



(86) Date de dépôt PCT/PCT Filing Date: 2008/04/18

(87) Date publication PCT/PCT Publication Date: 2008/11/06

(45) Date de délivrance/Issue Date: 2013/06/11

(85) Entrée phase nationale/National Entry: 2009/08/18

(86) N° demande PCT/PCT Application No.: NO 2008/000139

(87) N° publication PCT/PCT Publication No.: 2008/133524

(30) Priorité/Priority: 2007/04/30 (NO20072236)

(51) Cl.Int./Int.Cl. *G01M 3/02* (2006.01)

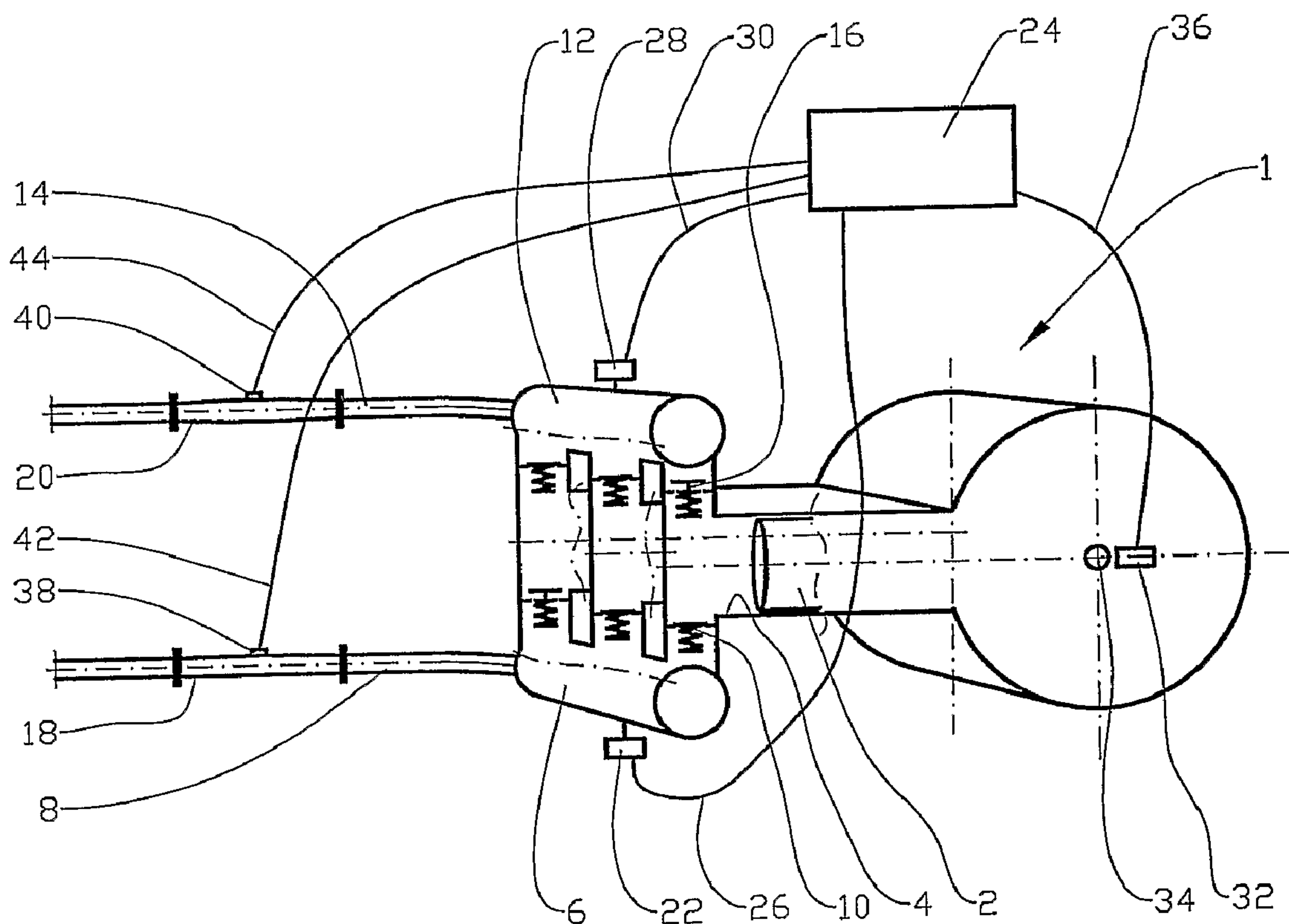
(72) Inventeur/Inventor:
KYLINGSTAD, AEGE, NO

(73) Propriétaire/Owner:
NATIONAL OILWELL NORWAY AS, NO

(74) Agent: RIDOUT & MAYBEE LLP

(54) Titre : PROCEDE POUR LA DETECTION D'UNE FUITE DE LIQUIDE D'UNE MACHINE A PISTON

(54) Title: METHOD FOR DETECTION OF A FLUID LEAK RELATED TO A PISTON MACHINE



(57) Abrégé/Abstract:

A method for detection of a fluid leak related to at least one piston machine (1), where the method includes: - attaching a vibration sensor (38, 40) to at least one of the upstream pipe (8) or the downstream pipe (14) of the piston machine (1); - measuring the



(57) Abrégé(suite)/Abstract(continued):

vibration at the at least one vibration sen-sor (38, 40); - attaching a sensor (32) to the at least one piston machine (1) that renders a signal for calculating the rotational speed and shaft position of the at least one piston machine (1); - calculating the rotational speed and angular shaft position of the at least one piston machine (1); - calculating at least one complex harmonic Fourier amplitude of the measured vibration signal; - low pass filtering said amplitude; - calculating the deviation amplitude as the magnitude of a complex difference between said filtered amplitude and a base amplitude; and - monitoring said deviation amplitude (46) to detect a leakage.

