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(54) Diagnostic method and apparatus for vacuum pumps

(57) The invention relates to a diagnostic method and apparatus for detecting in advance the wear of rotatable components in vacuum pumps, said pumps comprising gas pumping stages formed by rotor disks (113, 114) secured to a rotatable shaft (123) driven by an electric motor, wherein a warning signal for either a pre-alarm or an alarm wear condition is generated when predetermined wear conditions are reached, by expanding the signal from an accelerometer in contact with the vacuum pump into a Fourier spectrum.

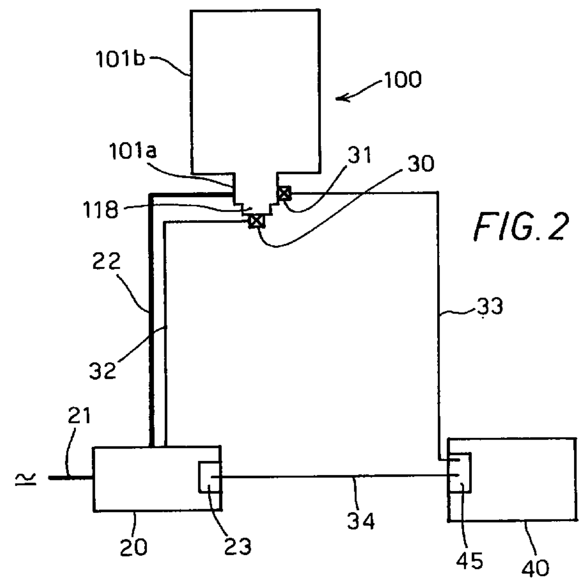

FIG. 2

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Description

The present invention relates to a diagnostic method and apparatus for vacuum pumps, particularly for vacuum pumps of the turbomolecular type.

As it is known, a turbomolecular vacuum pump comprises a plurality of pumping stages housed within a substantially cylindrical casing and provided with an axial inlet port of the sucked gases located at one end, and with a radial or axial exhaust port of the gases located at the opposite end.

Said pumping stages generally comprise a rotor disk, secured to the rotatable shaft of the pump, that is driven by an electric motor at a speed usually not lower than 25,000 rpm and in case as high as 100,000 rpm.

The rotor disk rotates within stator rings fastened to the pump casing and defining the stator of the pumping stage, with a very small gap therebetween.

In the space between a rotor disk and the associated stator disk it is further defined a pumping channel of the sucked gases.

The pumping channel defined between the rotor and the stator in each pumping stage communicates with both the preceding and the subsequent pumping stages through a suction port and an exhaust port, respectively, provided through the stator in correspondence of the pumping channel.

A turbomolecular pump of the above type is disclosed, for example, in EP-A-0 445 855 in the name of the present applicant.

The turbomolecular pump described in EP-A-0 445 855 employes both pumping stages provided with rotors formed as flat disks and pumping stages provided with rotors equipped with blades.

This combined arrangement of pumping stages results in a very good performance of the pump in respect of the compression ratio, while allowing to discharge the gases into the outer environment at atmospheric pressure by means of simple pre-vacuum pumps without lubricant, such as diaphragm pumps.

Moreover the construction of a vacuum pump of the turbomolecular type as teached by EP-A-0 445 855 allows for a considerable reduction of the pump power consumption.

For feeding and controlling the electric motor of the vacuum pump there is generally provided an external feeding unit.

It is known that the rotatable components of the vacuum pumps, particularly the bearings for supporting the rotatable shaft, are subjected to high stresses and are prone to wear and consequentely to a seizure.

Moreover, an incorrect alignement of parts rotating at high speed and any unbalance of the rotating components are sources of vibrations capable of leading to an early wear of the bearings.

Since an excessive wear or the seizure of the bearings in a vacuum pump during the working thereof can damage other parts della pump and cause a prolonged stopping of the pump due to the servicing operations, diagnosis or diagnostic methods have been developed for detecting in advance the presence of critical operating conditions.

Generally such diagnostic methods provide for analysing quantities of the vacuum pump such as the pump temperature and of the pump current.

Namely it is known that when the temperature of the vacuum pump exceedes a given threshold, the failure risk of its components increases.

In a similar manner, an increase of the current circulating in the vacuum pump motor generally indicates that critical wear conditions have been reached.

However, as a general rule, the values of the pump temperature and of the current in the motor are not affected by the wear level of the quickly rotating components only, but also by different factors, in case external to the pump.

As an example, the value di drawn current also depends on the gas load applied to the pump whereas the pump temperature is also a function of the temperature of the surrounding environment.

Theoretically such drawback could be overcome by providing the vacuum pump with a suitable number of sensors for taking into account all the significant reference parameters of the operating conditions.

This way at least a plurality of temperature sensors would be required at different locations in the pump, with at least one sensor for the environment temperature and at least one sensor measuring the pressure inside the vacuum chamber.

However this solution would imply the provision of a very large number of sensors, some of which to be located at critical areas, such as the vacuum chamber, and with the risk of jeopardizing the device efficiency.

It is therefore a first object of the present invention to realize a diagnostic method and apparatus for preventing faults and failures in vacuum pumps capable of supplying an accurate estimate of the wear conditions of the rotatable components in a vacuum pump without using a large number of sensors, with the apparatus being of simple working and rational construction.

This object of the present invention is accomplished through a method and an apparatus as claimed in claims 1 and 12, respectively.

Another problem related with the methods of diagnosing the operating conditions of vacuum pumps resides in that even when abnormal values for the controlled quantities are detected through dedicated sensors in the pump, such values do not imply as a necessary circumstance that the pump or parts thereof are to be replaced.

It is therefore of the utmost importance to properly construe the pump conditions from the values supplied by the sensors in order to prevent both incurring eccessive costs due to an untimely replacement of the pump components, and the risk of failures that have not been diagnosticated in advance.

A second object of the present invention is to realize a diagnostic method and apparatus for vacuum pumps capable of warning the user about the approaching of a failure or fault situation in the pump with such warning being sufficiently in advance but not too early.

This second object of the present invention is accomplished through the diagnostic method and apparatus for vacuum pumping devices as claimed in claims 8 and 17, respectively.

A further problem related to the methods for performing diagnostics on the operating conditions in vacuum pumps derives from the fact that a diagnosis has to be carried out with a constant degree of reliability even when the environment conditions in which the pump operates change.

A third object of the present invention is therefore to provide a diagnostic method and apparatus for vacuum pumping devices that are capable of being quickly adjusted to meet different operating conditions.

This third object of the present invention is accomplished through a diagnostic method for vacuum pumping devices as claimed in claim 9.

Additional objects of the present invention are achieved through the diagnostic method and apparatus for vacuum pumping devices as recited in the depending claims.

Further characteristics and advantages of the invention will become evident through a description of a preferred but not exclusive embodiment of the diagnostic method and apparatus for vacuum pumps according to the invention, illustrated as merely examplary and without limiting purposes in the attached drawings, in which:

Figure 1 a cross-sectional view of a vacuum pump of the turbomolecular type;
Figure 2 is a block diagram of a vacuum pumping device comprising a vacuum pump and a feeding unit equipped with a diagnostic apparatus in accordance with the invention;
Figure 3 is a block diagram of the processing unit of a diagnostic apparatus in accordance with the invention;
Figures 4a and 4b illustrate a flow chart of the diagnostic method in accordance with the invention:
Figures 5a and 5b are graphs showing the amplitude spectrum in two frequency ranges;
Figures 6a to 6d are graphs illustrating the acceleration as a function of the frequency for different ranges in the frequency spectrum;
Figures 7a to 7c are graphs illustrating the acceleration as a function of the frequency for two pumps working near to each other.

Referring to Figure 1, a turbomolecular vacuum pump indicated as a whole by reference 100, comprises a substantially cylindrical casing 101 having a first portion 101a with a smaller cross section and housing an electric motor 121 and a bearing 122 for supporting a rotatable shaft 123, and a second portion 101b, with a larger cross section and housing the gas pumping stages.

Rotor disks 113 having flat surfaces and rotor disks 114 equipped with blades are mounted to the rotatable shaft 123 of the vacuum pump 100, said disks cooperating with stator rings 115 and 116, respectively, that are secured to the casing 101 of the pump 100, and forming with them gas pumping channels.

