26**B. Cavitation alarm setup panel **611** may include a set point slider tool **628**, a set point scroll **630**, and/or other user interface input tools by means of which a user may enter a variable user input for establishing the cavitation alarm set point.

[0089] Microcontroller **50** may be programmed to register a cavitation error count corresponding to a consecutive number of times the cavitation occurrence condition has been met, and the alarm conditions may further include a cavitation error count condition that is met when the cavitation error count equals a cavitation error count setting specified by a user. As may be understood, the error count setting may be set to a value high enough to eliminate nuisance alarms. For example, in FIGS. **26**A and **26**B, the cavitation error count setting is set to five, so that five consecutive events in which the cavitation occurrence condition is met (i.e., the cavitation measurement signal drops below the cavitation alarm set point) are required to cause the output alarm. In one embodiment, the error count setting may be set to any integer value from **1** to **1000**, however other ranges may be provided for the error count setting. Cavitation alarm setup panel **611** may include an error count scroll **632** and/or other user interface input tools by means of which a user may enter a variable user input for establishing the error count setting.

[0090] Communications configuration panel **614** includes switches used to facilitate communications between an external computing device **70** and the ultrasonic transducers **15**, **17** for debugging and development purposes. Switch **634** controls Transmission Control Protocol (TCP) so that external computing device **70** may be selectively enabled as host by Ethernet connection. Switch **636** changes the operational mode of the ultrasonic transducers between a pulse transmission mode and a continuous transmission mode. Switch **638** pauses tuning sweeps for debugging purposes. Switch **640** turns tuning ON and OFF (when tuning is OFF, the ultrasonic transducers operate at a static frequency).

[0091] Tuning control panels **615** and **616** enable technicians to input other settings for development and debugging purposes. Tuning control panel **615** allows a user to alter ultrasonic transducer pulse and tuning settings. Tuning control panel **616** allows a user to adjust a tuning set point (i.e., an acceptable level for maximum reading). This panel will not be available in the commercial version.

[0092] Record capture panel **618** allows a user to set a file name for recording data, set a tuning range, and enable and disable capture for a status box **642**.

[0093] As mentioned above, communications configuration panel **514**, tuning control panels **615** and **616**, and record capture panel **618** are intended for use by factory and service technicians, and may be omitted from a commercial version of user interface screen **600** available to end users.

[0094] FIG. **26**A shows user interface screen **600** when no cavitation bubbles are present. As may be seen in strip chart recorders **620** and **624**, the strength of the cavitation measurement signal remains very high. By contrast, FIG. **26**B shows user interface screen **600** when several cavitation bubbles are present. Strip chart recorders **620** and **624** show at least four large cavitation events where the instantaneous strength of the cavitation measurement signal drops to nearly 0%. The trace of strip chart recorders **620** and **624** is moving from right to left, such that the current cavitation measurement signal strength is on the right axis (right edge) of each chart.

[0095] The numeric strength value of the current instantaneous signal is displayed in the top text box in signal data panel **608**. In this example, the signal strength is 0.0%. If the signal strength drops below the cavitation alarm set point and meets the cavitation error count setting inputted by a user at cavitation alarm setup panel **611**, program instructions executed by microcontroller **50** cause the microcontroller to generate a cavitation alarm signal. The cavitation alarm signal may be transmitted to external control equipment connected directly or over industrial network **80** to circuit board assembly **118**. For example, the cavitation alarm signal may be transmitted to a flow valve controller and/or a pump controller to automatically reduce or halt liquid flow through conduit **130** in response to the alarm signal to prevent cavitation damage before it begins. Alternatively or additionally, the cavitation alarm signal may be transmitted to trigger audible and/or visible alarm equipment to alert personnel of cavitation. If a cavitation alarm signal is generated, a visual indication of the alarm signal may be provided on user interface screen **600**, such as changing a color of the top text box in signal data panel **608** to red to show alarm status.

[0096] Cavitation sensor module **10** and cavitation sensor apparatus **110** of the present disclosure directly detect and measure cavitation vapor bubbles in flowing liquid. This differs from the aforementioned indirect sensing methods which detect an artifact of cavitation such as noise, vibration, or pump behavior. Consequently, cavitation bubbles are detected before they can be heard acoustically or seen visually so that equipment damage may be prevented. Moreover, the cavitation can be quantified by measuring the size and/or number of bubbles present. Cavitation may be detected at a very low level, and the sensing logic is adjustable or tunable to ignore cavitation below a set level where the cavitation is only a nuisance and not damaging. Unlike some indirect cavitation sensors of the prior art, cavitation sensor module **10** and cavitation sensor apparatus **110** of the present disclosure are suitable for use in noisy environments. Cavitation sensor module **10** and cavitation sensor apparatus **110** are compact and inexpensive to produce.

[0097] Cavitation sensors of the present disclosure, and the methodology employed thereby, find useful application in heavy industry to protect expensive pump systems from potential cavitation damage. Other applications include predictive maintenance, leak detection, and safety alarms.

[0098] While the disclosure describes various exemplary embodiments, the detailed description is not intended to limit the scope of the disclosure to the particular forms set forth. The disclosure is intended to cover such alternatives, modifications and equivalents of the described embodiment as may be apparent to one of ordinary skill in the art.