(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau



(43) International Publication Date
6 November 2008 (06.11.2008)

PCT

(10) International Publication Number
WO 2008/133524 A1

(51) International Patent Classification:
G01M 3/02 (2006.01)

(21) International Application Number:
PCT/NO2008/000139

(22) International Filing Date: 18 April 2008 (18.04.2008)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
20072236 30 April 2007 (30.04.2007) NO

(71) Applicant (for all designated States except US): **NATIONAL OILWELL NORWAY AS** [NO/NO]; Postboks 8181, N-4069 Stavanger (NO).

(72) Inventor; and

(75) Inventor/Applicant (for US only): **KYLLINGSTAD, Åge** [NO/NO]; Hogstadbakken 8, N-4330 Ålgård (NO).

(74) Agent: **HÅMSØ PATENTBYRÅ ANS**; Postboks 171, N-4302 Sandnes (NO).

(81) Designated States (unless otherwise indicated, for every kind of national protection available): AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BR, BW, BY, BZ, CA, CH, CN, CO, CR, CU, CZ, DE, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IS, JP, KE, KG, KM, KN, KP, KR, KZ, LA, LC, LK, LR, LS, LT, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PG, PH, PL, PT, RO, RS, RU, SC, SD, SE, SG, SK, SL, SM, SV, SY, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(84) Designated States (unless otherwise indicated, for every kind of regional protection available): ARIPO (BW, GH, GM, KE, LS, MW, MZ, NA, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European (AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MT, NL, NO, PL, PT, RO, SE, SI, SK, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

Published:

- with international search report
- before the expiration of the time limit for amending the claims and to be republished in the event of receipt of amendments