The casing portion 101a is further provided with an axial port 119 located at one end thereof for sucking the gases, and with a radial port (not shown) for exhausting the gases, located at the opposite end.

The turbomolecular pump 100 is further provided with an annular protruding ring or flange 110 with peripherally spaced holes 117 for securing the turbomolecular pump 100 to a vessel or chamber (not shown) in which vacuum is to be created.

A cylindrical extension 118 is provided on casing 101, on the opposite side with respect to the flange 110, in correspondence of the base of said first smaller portion 101a, such extension being due to the presence within the pump 100 of the lower bearing.

A second bearing for supporting the shaft 123 is generally located between the motor 121 and the pumping stages housed in the portion 101b.

With reference to the block diagram of Figure 2 there is illustrated a diagnostic apparatus in accordance with the present invention applied to a vacuum pump 100.

As disclosed with reference to the description of Figure 1, the vacuum pump that is schematically illustrated in Figure 2 comprises a first portion having a smaller cross section, indicated by the same reference 101a as used in Figure 1 and housing the motor 121 and the lower bearing 122 for supporting the rotatable shaft 123, and a second portion having a larger cross section and indicated by the same reference 101b as used in Figure 1, and housing the gas pumping stages.

The diagnostic apparatus of Figure 2 comprises a temperature sensor 30, adapted to produce an electrical signal the intensity of which is proportional to the temperature measured on the vacuum pump 100.

This temperature sensor 30 is preferably located in correspondence with the axial extension 118 of the portion 101a of the casing 101 of the vacuum pump 100.

For large size pumps, a second temperature sensor can be provided for measuring the temperature in another area of the pump body, for example the area of the second bearing located between the pumping stages and the pump motor 121.

The diagnostic apparatus in accordance with the invention further provides for a vibration transducer 31 such as an accelerometer, a velocimeter, a position sensor or the like, adapted to generate an electric signal having an intensity that is proportional to an acceleration, a speed or a displacement measured in correspondence of the rotatable components of the vacuum pump 100.

As an example, such transducer 31 can be a piezoelectric accelerometer, preferably disposed in contact with the body of the vacuum pump 100 at one of its portions housing the support bearings of the rotatable shaft 123.

As already discussed, during the rotation of the rotatable components of a vacuum pump, these latter are subjected to periodic vibrations with a period substantially equal to the rotation period, since their rotation axes are not perfectly aligned with the main inertia axis.

In other words, since stresses are transferred to the portion 101a of the casing 101 at each rotation of a rotatable component, the frequency of the induced vibrations substantially corresponds to the rotation frequency.

An accelerometer is a device capable of measuring the acceleration amount of a vibrating surface on which the device is disposed.

Generally an accelerometer supplies an electric signal the voltage of which is proportional to the acceleration as measured along the sensitivity axis, in accordance with the following relationship:

$$V_{out} = Scale\_Factor * Acceleration + Offset\_Voltage$$

where

Scale Factor = sensor sensitivity in Volts/G;
Acceleration = acceleration in G measured along the sensitivity axis of the sensor;
Offset_Voltage = sensor output voltage in absence of any acceleration;
G = gravitational acceleration.

Figure 2 additionally shows a control and feeding unit 20, leads 21 for feeding said control unit 20 through the public power distribution network, and leads 22 for feeding the vacuum pump 100 through said control unit 20.

Still with reference to Figure 2, the diagnostic apparatus of the present invention further comprises a processing unit 40 receiving the signal from said transducer 31 on the vacuum pump 100, through a lead 33.

According to a preferred embodiment of the diagnostic apparatus of the invention, illustrated in Figure 2, the output signal of said temperature sensor 30 is applied to the control unit 20 through leads 32 and is rendered available as an output signal on a serial communication port of this unit 20.

The above arrangement is preferred since the temperature information is used also in the control functions accomplished by the control and feeding unit 20.

Through said serial communication port 23, the control and feeding unit 20 further supplies a plurality of signals related to significant operating parameters of the vacuum pump 100.

In accordance with a preferred embodiment, these signals are proportional to the feeding voltage applied to the electric motor, preferably a three-phase A.C. asynchronous motor that drives the vacuum pump 100, such voltage being supplied by said control and feeding unit 20 (WOMO signal), to the current circulating in the electric motor of the vacuum pump 100 (CUMO signal), to the drive frequency of said electric motor (FRMO signal), to the type of the cooling system of the vacuum pump 100 i.e. an air cooled or a water cooled system, (WACO signal), and to the overall operating condition of the vacuum pump, i.e. "normal", "loaded" or at "low speed" (STATUS signal).

The above signals are applied through a serial data transmission line 34 to the processing unit 40 that is in turn equiped with a serial communication port 45.

Referring to Figure 3, the processing unit 40 comprises a microprocessor 41, a first memory device 42 storing the control instructions for the microprocessor 41, a second memory device di 43 storing predetermined threshold values of the characteristic parameters of the moving parts of the vacuum pump 100, and a third memory device 44, for periodically storing the values of said characteristic parameters of the moving parts of the vacuum pump 100.

The microprocessor 41 is connected to the above memory devices 42 to 43 through data transmission "buses", indicated in Figure 3 by the references 46 to 48, respectively.

Microprocessor 41 is further provided with an additional data transmission "bus" 49 for communicating outside the processing unit 40, through the serial communication port 45 provided on such unit.

The diagnostic apparatus of the present invention further comprises devices (not shown) for the visual and/or audio warning signals that are activated by a signal generated by the microprocessor 41 upon reaching predetermined pre-alarm or alarm conditions.

Additional means can be provided for shut off the electric feeding to the vacuum pump upon reaching a predetermined alarm condition.

A preferred embodiment of the diagnostic method for vacuum pumps in accordance with the invention will be disclosed with reference to the Fig.s 4a, 4b, 5 and 6a to 6d.

In a preferred embodiment, the control logic of the diagnostic method in accordance with the invention is implemented through a sequence of instructions stored in the first memory device 42 for controlling of the microprocessor working.

However this logic can also be directly embedded in a microprocessor expressely designed for this purpose.

With reference to the flow charts of Figures 4a and 4b, at step or logic block 200 the microprocessore 41 receives, through the STATUS signal from the control and feeding unit 20, information relating to the working condition of the vacuum pump 100, such as "normal", "loaded" or "low speed" conditions.

In the next step or block 205, if neither a "normal" nor a "loaded" condition has been received, the control is returned to the logic block 200 for a further acquisition of the STATUS signal.

On the other hand, when at block 205, either a "normal" or a "loaded" condition is detected, then the control is transferred to the next logic block 210 for the acquisition (through the corresponding associated signals) of information relating to the following parameters of the vacuum pump, that are referred hereinbelow to the corresponding signals:

PARAMETER	SIGNALS
Water cooling	WACO
Current drawn by the motor	CUMO
Feeding voltage to the motor	VOMO
Motor drive frequency	FRMO
Pump temperature	TEBE

At the next logic block 215, if the difference between the temperature T_{bm}, available through the signal TEBE and measured in corrispondence of the portion 101a housing the bearings and the motor of the vacuum pump 100, and an optimum estimated temperature T_{bs} is greater than zero (that is $T_{bm} - T_{bs} > 0$) then the control is transferred to the logic block 216 and from here directly to the logic block 225.

In this embodiment the optimum estimated temperature T_{bs} is obtained through the following relationship:

$$T_{bs} = T_{est} + (C_p * W_p) + (C_b * W_b)$$

where

T_{est} is the room temperature;
C_p is a dimensional constant for any given pump;
W_p is the power drawn by the pump for an assigned gas load and is given by the difference betwen the total power W_t drawn by the pump and the power W_b dissipated in the bearing(s);
C_b is a dimensional constant for any given pump bearing;
W_b is the power dissipated by the pump bearing(s).

Thus the temperature T_c can be also expressed as:

$$T_{bs} = T_{est} + [(C_p * (W_t - W_b)] + (C_b * W_b).$$

The power W_b dissipated by the pump bearing(s) and the dimensional constant C_b of the bearing(s) are variable but known for a given bearing since they do not depend on the amount of gas (load) sucked by the pump.