What is claimed is:

1. An apparatus for sensing cavitation in liquid flowing through a liquid conduit, the apparatus comprising:

an ultrasonic transducer system including one or more ultrasonic transducers each arranged in acoustic communication with the liquid flowing through the conduit; and

control electronics connected to the ultrasonic transducer system, the control electronics being configured to drive the ultrasonic transducer system to send an ultrasonic signal through liquid flowing through the conduit, wherein the ultrasonic transducer system receives the ultrasonic signal and generates an electronic cavitation detection signal representing a strength of the ultrasonic signal as received by the ultrasonic transducer system;

the control electronics being further configured to process the cavitation detection signal to i) provide a cavitation measurement signal indicative of whether or not the ultrasonic signal interacted with one or more cavitation bubbles in liquid flowing through the conduit, ii) evaluate the cavitation measurement signal to determine if one or more cavitation alarm conditions is met, and iii) output an alarm signal when each of the one or more cavitation alarm conditions is met.

2. The apparatus according to claim **1**, further comprising a housing having the conduit, wherein each of the one or more ultrasonic transducers is attached to the housing.

3. The apparatus according to claim **1**, wherein the one or more ultrasonic transducers of the ultrasonic transducer system includes a first ultrasonic transducer and a second ultrasonic transducer facing the first ultrasonic transducer across the conduit, wherein the control electronics is configured to drive the first ultrasonic transducer to send the ultrasonic signal through liquid flowing through the conduit, and wherein the second ultrasonic transducer receives the ultrasonic signal and generates the electronic cavitation detection signal.

4. The apparatus according to claim **1**, wherein the one or more ultrasonic transducers of the ultrasonic transducer system includes a single ultrasonic transducer, wherein the control electronics is configured to drive the single ultrasonic transducer to send the ultrasonic signal through liquid flowing through the conduit such that the ultrasonic signal is retro-reflected by the housing back to the single ultrasonic transducer, and wherein the single ultrasonic transducer receives the ultrasonic signal and generates the electronic cavitation detection signal.

5. The apparatus according to claim **1**, further comprising a user interface connected to the control electronics.

6. The apparatus according to claim **5**, wherein the user interface is configured to display the cavitation measurement signal and/or a value representing an instantaneous strength of the cavitation measurement signal.

7. The apparatus according to claim **5**, wherein the control electronics has a cavitation alarm set point, and the one or more cavitation alarm conditions includes a cavitation occurrence condition that is met when a strength of the cavitation measurement signal falls below the cavitation alarm set point.

8. The apparatus according to claim **7**, wherein the user interface is configured to receive a first variable user input for establishing the cavitation alarm set point.

9. The apparatus according to claim **7**, wherein the control electronics has a cavitation error count setting, the control electronics is configured to register a cavitation error count corresponding to a consecutive number of times the cavitation occurrence condition has been met, and the one or more cavitation alarm conditions includes a cavitation error count condition that is met when the cavitation error count equals the cavitation error count setting.

10. The apparatus according to claim **9**, wherein the user interface is configured to receive a second variable user input for establishing the cavitation error count setting.

11. The apparatus according to claim **1**, wherein the control electronics is located remote from the housing.

12. The apparatus according to claim **1**, wherein the control electronics is mounted on the housing.

13. The apparatus according to claim **1**, wherein the housing is selected from a group of housings consisting of a pipe segment, a pump housing, a valve housing, and a flow reducer.

14. A method for sensing cavitation in liquid flowing through a conduit, the method comprising the steps of:

arranging a first ultrasonic transducer in acoustic communication with the liquid flowing through the conduit;

arranging a second ultrasonic transducer in acoustic communication with the liquid flowing through the conduit, wherein the second ultrasonic transducer faces the first ultrasonic transducer across the conduit;

driving the first ultrasonic transducer to send an ultrasonic signal through liquid flowing through the conduit;

receiving, by the second ultrasonic transducer, the ultrasonic signal;

generating, by the second ultrasonic transducer, an electronic cavitation detection signal representing a strength of the ultrasonic signal as received by the second ultrasonic transducer;

processing the cavitation detection signal to provide a cavitation measurement signal indicative of whether or not the ultrasonic signal interacted with one or more cavitation bubbles in liquid flowing through the conduit;

evaluating the cavitation measurement signal to determine if one or more cavitation alarm conditions is met; and

outputting an alarm signal when each of the one or more cavitation alarm conditions is met.

15. The method according to claim **14**, further comprising the step of displaying the cavitation measurement signal and/or a value representing an instantaneous strength of the cavitation measurement signal.

16. The method according to claim **15**, wherein the one or more cavitation alarm conditions includes a cavitation occurrence condition, and wherein the step of evaluating the cavitation measurement signal includes comparing a strength of the cavitation measurement signal to a predetermined cavitation alarm set point, and determining that the cavitation occurrence condition is met when a strength of the cavitation measurement signal falls below the cavitation alarm set point.

17. The apparatus according to claim **16**, wherein the one or more cavitation alarm conditions includes a cavitation error count condition, and wherein the step of evaluating the cavitation measurement signal includes registering a cavitation error count corresponding to a consecutive number of times the cavitation occurrence condition has been met, and determining that the cavitation error count condition is met when the cavitation error count equals a predetermined cavitation error count setting.

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