(54) Title: METHOD FOR DETECTION OF A FLUID LEAK RELATED TO A PISTON MACHINE

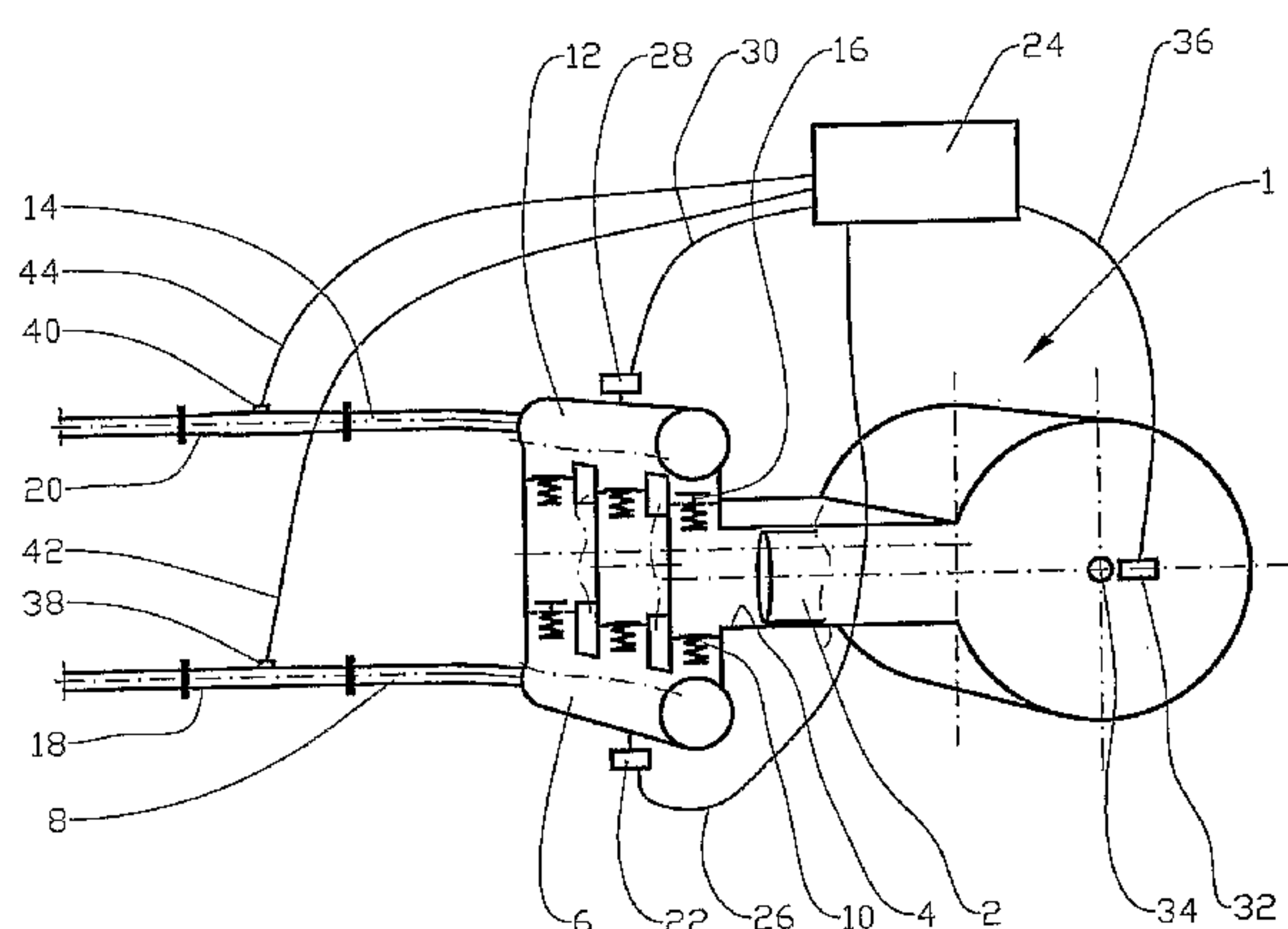


Fig. 1

(57) Abstract: A method for detection of a fluid leak related to at least one piston machine (1), where the method includes: - attaching a vibration sensor (38, 40) to at least one of the upstream pipe (8) or the downstream pipe (14) of the piston machine (1); - measuring the vibration at the at least one vibration sensor (38, 40); - attaching a sensor (32) to the at least one piston machine (1) that renders a signal for calculating the rotational speed and shaft position of the at least one piston machine (1); - calculating the rotational speed and angular shaft position of the at least one piston machine (1); - calculating at least one complex harmonic Fourier amplitude of the measured vibration signal; - low pass filtering said amplitude; - calculating the deviation amplitude as the magnitude of a complex difference between said filtered amplitude and a base amplitude; and - monitoring said deviation amplitude (46) to detect a leakage.

WO 2008/133524 A1

METHOD FOR DETECTION OF A FLUID LEAK RELATED TO A PISTON MACHINE

This invention concerns detection of a fluid leak in relation to a piston machine. More specifically the invention concerns
5 a method for detection of a fluid leak related to at least one piston machine, where the method includes:

- attaching a vibration sensor to at least one of the upstream pipe or the downstream pipe of the piston machine;
- measuring the vibration at the at least one vibration sensor;

- attaching a sensor to the at least one piston machine that renders a signal for calculating the rotational speed and shaft position of the at least one piston machine;

- calculating the rotational speed and angular shaft position of the at least one piston machine;

- calculating at least one complex harmonic Fourier amplitude of the measured vibration signal;

- low pass filtering said amplitude;

- calculating the deviation amplitude as the magnitude of a

- complex difference between said filtered amplitude and a base amplitude; and

- monitoring said deviation amplitude to detect a leakage.

Leakage in this context cover a wide range of malfunctions

having in common that they lead to cyclic drops in the flow rate through the machine, relative to a normal situations with no defective components. Examples of such malfunctions are:

- 5 - piston seal failure;
- valve seal defects causing a reverse flow past the seal during the closing time of the seal; and
- a broken valve return spring causing an extended delay of valve closing.

10 Detection and localization of leaks related to piston machines (hereafter referred to as pumps, for simplicity) is important for minimizing costs and down time related to valve and piston failures. Today's practice offers no certain way to detect and localize leaks.

15 It is well known that a leak in one or more valves or pistons will cause a drop in the total flow and that this drop will, in turn, cause a drop also in the discharge pressure. However, such a pressure drop can also result from leaks outside the pump or even reductions in the flow resistance not re-
20 lated to leaks. Such reductions can come from changes in fluid temperature and viscosity, or from a bypass of one or more flow restrictors. Therefore, a pressure drop cannot alone be used for localizing the leak.

A leak in a valve or piston manifests itself by several ef-
25 fects that can be picked up by various sensors. The most striking changes due to a growing leak are:

- The discharge pressure starts dropping, provided that the loss in pressure is not compensated by an increase of the total pump rate.
- 30 - The discharge pressure for a pump starts to vary cyclically with a period equal to the pump rotation period.
- The suction pressure for a pump also starts to vary cyclically with the same period.
- Low frequency and cyclic vibrations increase, especially on

flexible hoses, both the high-pressure hose and the low-pressure hose.

All the mentioned leak indicators can be used, either as stand-alone indicators or in combination with the others.

It is well known that the lower harmonics of the pressure, especially the first and second harmonics, increase in magnitude as the leak develops and the reverse flow through one of the pistons or valves increases, see US-patent 5720597.

Experience has proved it difficult to normalize the first harmonic pressure component so that it is nearly independent of speed and mean pressure. This is due to the fact that a dynamic pressure is a complicated function of the frequency of the leak flow variations and the piping geometry, upstream piping geometry for the suction pressure and downstream piping geometry for the discharge pressure.

WO document 03/087754 describes a method using a combination of active speed variation tests and harmonic analysis to both quantify and localize leakage. Experience has shown, however, that this method does not work satisfactory in field environments.

The object of the invention is to increase the cost efficiency of recovery of petroleum from a reservoir rock formation. The object is sought to be achieved by the method and machine disclosed herein.

In one embodiment, there is provided a method for detection of a fluid leak related to a machine comprising at least one piston and a pump shaft, the method comprising: receiving a vibration signal from a vibration sensor disposed on at least one of an upstream pipe and a downstream pipe of the machine; receiving a

rotational speed signal and an angular shaft position signal from a speed and position sensor disposed on the machine; calculating a rotational speed and an angular shaft position of the pump shaft; calculating at least one complex harmonic Fourier amplitude of the vibration signal; low pass filtering the at least one complex harmonic Fourier amplitude to obtain a filtered amplitude; calculating a deviation amplitude as the magnitude of a complex difference between the filtered amplitude and a measured base amplitude; and detecting, when present, fluid leakage within the machine based upon the deviation amplitude.

It is greatly advantageous to monitor the *deviations* of the dynamic variations instead of just the amplitudes. The reason is that the observed variations may consist of several components having different phases. Each component may be regarded as a vector, characterized by having both a length and direction, and the total dynamic component is the vector sum. It can often happen that the length of the vector sum is less than the length of the largest component.