To compensate for the lack of a sensor measuring the room temperature in the estimation of the bearing temperature, the maximum allowable value is used as room temperature.

Since the WACO signal supplies information on the pump cooling typology, in this embodiment it has been set:

T_{est} =25 °C when the pump is liquid cooled, and
T_{est} =35 °C when the pump is air cooled.

In the logic block 216 the content of a variable FLAG(Temp) is changed from the value construed by the microprocessor 41 as corresponding to a mormal temperature condition, for example: FLAG(Temp) = 0, into a value construed as corresponding to an excessive temperature condition, for example FLAG(Temp) = 1.

On the other hand when, at logic block 215, the difference between the measured temperature T_{bm} and the optimum estimated value T_{bs} is minor or equal to zero ($T_{bm} - T_{bs} \leq 0$), then the control is transferred to the logic block 220 where the content of the variable FLAG(Temp) is changed from the actual value to a value that is regarded by the microprocessor 41 as corresponding to a normal temperature condition.

In the next logic block 225 the microprocessor 41 receives data relating to the vibration acceleration of the vacuum pump rotatable components, generated by the accelerometer 31.

In accordance with a preferred embodiment of the diagnostic method of the invention, the data acquisition of the acceleration data is such as to generate two signals ACQSL and ACQSH for frequencies between 0 and 2,000 Hz, and between 0 and 12 kHz, respectively.

Fig.s 5a and 5b show the acceleration levels in the frequency ranges comprised between 0 and 2,000 Hz, and between 0 and 12 kHz, respectively, for a turbomolecular pump.

The acceleration data acquisition procedure provides the sampling of the analog signal from the accelerometer 31 at a rate that must be at least twice the maximum frequency of the signal for an accurate recovery of the original signal (Nyquist theorem).

Again with reference to Figures 4a and 4b, at logic block 230 the acquired signals ACQSL and ACQSH are subjected to a FFT (Fast Fourier Transform) algorithm to obtain the envelope of said signals in the corresponding spectral distribution, arranged in frequency order, thus achieving a signal representative of the distribution of the vibration acceleration as a function of the frequency.

In accordance with the diagnostic method of the present invention the following typical vibration frequencies of the rotatable pump components are taken into consideration:

F_t = frequency of the rotor of the vacuum pump;
f_{or} = frequency of the bearing outer ring;
f_{ir} = frequency of the bearing inner ring;
f_{rb} = frequency of the bearing balls;
f_c = frequency of the bearing cage (retainer).

At logic block 235 the microprocessor 41 estimates the theoretical rotation frequency F_t of the vacuum pump rotor through the following formula:

$$F_t = F_{ecc} - K * I/V$$

where:

F_{ecc} is the drive frequency of the motor of the vacuum pump (made available by the signal FRMO on the output of the serial port of the feeding unit 20);
K is a dimensional constant depending on the type of the motor;
I is the current circulating in the vacuum pump motor and is made available through the signal CUMO;
V is the feeding voltage to the motor of the vacuum pump and is available through the signal VOMO.

At the next logic block 240 there is defined an operating range of the theoretical rotation frequency F_t corresponding to the range [F_c - 50 Hz, F_t + 50 Hz].

At the next logic block 245 the method of the invention looks for the peak having the maximum amplitude within said operating range [Ft - 50 Hz, Ft + 50 Hz], and the frequency value corresponding to said peak is associated to the experimental rotation frequency F_r of the rotor in the vacuum pump.

The next logic block 250 calculates the typical theoretical frequencies (ftt) of the vacuum pump, by using the following equations:

$$f_{or} = F_r * 0.5 * z * [1 - D/d_m * \cos(\alpha)];$$

$$f_{ir} = F_r * 0.5 * z * [1 + D/d_m * \cos(\alpha)];$$

$$f_{rb} = F_r * d_m/D * \{1 - [D/d_m * \cos(\alpha)]^2\};$$

$$f_c = F_r * 0.5 * [1 - D/d_m * \cos(\alpha)],$$

where D, z, d_m and α are geometrical parameters typical of the bearings present in the pump, and more precisely:

- D = diameter of trhe bearing balls;
- z = number di balls in the bearing;
- d_m = mean diameter of the bearing;
- α = contact angle between the balls and the bearing.

Since two bearings are provided in the vacuum pump 100, the estimate of the typical theoretical frequencies is carried out for both the upper bearing (f2) and the lower one (f1).

Moreover, for each estimated ftt, all the higher harmonics up to the frequency di 12 kHz will be considered.

In the method according to the invention, at logical blocks 255 to 310 a search is performed - over the spectrum obtained through the FFT processing of the acceleration signals - of the peaks corresponding to the experimental vibration frequencies (ftr) of the rotating components and said peaks are then associated to the corresponding typical theoretical frequencies ftt.

The above search comprises the following steps.

At logic block 255, for each typical theoretical frequency ftt_x that has not yet been considered or to which an experimental amplitude value has not yet been associated, an operating range $[ftt_x - n\Delta f, ftt_x + n\Delta f]$ is defined, where

n = number of the considered spectral lines (for example 5÷10);
Δf = resolution of the considered spectrum.

At logic block 260 it is calculated the number di ftts present within the operating range $[ftt_x - n\Delta f, ftt_x + n\Delta f]$ defined by the previous logic block 255.

After calculating the number of ftts within the operating range, the logic block 265 localizes a new operating range $[ftt_{min}, ftt_{max}]$, within the first operating range.

Said second operating range is comprised between the minimum and the maximum ftts that are located within the first operating range $[ftt_x - n\Delta f, ftt_x + n\Delta f]$.

After the boundaries of the second operating range $[ftt_{min}, ftt_{max}]$ have been established, they are widened by the n.f in the logic block 270, thus obtaining a third extended operating range $[ftt_{min} - n\Delta f, ftt_{max} + n\Delta f]$ that is indicated as $[x_{min}, x_{max}]$ for brevity.

Then logic block 275 calculates the number NN of ftts that are present in the extended operating range $[x_{min}, x_{max}]$ selected in the previous logic block 270.

If the extended operating range $[X_{min}, x_{max}]$ contains additional ftts in respect of those considered in the first operating range, the number of which has already been calculated by logic block 260, these ftts too will be considered in the subsequent calculations.

Logic block 280 calculates the mean amplitude value of the spectrum within the extended operating range $[x_{min}, x_{max}]$.

At the next logic block 285 an auxiliary spectrum is formed where the amplitude values within the range $[x_{min}, x_{max}]$ that are lower than the mean value calculated by the previous logic block 280 are set equal to said mean value.

Logic block 290 calculates the number NNP of the peaks in the auxiliary spectrum that are located within the extended operating range $[x_{min}, x_{max}]$.

The above disclosed procedure illustrated with reference to logic blocks 280 to 290 aims to cancel the spectrum components deriving from the background noise.

At logic blocks 300 to 305, the NNP detected peaks are associated to the NN amplitudes corresponding to the theoretical frequencies ftts in the considered frequency range, in accordance with the principle of associating each theoretical frequency with the peak detected at the nearest frequency.

More precisely one of the following four conditions has to be satisfied, each one excluding the others.

If at logic block 300, the condition NNP=0 is satisfied, that is a condition in which no peak has been traced within the extended operating range $[x_{min}, x_{max}]$, then logic block 301 associates to the theoretical frequencies ftts in the extended operating range a frequency that has been detected equal to the theoretical one and has an amplitude equal to the bottom level in the range.

An example relating to such a condition is illustrated in Figure 6a where a single theoretical frequency (dashed line) exists in the considered range and to such frequency there is associated an amplitude value that is relative to the bottom level (mean value of the amplitudes) since the experimental amplitude values are always increasing inside the range.

In Figure 6a the vertical continuous lines delimitate the extended operating range and the horizontal continuous line indicates the mean value of the amplitudes in said range.

On the other hand, if at logic block 300 the condition NNP#0 is satisfied, the control is transferred to the next logic block 302.

If at logic block 302, the condition NNP=NN is satisfied, the next logic block 303 assigns to each theoretical frequency in the extended operating range $[x_{min}, x_{max}]$, the peak detected at the nearest fequency.

Figure 6b illustrates an example relating to a situation where NNP=NN , in which at each theoretical frequency ftt (dashed lines) there is associated the maximum value corresponding to the nearest frequency (cross).