As an example, imperfect balancing of the piston machine will cause a cyclic first harmonic motion. When a leak-induced motion is superimposed on this unbalanced motion, it is not unlikely that the directions or phases differ by more than 90° , causing the resulting amplitude to drop when a leak develops. By monitoring the deviation amplitude instead of the resultant amplitude, a growing leak can be detected even though the resulting amplitude decreases.

Monitoring of deviations implies that reference or base values must be established before a deviation can be detected. The procedure for finding the base line values is discussed

below.

The lower harmonics of the vibrations can be calculated in several ways. One method is to apply standard Fourier transform of a time record and pick the components corresponding to the pump harmonics. A more accurate method that is preferred if the pump speed and/or the sampling time intervals vary, is to use a Fourier analysis based on the measured angular shaft position θ as shown below.

Below, complex notation where $i=\sqrt{-1}$ is the imaginary unit, is utilized. The complex Fourier coefficients of a dynamic, time dependent variable f is given by

$$F_k = \frac{1}{\pi} \int_0^{2\pi} f \cdot e^{ik\theta} d\theta = \frac{1}{\pi} \int_0^{2\pi} f \cdot \cos(k\theta) d\theta + \frac{i}{\pi} \int_0^{2\pi} f \cdot \sin(k\theta) d\theta \quad (E1)$$

where k is a positive integer representing the harmonics number. In principal, any harmonics of the vibration signal can be used as leak indicators, but the first harmonic is normally the most sensitive one and the most convenient to use. Unless otherwise stated it is assumed that $k=1$, and the harmonics index will be omitted, for convenience. The integrals must be implemented by summations in a computer, in accordance with well-known techniques for numerical integrations. The amplitudes are updated at every completed revolution of the pump.

The complex amplitude defined above may be regarded as a vector in the complex plane. The length of this vector, which equals the magnitude of the complex amplitude, is not suitable for early leak detection as the amplitude is disposed to fluctuations if there is much noise or non-harmonic variations present in the signal, and the signal may also include true harmonic variations that are not coming from a leak.

Applying a smoothing filter to the complex amplitude will effectively reduce the disturbances from noise and non-harmonic variations. Smoothing, which is another word for low pass filtering, will dampen all components except the true harmonic components. A wide range of low pass filter types may be used. In general, the lower the cut-off frequency and the steeper the roll-off rate of the filter is, the more effectively the dampening is. However, the drawback of a very low cut-off frequency is a poor response time, meaning that detection of rapidly growing leaks is delayed.

Monitoring the deviation amplitude instead of the variation amplitude solves the problem of disturbing harmonic base variations not originating from a growing leak. The deviation amplitude is defined by

$$\delta F = |F_s - F_b| \quad (E2)$$

thus representing the magnitude or length of the complex difference between the smoothed amplitude F_s and the base amplitude F_b . An alarm should be triggered when this deviation amplitude exceeds a certain alarm limit. The normal conditions not deviating too much from the base conditions are visualized as a hatched circular area in figure 2. Methods to find the base amplitude F_b and the maximum deviation amplitude δF are discussed below.

If the lowest harmonics from only one sensor is used, there is a risk that the deviation amplitude will respond poorly to a leak, because the sensor is placed close to a node of a standing wave, or the leak induced motion is polarized in a direction with low sensor sensitivity. To minimize this risk, the method above can be generalized to use multiple harmonics and/or multiple sensors. The additional sensors can either be at the same location but have different orientation, or they

may be placed at different locations. From each combination of harmonics k and locations/orientations l a partial deviation amplitude δF_{kl} is calculated, using the procedure outlined above. These partial amplitudes can conveniently be combined into one global deviation amplitude defined as the square root of a weighted sum of the partial deviations amplitudes squared:

$$\Delta F = \sqrt{\sum_{kl} w_{kl} (\delta F_{kl})^2} \quad (\text{E3})$$

where w_{kl} are chosen weight factors. If all partial deviation amplitudes are expected to have the same order of amplitude, the weight factors can simply be a constant equal to unity divided by the number of combinations. Then the global deviation amplitude is the rms value of all partial vibration amplitudes.

The method of using multiple vibration sensor signals can be further generalized to include harmonic pressure variations, measured either on the high pressure side and/or the low pressure side. The deviation amplitudes for the pressures can be found in the same way as the vibration deviation amplitudes, but they must be rescaled and transformed to equivalent displacement amplitudes by selecting a proper scaling factor. As an example, if a leak typically generates a deviation displacement amplitude of 1 mm and a first harmonic discharge pressure variation of 1 bar, the scaling factor for this pressure could be 1 mm/bar.

The main advantages of combining several harmonics and/or measurement signals into one global deviation amplitude are:

- the risk for hitting a condition or frequency with very low leak response is minimized; and
- the logics for triggering the leak alarm based on multiple signals is greatly simplified.

As mentioned under the discussion of prior art, the lower harmonics of the pump vibrations are closely related to the cyclic leak flow and to the corresponding variations of the suction pressure and the discharge pressure.