In Figure 6b the vertical continuous lines delimitate the extended operating range $[x_{min}, x_{max}]$ and the horizontal continuous line indicates the mean value of the amplitudes in said range.

On the other hand, if the condition NNP>NN is satisfied at logic block 302, at logic block 304 only those peaks that have been detected nearest to those theoretical in terms of frequency will be used.

The peaks that have been detected and not used, that is not associated to any ftt, will be excluded since they are to be considered as due to external disturbances.

Figure 6c illustrates an example relating to such situation where the nearest experimental peak (cross) is associated to the single theoretical frequency (dashed line) present in the considered range.

In Figure 6c the vertical continuous lines delimitate the extended operating range $[x_{min}, x_{max}]$ and the horizontal continuous line indicates the mean value of the amplitudes in said range.

In case that at logic block 302, the condition NNP<NN is satisfied, logic block 305 associates to each ftt the peak detected at the nearest frequency.

When during the procedure for assigning the detected peaks to the theoretical frequencies ftt, disclosed with reference to blocks 300 to 305, the condition that a same experimental peak has been associated with more than one theoretical frequency ftt is satisfied, then at block 309 said detected experimental peak is now associated to the nearest theoretical frequency whereas to the other theoretical frequencies previously associated with the same peak, it is now associated the amplitude corresponding to the bottom level in the considered operating range.

Such condition is compulsorily satisfied when NNP<NN.

Figure 6d illustrates an example relating to a situation where NNP<NN. In the Figure the only experimental peak identified (right cross) is associated with the nearest theoretical frequency (right dashed line) whereas to the remaining theoretical frequency (left dashed line) it is associated the amplitude value corresponding to the bottom (mean) level of the amplitudes (left cross).

In Figure 6d the vertical continuous lines delimitate the extended operating range $[x_{min}, x_{max}]$ and the horizontal continuous line indicates the mean value of the amplitudes in said range.

According to another embodiment of the method of the invention, when the same experimental peak has been associated with more than one ftt, the corresponding associated amplitude is reduced proportionally to the number di ftts to which the same peak has been associated.

As an example, when the same peak has been associated with two ftts, the corresponding amplitude associated to such two ftts will be half of the peak amplitude.

This second embodiment of the method of the invention is particularly advantageous when using small size pumps on which there are mounted equal bearings having their ftts coincident.

Next at logic block 310 the amplitude of each peak associated with the ftts is stored so as to generate the following data matrix for the rotor, the lower bearing and the upper bearing.

Theoretical frequency	Detected fr.	Peak amplitude
F_{ecc}	F_r	$A(F_r)$
$f1_{or}$	$f1_{or,r}$	$A1(f_{or,r})$
$f1_{ir}$	$f1_{rb,r}$	$A1(f_{ir,r})$
$f1_{rb}$	$f1_{rb,r}$	$A1(f_{rb,r})$
$f1_c$ $f1_{c,r}$	$A1(f_{c,r})$	
$f2_{or}$	$f2_{or,r}$	$A2(f_{or,r})$

(continued)

Theoretical frequency	Detected fr.	Peak amplitude
$f2_{ir}$	$f2_{rb,r}$	$A2(f_{ir,r})$
$f2_{rb}$	$f2_{rb,r}$	$A2(f_{rb,r})$
$f2_c$ $f2_{c,r}$	$A2(f_{c,r})$	$A2(f_{c,r})$

At the next logic block 315 the amplitudes of the maxima previously associated with the ftts are compared with the reference thresholds contained in the storing device 43 of the processing unity 40.

Said reference thresholds are determinated on the basis of the spectra obtained for new pumps and used pumps.

If one of the stored amplitude values is higher than the corresponding reference threshold, at logic block 320 the content of the variable FLAG(ftt) is changed from the value construed by the microprocessor 41 as corresponding to a regular amplitude condition, e.g. FLAG(ftt) = 0, to a value corresponding to an excessive amplitude condition FLAG(ftt)=1.

On the other hand, if at logic block 315 the amplitude value is lower than the corresponding reference threshold, at logic block 325 the content of the variable FLAG(ftt) is changed from the value construed by the microprocessor 41 as corresponding to an excessive amplitude condition, FLAG(ftt) = 1, to the value corresponding to a regular amplitude condition, FLAG(ftt) = 0.

The reference thresholds for the acceleration amplitudes used in the illustrated embodiment were the following:

F_{rot}	1.10 m/sec^2
f_c upper bearing	0.50 m/sec^2
f_c lower bearing	0.34 m/sec^2

ftr comprised between

F_{rot} and 8,500 Hz	0.60 m/sec^2
F_{rot} higher than 8,500 Hz	1.20 m/sec^2

The above thresholds are those for a particular type of pump used in an embodiment, and therefore should be modified to adjust the diagnostic method to pumps of different type by storing suitable values in the storing device 43.

As already pointed out the interpretation of the results supplied by the diagnostic method are of the utmost importance since from this interpretation the user gets informations about the fault probability of the pump and consequentely on the need to carry out the servicing.

In a preferred embodiment of the method according to the invention, at logic block 330, the calculation of an attention level LEVEL is carried out, when the temperature and vibration safety thresholds have been exceeded by the pump.

The number LEVEL of FLAGs indicating that the corresponding threshold level has been exceeded is calculated through the following sum weighted on all the typical theoretical frequencies:

$$LEVEL = \Sigma_i\,[W(i) * FLAG(i)] + W(Temp) * Flag(Temp)$$

where W(i) are the weights assigned to the FLAGs associated with the amplitudes of the vibration spectrum.

In the disclosed embodiment the following weights have been used:

W(Temp)	1	
$W(F_{rot})$	1	

(continued)

$W(F_c)$	3	upper bearing
$W(F_c)$	3	lower bearing
W(ftr)	2	

In case there are provided more temperature sensors located in different areas of the pump housing, e.g. as previously indicated when using a large size pump, the above sum will take into account the temperature values supplied by all such sensors, properly weighted.

On the basis of the value assumed by the LEVEL signal, at logic block 335 the microprocessor 41 will indicate one of the following operating conditions.

A first operating condition is indicated when LEVEL=0.

This condition relates to a normal operating situation that does not require any intervention.

A second operating condition is indicated when LEVEL≤3.

This condition relates to a operating situation that requires a medium-term intervention.

A third operating condition is indicated when LEVEL>3.

This condition relates to a operating situation that requires an immediate intervention.

It is further provided that an alarm level is signalled only when such level is maintained for a given time interval. In the considered embodiment, for example, this time interval has been set equal to 60 minutes.

It is also provided that the parameters relating to the pump working are periodically stored for being subsequentely analyzed and used for modifying the predetermined threshold levels.

Since, as indicated above, the vibration spectrum is affected also by machineries that are located near a vacuum pump to be subjected to diagnostics, in a second embodiment of the method according to the invention, a preliminary analysis step of the vibration spectrum is provided for distinguishing between signals due for example to the presence of two vacuum pumps working one near the other.

Differently from the above illustrated method, in this second embodiment the theoretical rotation frequencies F_{t1} and F_{t2} of the pump rotor are calculated through the following formula:

$$F_{t1} = F_{ecc1} - K_1 * I_1/V_1$$

$$F_{t2} = F_{ecc2} - K_2 * I_2/V_2$$

Similarly to the method illustrated with reference to Figures 4a and 4b, a suitable range is defined containing the two theoretical rotation frequencies. Assuming that $F_{t1} < F_{t2}$, such range will be, for example, $[F_{t1}$ - 50 zH, F_{t2} + 50 zH].

Within this range the two peaks of maximum amplitude will be looked for, and the frequency values corresponding to said peaks are associatedd to the experimental rotation frequencies F_{r1} and F_{r2} of the rotors of the vacuum pumps.

Then the method is applied in a manner similar to what has been disclosed with reference to the previous embodiment for both the frequencies F_{r1} and F_{r2}.

Being known the origin of the typical theoretical frequencies calculated, it is possible to distinguish the experimental peaks caused by either of the pumps and to associate the experimental amplitudes to the corresponding pump.

Figures 7a, 7b and 7c illustrate the spectra relating to a pump rotating at a speed of 680 Hz, an adjacent pump rotating at a speed of 700 Hz as well as the superimposing of the two spectra.