- 5 According to the invention a leak is detected, usually at an early stage, through monitoring the lowest vibration harmonics of the piping or flexible hoses. Preferably the vibration harmonics are calculated with reference to the angular position of each pump.
- 10 In a preferred embodiment a vibration sensor is attached to the most motion sensitive part of the piping, for instance outside the centre part of the high pressure flexible hose, and monitor the low frequency vibrations. The vibration sensor is typically an accelerometer, but velocity or displacement sensors can alternatively be used. Because acceleration
- 15 amplitudes, in contrast to displacement amplitudes, tend to increase rapidly with the pump rotation speed, it is recommended to monitor the vibration amplitude in terms of displacement amplitude. The displacement amplitude can be derived even from an accelerometer signal by time integrating
- 20 the raw signal twice before the harmonics analysis is applied. However, this method has the disadvantage that each integration step must be combined with a so-called AC filter to avoid uncontrolled growth of DC components or slowly varying noise components. To avoid this problem it is recommended
- 25 to use a different procedure briefly outlined below.

It is well known for a skilled person that the Fourier transform of a time integrated variable equals the Fourier transform of the variable itself divided by the imaginary factor $i\omega$ where ω denotes the angular frequency. When the frequencies are restricted to pump harmonics only, we can put

30 $\omega = k\Omega$, where k is the harmonics number and Ω is the angular rotation speed of the pump. Because displacement is the time integral of velocity, the displacement amplitude of harmonics

no k can be found from the corresponding velocity amplitude by dividing by $ik\Omega$. Similarly, the displacement amplitude can be found from the acceleration amplitude by dividing the latter by the same factor twice, or just $-(k\Omega)^2$ since $i^2 = -1$.

- 5 Each of the leak indicators discussed above will have a base line that can change much with varying conditions, such as pump speed and discharge pressure. If these indicators shall be used for triggering leak alarms their normal bands or alarm limits cannot be fixed.
- 10 In a preferred embodiment the base values and alarm limits are set automatically by the following procedure:
- When a substantial change in the flow conditions is encountered, for instance a change in the rotation speed of at least one of the pumps, a quarantine timer is
15 started. The duration of the quarantine time must be sufficiently long to allow transient changes in the dynamic amplitudes to fade away, typically a few tens of seconds.
 - During this quarantine time the low pass filtered amplitudes are frozen, the transient changes are ignored and
20 the alarm logic is disabled.
 - By the end of the quarantine time, a base estimation timer is started. The duration of this base estimation period is typically 2-10 times longer than the quaran-
25 tine time.
 - At the end of the base estimation period the base values for the complex variation amplitudes are set equal to the average values measured during the base estimation period, and the alarm limits for the deviation amplitude

are determined. The limits may be relative, which is set to a fraction of base value magnitude, or absolute. In a further embodiment the alarm limits can be determined from more advanced functions taking into account also the measured variations and extreme values.

5

After this base estimation period, and while the piston machines are running at steady conditions the alarm limits are kept constant, meaning that an alarm is set if the deviation amplitude, or the global deviation amplitude, exceed the alarm limit.

10 The automatic updating of base values and alarm values for the deviation amplitudes should preferably be carried out for all pumps even if the speed of only one pump is substantially changed. This is important as the total flow and discharge pressure may affect the base amplitudes for all running pumps.

15 The invention not only teaches a relatively simple method for detecting a leak, but also renders it possible to point out which pump is leaking.

In the following there is described an example of use of the method illustrated in the accompanying drawings, in which:

20

Fig. 1 schematically shows a pump with upstream and downstream pipe connections; and

Fig. 2 shows a smoothed value and base value for the harmonic amplitude as vectors in the complex plane, and the alarm limit for deviation amplitudes as the periphery of circle with its centre at the end of the base amplitude vector.

25

On the drawings the reference numeral 1 denotes a so-called triplex pump, below termed pump, provided with three indi-

30

vidually acting pistons 2, extending through their respective cylinders 4. Only the first piston 2 and corresponding cylinder 4 is shown. The cylinders 4 communicate with an inlet manifold 6 and an upstream pipe 8 through their respective inlet valves 10, and an outlet manifold 12 and a downstream pipe 14 through their respective outlet valves 16.

A first flexible connection 18 is included in the upstream pipe 8 while a second flexible connection 20 is included in the downstream pipe 14.

An inlet pressure sensor 22 is connected to the inlet manifold 6, communicating with a computer 24 via a cable 26, and an outlet pressure sensor 28 is connected to the outlet manifold 12, communicating with the computer 24 via a cable 30. A rotational angle transmitter 32 is arranged to measure the rotational angle of a pump shaft 34 of the pump 1, and is communicatively connected to the computer 24 by means of a cable 36.

A first vibration sensor 38 in the form of an accelerometer is connected to the first flexible connection 18, and a second vibration sensor 40, also in the form of an accelerometer, is connected to the second flexible connection 20. The vibration sensors 38 and 40 are coupled to the computer 24 by respective cables 42, 44. The first vibration sensor 38 and the second vibration sensor 40 may include more than one sensor as outlined in the general part of the description.

The sensors 22, 28, 38 and 40, the transmitter 32 and the computer 24 are of types that are known *per se*, and the computer is programmed to carry out the calculations in question.

In the event of a leak in a valve 10 or 16, or in a not shown packing of the piston 2, the discharge through the outlet

valve 16 during the pumping phase will be reduced by a quantity equal to the leakage flow past the piston 2.

The leak past piston 2 induce an asymmetry into the flow trough the pump 1. The asymmetry sets up an increased vibration in the downstream pipe 14 including the second flexible connection 20. The second vibration sensor 40 senses the increased vibration.

By substantially continuously performing an angular position-based Fourier analysis of the vibration from the sensors 38, 40 as outlined in the general part of the description, an oncoming increase in the deviation amplitude δF of the vibrations of the pump 1 will be detected.

An alarm limit 46 is automatically set as lined out in the general part of the description. When deviation amplitude δF , see fig. 2, reaches the alarm limit 46 the computer 24 will set an alarm, and in the case that more than one pump 1 are supplying the downstream pipe 14, also identify which pump 1 is leaking.

The identification of the leaky pump is most certain when the pumps run at different speeds, because the lower harmonics then have different and unique frequencies. However, leaky pump identification is also possible when two or more pumps are running synchronously, due to the fact that the change vibration level will be highest near the leaky pump.

The alarm set by the computer 24 may trigger a further investigation in order to locate the leak either in one of the pumps 1 if a frequency alarm is set, or elsewhere if only the normalized pressure alarm is set.

Claims:

1. A method for detection of a fluid leak related to a machine comprising at least one piston and a pump shaft, the method comprising:

5 receiving a vibration signal from a vibration sensor disposed on at least one of an upstream pipe and a downstream pipe of the machine;

receiving a rotational speed signal and an angular shaft position signal from a speed and position sensor disposed on
10 the machine;

calculating a rotational speed and an angular shaft position of the pump shaft;

calculating at least one complex harmonic Fourier amplitude of the vibration signal;

15 low pass filtering the at least one complex harmonic Fourier amplitude to obtain a filtered amplitude;

calculating a deviation amplitude as the magnitude of a complex difference between the filtered amplitude and a measured base amplitude; and

20 detecting, when present, fluid leakage within the machine based upon the deviation amplitude.

2. The method according to claim 1, wherein the method further includes:

activating an alarm when the magnitude of the deviation
25 amplitude exceeds an alarm limit.

3. The method according to claim 1 or claim 2, wherein the

method further includes:

determining an alarm limit for the deviation amplitude automatically, as a function of the measured base amplitude.

4. The method according to any one of claims 1 to 3, wherein
5 the method further includes:

setting a base value for the at least one harmonic Fourier amplitude automatically by the following procedure:

starting a quarantine time during which the transient changes in the at least one harmonic Fourier amplitude is ignored
10 and alarm logic is disabled when a substantial change in flow conditions is encountered; and

determining a new base value as an average of the at least one harmonic Fourier amplitude measured during a base estimation time subsequently following the quarantine time.

15 5. The method according to any one of claims 1 to 4, wherein the speed and position sensor comprises an accelerometer.

6. The method according to any one of claims 1 to 4, wherein the speed and position sensor comprises a velocity sensor.

7. The method according to any one of claims 1 to 4, wherein
20 the speed and position sensor comprises a displacement sensor.

8. The method according to any one of claims 1 to 7, wherein an amplitude for displacement is calculated from a harmonic acceleration amplitude by dividing by the factor $-(k\Omega)^2$, wherein k is a positive integer representing a harmonics number and Ω is
25 an angular rotation speed of the pump shaft.

9. The method according to any one of claims 1 to 7, wherein an

amplitude for displacement is calculated from a harmonic velocity amplitude by dividing by the factor $ik\Omega$, wherein $i=\sqrt{-1}$ is the imaginary unit, k is a positive integer representing a harmonics number and Ω is angular an rotation speed of the pump shaft.

5 10. The method according to claim 8 or claim 9, wherein the method further includes:

deriving partial deviation amplitudes for at least two harmonics numbers based on the same vibration sensor signal;

calculating a global deviation amplitude as the square root
10 of a weighted sum of the partial deviation amplitudes squared;
and

detecting, when present, fluid leakage within the machine based upon the global deviation amplitude.

11. The method according to claim 8 or claim 9, wherein the
15 vibration sensor comprises at least two sensors that are at least one of different locations and orientations, and the method further comprises;

deriving partial deviation amplitudes from each selected combination of harmonics numbers and vibration sensor signals;

20 calculating a global deviation amplitude as the square root of a weighted sum of the partial deviation amplitudes squared;
and

detecting, when present, fluid leakage within the machine based upon the global deviation amplitude.

25 12. The method according to claim 8 or claim 9, wherein the method further includes:

receiving a pressure signal from a pressure sensor attached to at least one of an inlet manifold and an outlet manifold of the machine;

deriving partial pressure deviation amplitudes from each
5 selected combination of harmonics numbers and pressure sensor signals;

transforming the pressure deviation amplitudes into equivalent vibration deviation amplitudes by multiplying by proper transformation factors;

10 calculating a global deviation amplitude as the square root of a weighted square sum of the equivalent partial deviation amplitudes and vibration sensor based deviation amplitudes; and

detecting, when present, fluid leakage within the machine based upon the global deviation amplitude.

15 13. A vibration monitored machine, comprising:

at least one piston;

a shaft;

an upstream pipe and a downstream pipe;

a vibration sensor coupled to at least one of the
20 upstream pipe and the downstream pipe;

a speed and position sensor configured to render a signal for calculating a rotational speed and an angular shaft position; and

a controller coupled to the vibration sensor and the
25 speed and position sensor, wherein the controller is configured to: calculate the rotational speed and the angular

shaft position from the signal from the speed and position sensor, calculate at least one complex harmonic Fourier amplitude of a vibration signal from the vibration sensor, low pass filter the at least one complex harmonic Fourier amplitude to obtain a filtered amplitude, calculate a deviation amplitude as a magnitude of a complex difference between the filtered amplitude and a measured base amplitude, and detect, when present, fluid leakage within the machine based upon the deviation amplitude.

10 14. The machine of claim 13, wherein the controller is further configured to activate an alarm when a magnitude of the deviation amplitude exceeds an alarm limit.