In Figures 7a to 7c the vertical continuous lines correspond to the theoretical peaks and the crosses to the experimental peaks.

In a further embodiment of the diagnostic method according to the present invention, it also provided to evaluate the level of the vibrational amplitudes of the components of the vacuum pump. More particularly an alarm level can be defined that is proportional to the difference between the measured amplitude and the theoretical amplitude.

The diagnostic method of the invention allows to identify - within the vibrational spectrum of the pump - the spectral lines caused by the vibrations of the rotatable components during their rotation and supplies an indication of the pump wear, regardless of environmental disturbances for example those caused by pumps operating nearby, voltage transformers, relais and other sources of vibrations. This has been achieved through an accurate spectral analysis and a combination with further information relating to the working of the vacuum pump but different from the acceleration spectrum, such as the temperature and the current drawn by the electric motor driving the pump.

Claims

1. A diagnostic method for preventing faults and failures in a vacuum pump (100), said pump comprising:

   - a casing (101) provided with a suction port (119) and an exhaust port, a first portion (101a) and a second portion (101b) being axiallly defined in said casing,

     a plurality of gas pumping stages formed by rotor disks (113, 114) secured to a rotatable shaft (123) of the vacuum pump, said disks cooperating with stator rings (115, 116) secured to said casing of the vacuum pump, said pumping stages being housed inside said second portion (101b) of said casing (101b);
   - an electric motor (121) for driving said rotatable shaft of the vacuum pump, and at least one bearing (122) for supporting said rotatable shaft (123), said motor (121) and at least one bearing (122) being housed inside said first portion (101a) of said casing,

     said method being characterized in that it provides the steps of:

     - providing at least one signal representative of the vibration acceleration of the rotatable components of the vacuum pump;
     - transforming said signal representative of the vibration acceleration of the vacuum pump rotatable components into a corresponding spectral distribution arranged in frequency order, thus achieving a signal representative of the amplitude distribution of the vibration acceleration as a function of the frequency;
     - tracing within said spectral distribution the peaks corresponding to the typical vibration frequencies of said rotatable components of the vacuum pump;
     - comparing the amplitudes of said peaks with respective and predetermined reference thresholds;
     - generating an alarm signal when at least one of said reference thresholds is exceeded by the corresponding peak amplitude.

2. A diagnostic method as claimed in claim 1, wherein said step of tracing the peaks corresponding to the typical vibration frequencies of said rotatable components of the vacuum pump, further comprises the steps of:

   - estimating a theoretical rotation frequency (F_{tot}) of the pump rotor as a function of the excitation frequency (F_{ecc}) of the pump motor, of the current (I) circulating in said motor and of the feeding voltage (V) to the motor;
   - tracing within a predetermined frequency range of said spectral distribution the peak having the maximum amplitude;
   - associating the frequency value corresponding to said maximum amplitude peak to the experimental rotation frequency (F_r) of the vacuum pump rotor;
   - calculating the typical theoretical vibration frequencies (ftt) of said rotatable components of the vacuum pump as a function of said experimental frequency (F_r);
   - tracing, for each of the typical theoretical vibration frequencies (ftt) in said calculated spectral distribution, the peaks relating to the corresponding experimental vibration frequency (F_r).

3. A diagnostic method as claimed in claim 2, wherein said predetermined frequency range corresponds to a ±50Hz range centered at said theoretical rotation frequency (F_{rot}) of the rotor.

4. A diagnostic method as claimed in claim 3, wherein the step of tracing - in said spectral distribution and for each of the theoretical vibration frequencies - the corresponding experimental vibration frequency, further comprises the steps of:

   - tracing in said spectral distribution an operating range for each of the typical theoretical vibration frequencies (ftt) of the rotatable components of the vacuum pump;

     locating within said operating range, the peak with the minimum frequency (ftt_{min}) and the peak with the maximun frequency (ftt_{max});
   - determining on said spectral distribution, for each of the operating ranges, an extended operating range having an extension not smaller than the range delimited by the frequencies corresponding to said peak of minimum frequency (ftt_{min}) and by said peak of maximum frequency (ftt_{max});
   - calculating the number of theoretical typical vibration frequencies (ftt) located within said extended operating range;
   - associating to each typical theoretical vibration frequency (ftt) located within said extended operating range, the amplitude corresponding to the traced peaks in accordance with the criterion that to each typical theoretical vibration frequency (ftt) there is associated the peak traced at the nearest frequency and for which the peak

associated to one or more of said frequencies (ftt) is associated only to the nearest frequency (ftt), while to the remaining frequencies (ftt) there is associated the mean amplitude of the considered extended operating range.

5. A diagnostic method as claimed in claim 4, wherein said operating range determined for each typical theoretical rotation frequency (ftt) corresponds to a neighborhood of said rotation frequency (ftt) having an extension of ±n .f, where .f is the spectrum resolution and n is an integer comprised between 5 and 10, and wherein said extended operating range corresponds to the range [ftt_{min} - .f, ftt_{max} + .f].

6. A diagnostic method as claimed in claim 5, further providing the step of:

- modifying the content of alarm indicators from the value corresponding to the normal working condition of the vacuum pump into a value corresponding to critical working conditions of said pump when the respective amplitudes exceed said tresholds.

7. A diagnostic method as claimed in claim 5, further providing the steps of:

- providing at least one signal representative of the temperature in said first portion (101a) of the vacuum pump;
- comparing said at least one signal representative of the temperature in said first portion of the vacuum pump with at least one corresponding reference threshold;
- modifying the content of at least one alarm indicator from the value corresponding to the normal operating condition of the vacuum pump into a value corresponding to critical operating conditions of said pump when said at least one reference threshold is exceeded by the corresponding at least one signal representative of the temperature.

8. A diagnostic method as claimed in claims 6 and 7, further providing the steps of:

- storing the content of said alarm indicators in storage means;
- summing the number of the alarm indicators the content of which corresponds to a normal operating condition of the pump;
- generating a pre-alarm signal when said sum exceeds a pre-alarm threshold, and an alarm signal when said sum exceeds an alarm threshold.

9. A diagnostic method as claimed in claim 8, further providing the step of periodically storing the data relating to the vibration theoretical frequencies (ftt), to the corresponding vibration experimental frequencies and to the experimental vibration amplitudes associated with said frequencies vibration experimental frequencies.

10. A diagnostic method as claimed in claim 1, wherein the step of transforming said signal representative of the vibration acceleration of the vacuum pump rotatable components into a spectral distribution is obtained by means of an FFT (Fast Fourier Transform).

11. A diagnostic method as claimed in any preceding claims, wherein said vacuum pump is a turbomolecular pump.

12. A diagnostic apparatus for preventing faults and failures in a vacuum pump (100), said pump comprising:

- a casing (101) provided with a suction port (119) and an exhaust port, in which a first portion (101a) and a second portion (101b) are axiallly defined;
- a plurality of gas pumping stages comprising rotor disks (113, 114) mounted to the rotatable shaft (123) of the vacuum pump and cooperating with stator rings (115, 116) secured to the casing of the vacuum pump 100, said pumping stages being housed in said second portion (101b) of said casing;
- an electric motor (121) for rotating said rotatable shaft and at least a second bearing (122) for supporting the rotatable shaft (123) of the vacuum pump, said motor (121) and said at least one bearing (122) being housed in said first casing portion (101a);
- an electronic unit (20) for feeding said electric motor (121) of the vacuum pump (100);

said apparatus comprising:

- at least a transducer (31) capable of generating an electric signal having an intensity proportional to an acceleration, speed or displacement value as measured at the the rotatable components of the vacuum pump (100);

- an electronic processing unit (40), comprising a microprocessor (41), storage means and communication means for receiving the signal from said transducer (31) and a plurality of signals representative of the operating condition of the vacuum pump output from said electronic feeding unit (20), means for transforming the signal from said transducer (31) into a corresponding spectral distribution arranged in frequency order, thus obtaining a signal representative of the amplitude distribution of the vibration acceleration as a function of the frequency, said processing unit (40) generating a signal representative of the wear condition of the rotatable components of the vacuum pump.

13. A diagnostic apparatus as claimed in claim 12, further providing communication means (45) for receiving through a communication (34) line said plurality of signals representative of the vacuum pump operating condition from the electronic feeding unit (20).

14. A diagnostic apparatus as claimed in claim 13, wherein said transducer (31) is a piezoelectric accelerometer disposed in contact with the body of the vacuum pump (100) in correspondence of a portion thereof housing the support bearings for the rotatable shaft.

15. A diagnostic apparatus as claimed in claim 13, further providing at least a transducer (30) for generating an electric signal having an intensity proportional to the temperature measured in correspondence of rotatable components of the vacuum pump (100).

16. A diagnostic apparatus as claimed in claim 14 and 15, wherein said plurality of signals representative of the vacuum pump operating condition from said electronic feeding unit (20) comprises at least:

- a signal representative of the presence of liquid cooling means for cooling the vacuum pump;
- a signal representative of the current circulating in the electric motor of the vacuum pump;
- a signal representative of the feeding voltage to the electric motor of the vacuum pump;
- a signal representative of the drive of the electric motor of the vacuum pump;
- a signal representative of the temperature of the vacuum pump.

17. A diagnostic apparatus as claimed in claim 16, further providing means indicating a pre-alarm condition and an alarm condition with respect to the wear state of the rotatable components of the vacuum pump.

18. A diagnostic apparatus as claimed in any of claims 12 to 17, wherein said vacuum pump is turbomolecular pump.

19. A vacuum pump comprising:

- a casing (101) provided with a suction port (119) and an exhaust port in which a first portion (101a) and a second portion (101b) are axiallly defined;
- a plurality of gas pumping stages comprising rotor disks (113, 114) mounted to the rotatable shaft (123) of the vacuum pump and cooperating with stator rings (115, 116) secured to the casing of the vacuum pump 100, said pumping stages being housed in said second portion (101b) of said casing;
- an electric motor (121) for rotating said rotatable shaft and at least a second bearing (122) for supporting the rotatable shaft (123) of the vacuum pump, said motor (121) and said at least one bearing (122) being housed in said first casing portion (101a);
- an electronic unit (20) for feeding said electric motor (121) of the vacuum pump (100),

  wherein there is provided a diagnostic apparatus comprising means for:

  - providing at least a signal representative of the vibration acceleration of the rotatable components of the vacuum pump;
  - transforming said signal representative of the vibration acceleration of the rotatable components of the vacuum pump into a corresponding distribution arranged in frequency order, for obtaining a signal representative of the amplitude distribution of the vibration acceleration as a function of the frequency;
  - tracing within said spectral distribution the peaks corresponding to the typical vibration frequencies of said rotatable components of the vacuum pump;
  - comparing the amplitudes of said peaks with corresponding predeterminated reference thresholds;
  - generating an alarm signal when the corresponding peak amplitude exceeds at least one of said reference thresholds.

20. A vacuum pump as claimed in claim 19, wherein means are provided to shut off the electric feeding to said pump when a predetermined number of said reference thresholds is exceeded.

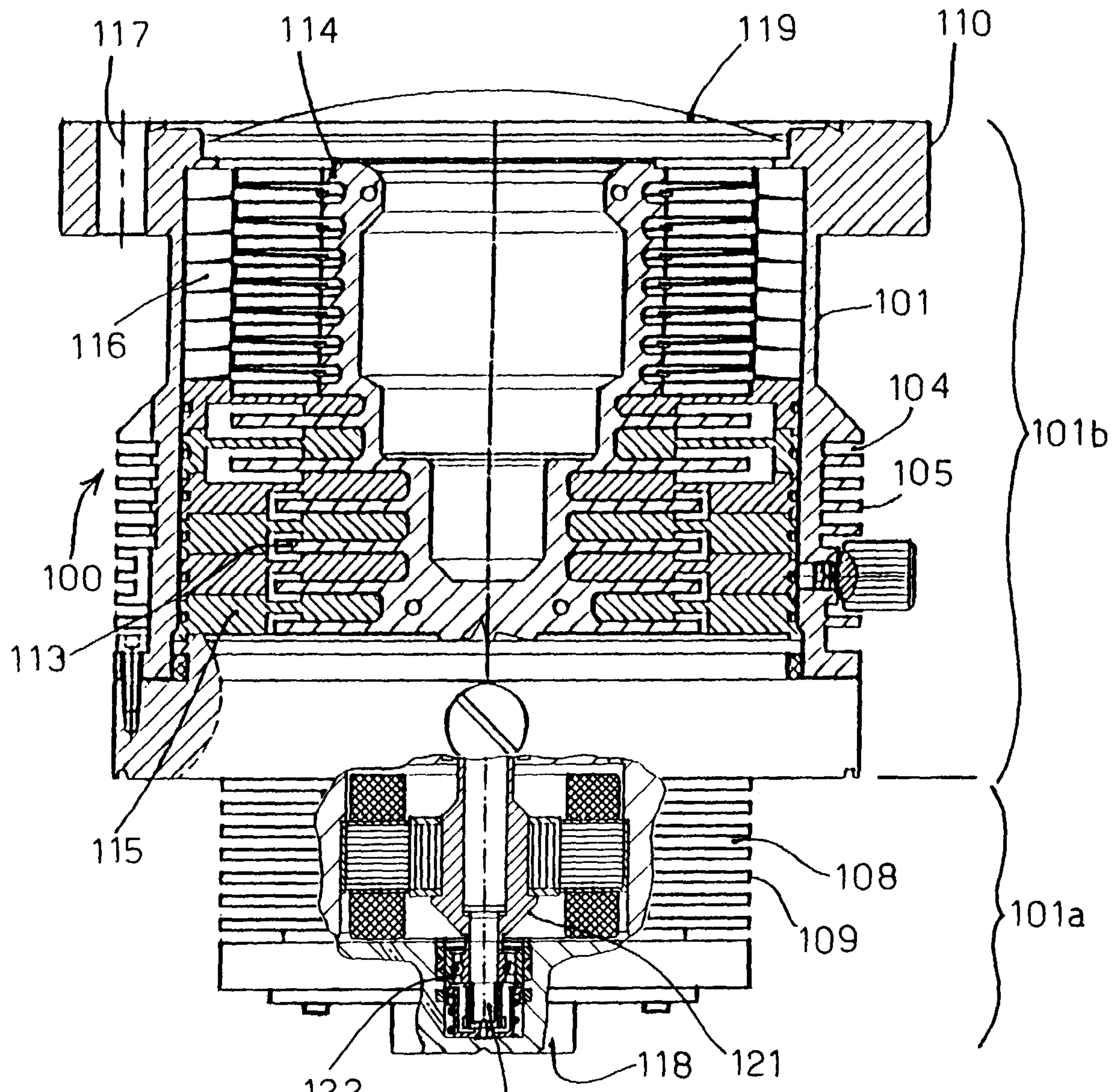
117
114
119
110
101
116
104
101b
105
100
113
115
108
109
101a
122
123
118
121