15 15. The machine of claim 13, wherein the controller is further configured to determine an alarm limit for the deviation amplitude automatically, as a function of the measured base amplitude.

16. The machine of any one of claims 13 to 14, wherein the controller is further configured to set a base value for the at least one harmonic Fourier amplitude automatically by the following procedure: starting a quarantine time during which the transient changes in the at least one harmonic Fourier amplitude is ignored and alarm logic is disabled when a substantial change in flow conditions is encountered; and determining a new base value as an average of the at least one harmonic Fourier amplitude measured during a base estimation time subsequently following the quarantine time.

17. The machine according to any one of claims 13 to 16, wherein the speed and position sensor comprises an accelerometer.

18. The machine according to any one of claims 13 to 16,
wherein the speed and position sensor comprises a velocity
sensor.

19. The machine according to any one of claims 13 to 16,
5 wherein the speed and position sensor comprises a displacement
sensor.

20. The machine according to any one of claims 13 to 19,
wherein the controller is further configured to calculate an
amplitude for displacement from a harmonic acceleration amplitude
10 by dividing by the factor $-(k\Omega)^2$, wherein k is a positive integer
representing a harmonics number and Ω is an angular rotation
speed of the pump shaft.

21. The machine according to any one of claims 13 to 19,
wherein the controller is further configured to calculate an
15 amplitude for displacement from a harmonic velocity amplitude by
dividing by the factor $ik\Omega$, wherein $i = \sqrt{-1}$ is the imaginary unit,
 k is a positive integer representing a harmonics number and Ω is
angular an rotation speed of the pump shaft.

22. The machine according to claim 20 or claim 21, wherein the
20 controller is further configured to derive partial deviation
amplitudes for at least two harmonics numbers based on the same
vibration sensor signal, calculate a global deviation amplitude
as the square root of a weighted sum of the partial deviation
amplitudes squared, and detect, when present, fluid leakage
25 within the machine based upon the global deviation amplitude.

23. The machine according to claim 20 or claim 21, wherein the
vibration sensor comprises at least two sensors that are at
least one of different locations and orientations, and wherein

the controller is further configured to derive partial deviation amplitudes from each selected combination of harmonics numbers and vibration sensor signals, calculate a global deviation amplitude as the square root of a weighted sum of the partial deviation amplitudes squared, and detect, when present, fluid leakage within the machine based upon the global deviation amplitude.

24. The machine according to claim 20 or claim 21, wherein the controller is further configured to receive a pressure signal from a pressure sensor attached to at least one of an inlet manifold and an outlet manifold of the machine, derive partial pressure deviation amplitudes from each selected combination of harmonics numbers and pressure sensor signals, transform the pressure deviation amplitudes into equivalent vibration deviation amplitudes by multiplying by proper transformation factors, calculate a global deviation amplitude as the square root of a weighted square sum of the equivalent partial deviation amplitudes and vibration sensor based deviation amplitudes, and detect, when present, fluid leakage within the machine based upon the global deviation amplitude.