FIG. 1

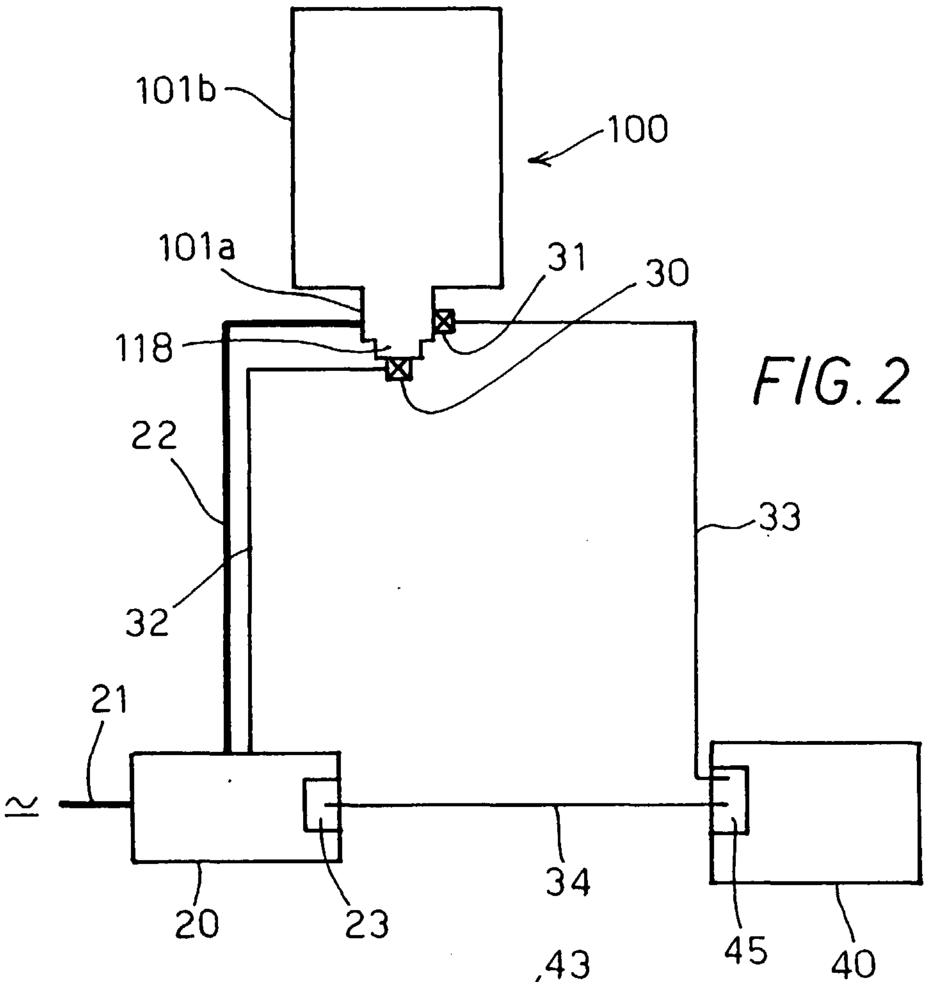
101b
100
101a
31
30
118
22
33
32
21
≈
34
20
23
45
40

FIG. 2

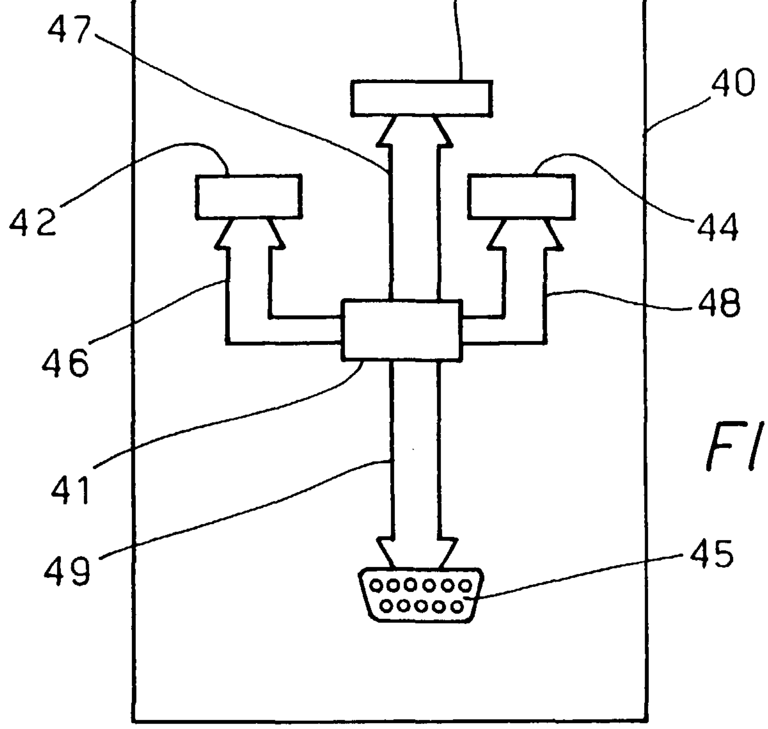
43
47
40
42
44
48
46
41
49
45

FIG. 3

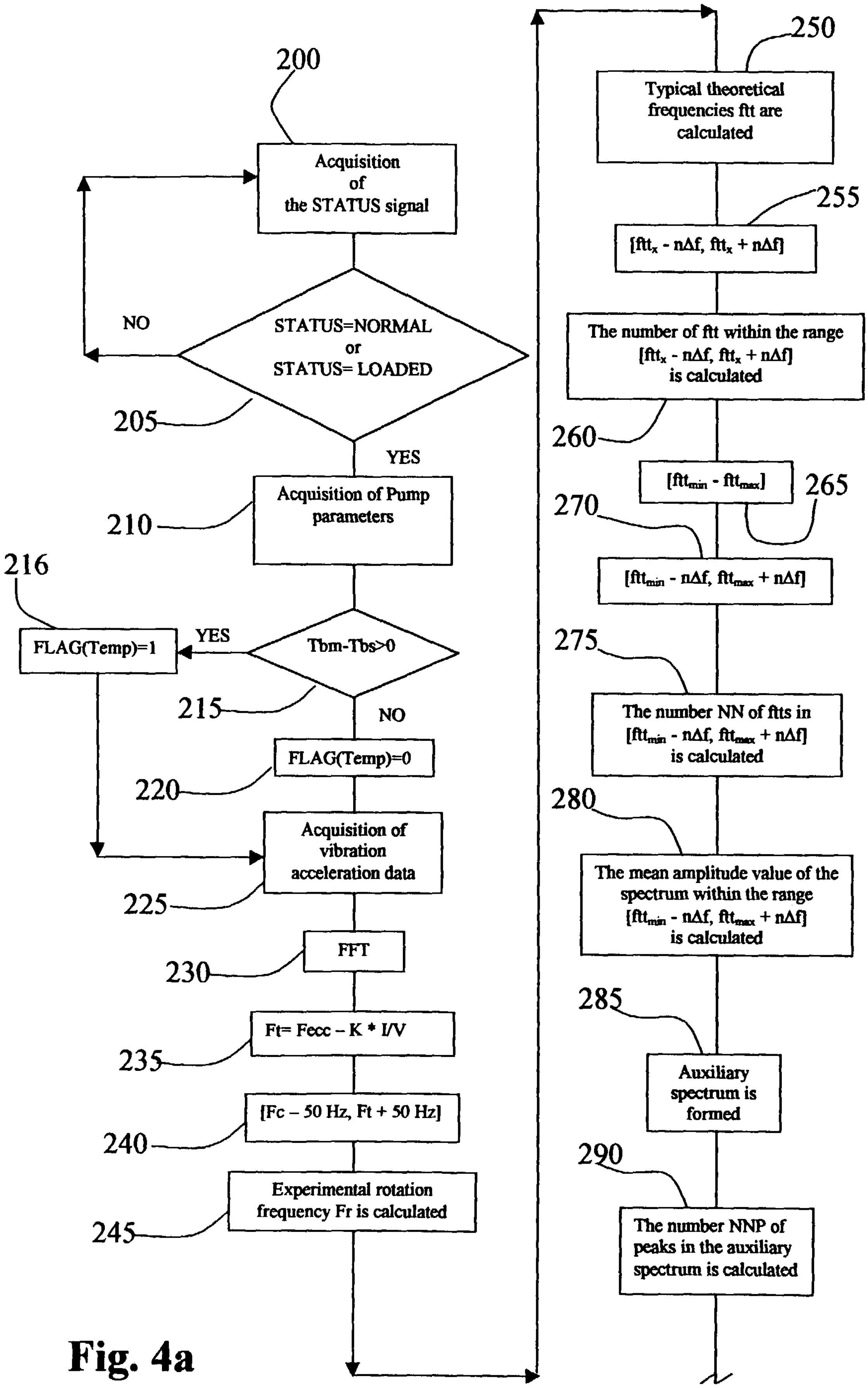
200
Acquisition of the STATUS signal
NO
STATUS=NORMAL or STATUS= LOADED
205
YES
Acquisition of Pump parameters
210
216
FLAG(Temp)=1
YES
Tbm-Tbs>0
215
NO
FLAG(Temp)=0
220
Acquisition of vibration acceleration data
225
FFT
230
Ft= Fecc – K * I/V
235
[Fc – 50 Hz, Ft + 50 Hz]
240
Experimental rotation frequency Fr is calculated
245
250
Typical theoretical frequencies ftt are calculated
255
[ftt_x - nΔf, ftt_x + nΔf]
The number of ftt within the range [ftt_x - nΔf, ftt_x + nΔf] is calculated
260
[ftt_min - ftt_max]
265
270
[ftt_min - nΔf, ftt_max + nΔf]
275
The number NN of ftts in [ftt_min - nΔf, ftt_max + nΔf] is calculated
280
The mean amplitude value of the spectrum within the range [ftt_min - nΔf, ftt_max + nΔf] is calculated
285
Auxiliary spectrum is formed
290
The number NNP of peaks in the auxiliary spectrum is calculated