25. The machine according to any one of claims 13 to 24, wherein the controller is provided by a computer.

1/2

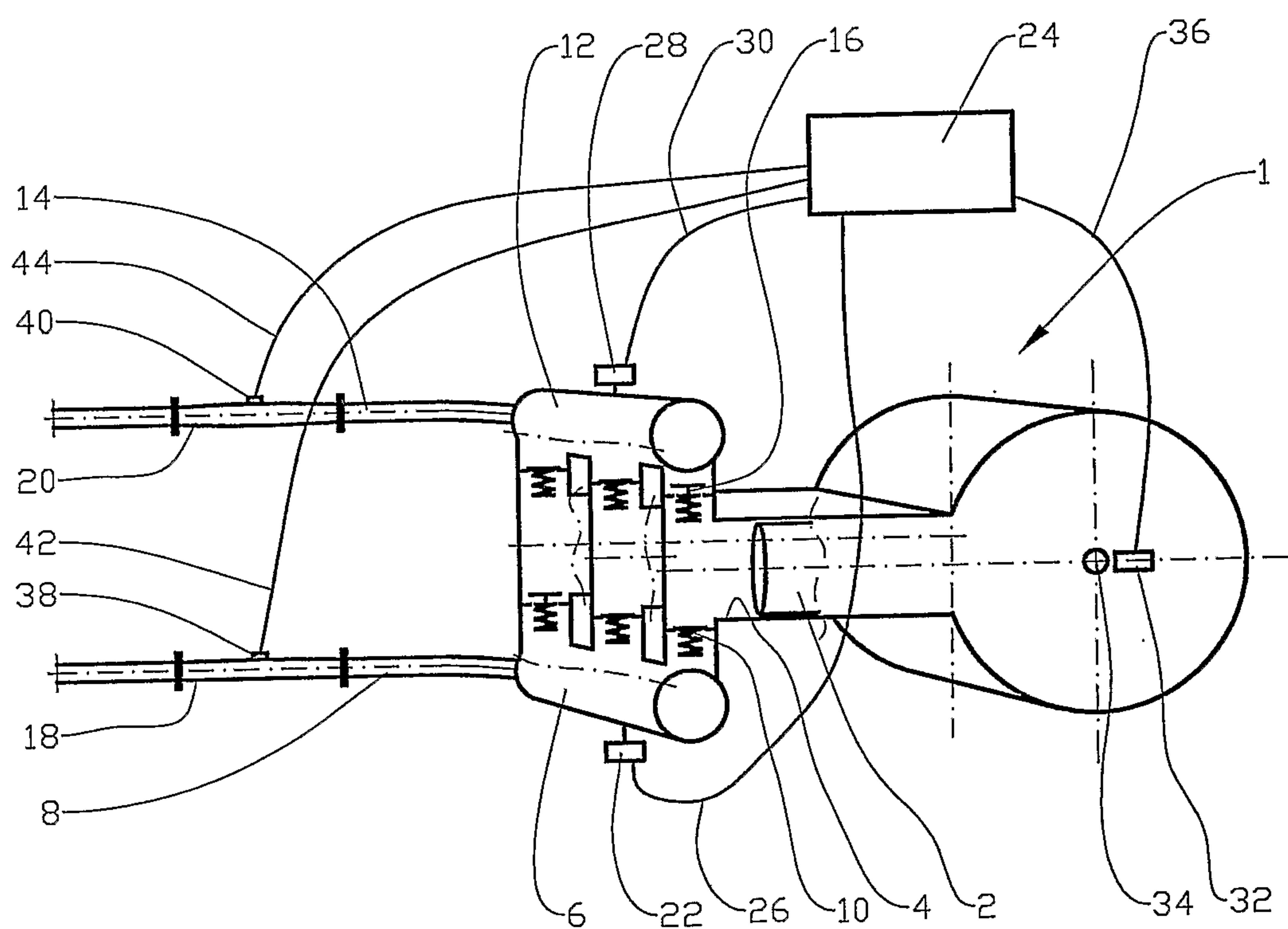


Fig. 1

2/2

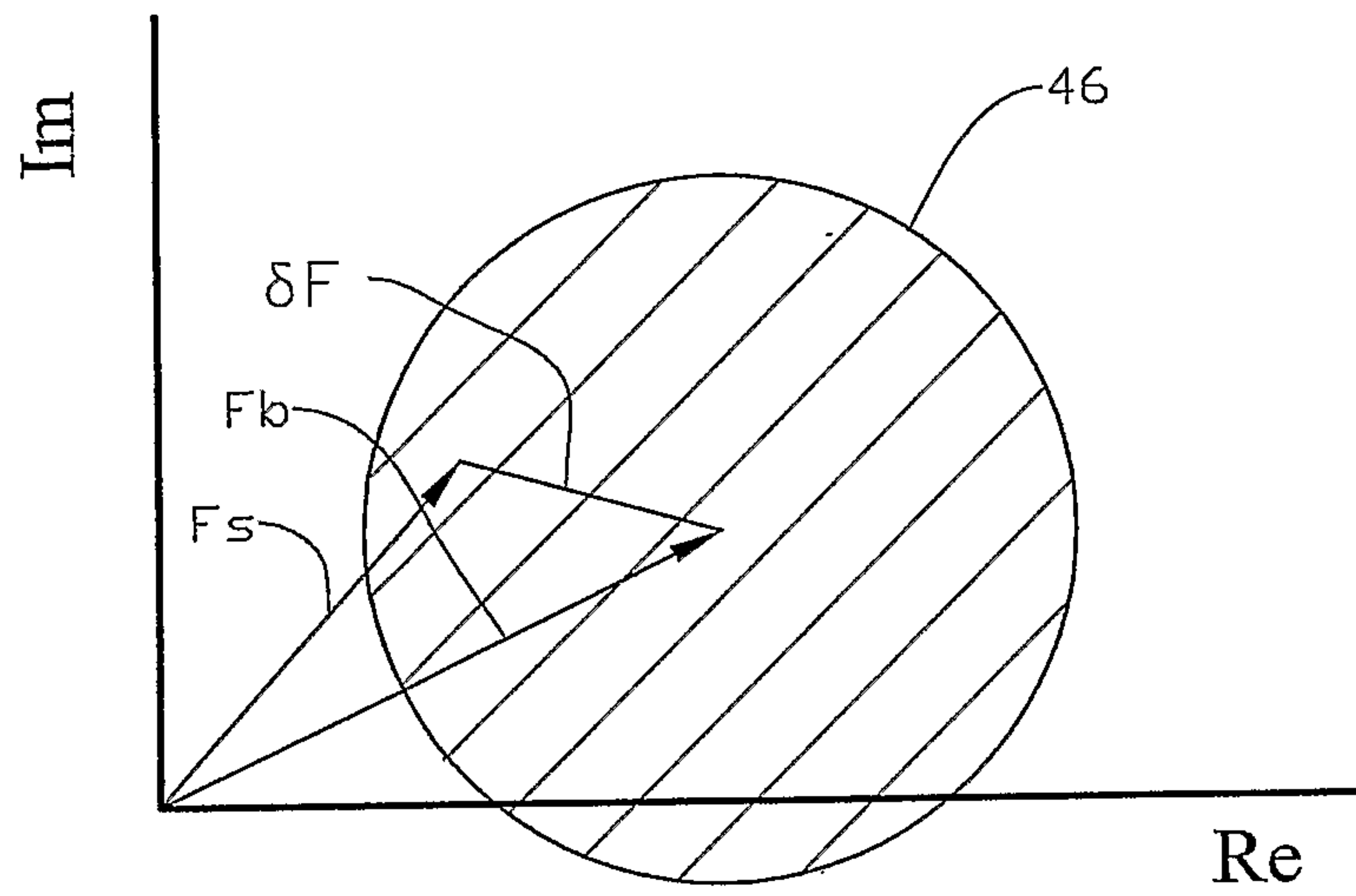


Fig. 2