Fig. 4a

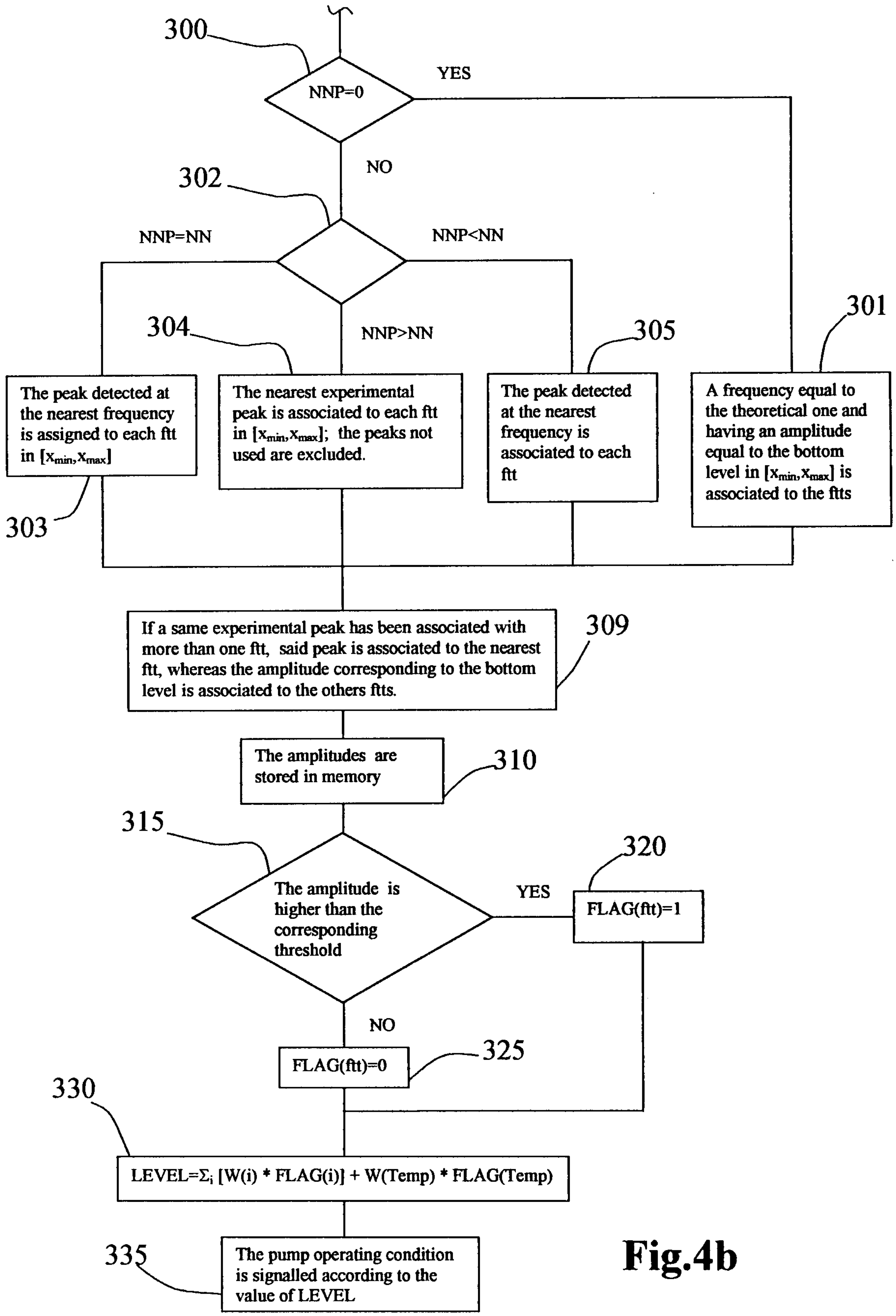
300
NNP=0
YES
NO
302
NNP=NN
NNP<NN
NNP>NN
304
305
301
303
The peak detected at the nearest frequency is assigned to each ftt in [x_{min},x_{max}]
The nearest experimental peak is associated to each ftt in [x_{min},x_{max}]; the peaks not used are excluded.
The peak detected at the nearest frequency is associated to each ftt
A frequency equal to the theoretical one and having an amplitude equal to the bottom level in [x_{min},x_{max}] is associated to the ftts
If a same experimental peak has been associated with more than one ftt, said peak is associated to the nearest ftt, whereas the amplitude corresponding to the bottom level is associated to the others ftts.
309
The amplitudes are stored in memory
310
315
The amplitude is higher than the corresponding threshold
YES
320
FLAG(ftt)=1
NO
FLAG(ftt)=0
325
330
LEVEL=Σ_i [W(i) * FLAG(i)] + W(Temp) * FLAG(Temp)
335
The pump operating condition is signalled according to the value of LEVEL

Fig.4b

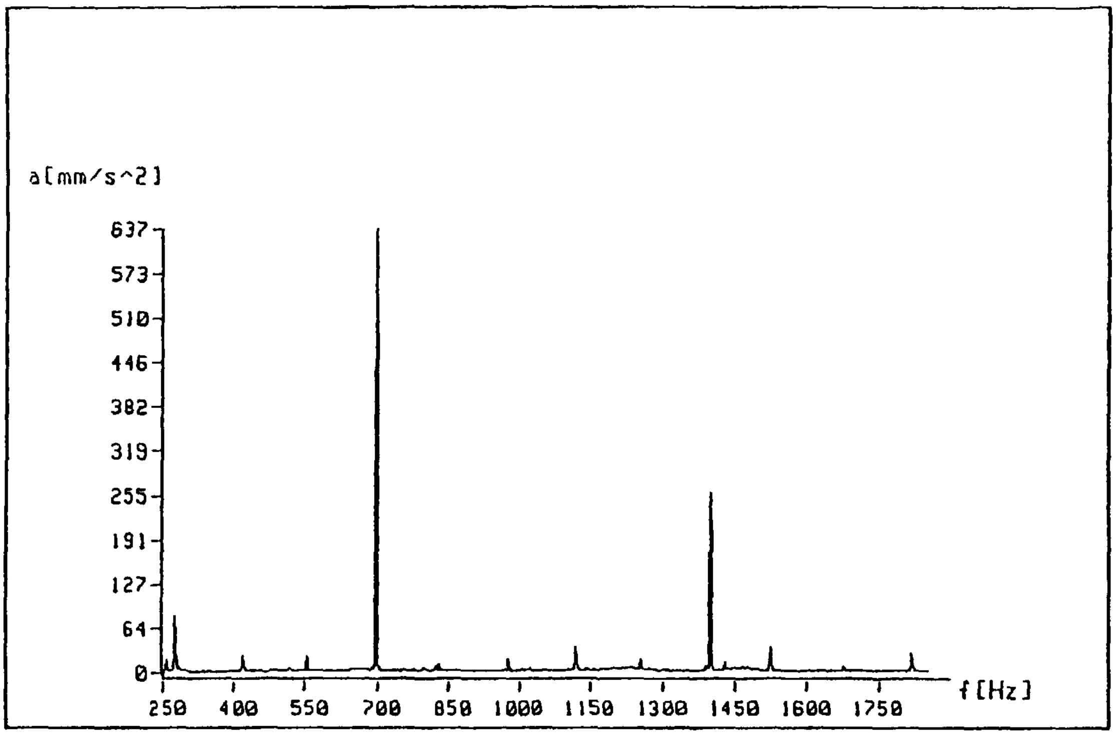
a[mm/s^2]
637
573
510
446
382
319
255
191
127
64
0
250
400
550
700
850
1000
1150
1300
1450
1600
1750
f[Hz]

FIG. 5a

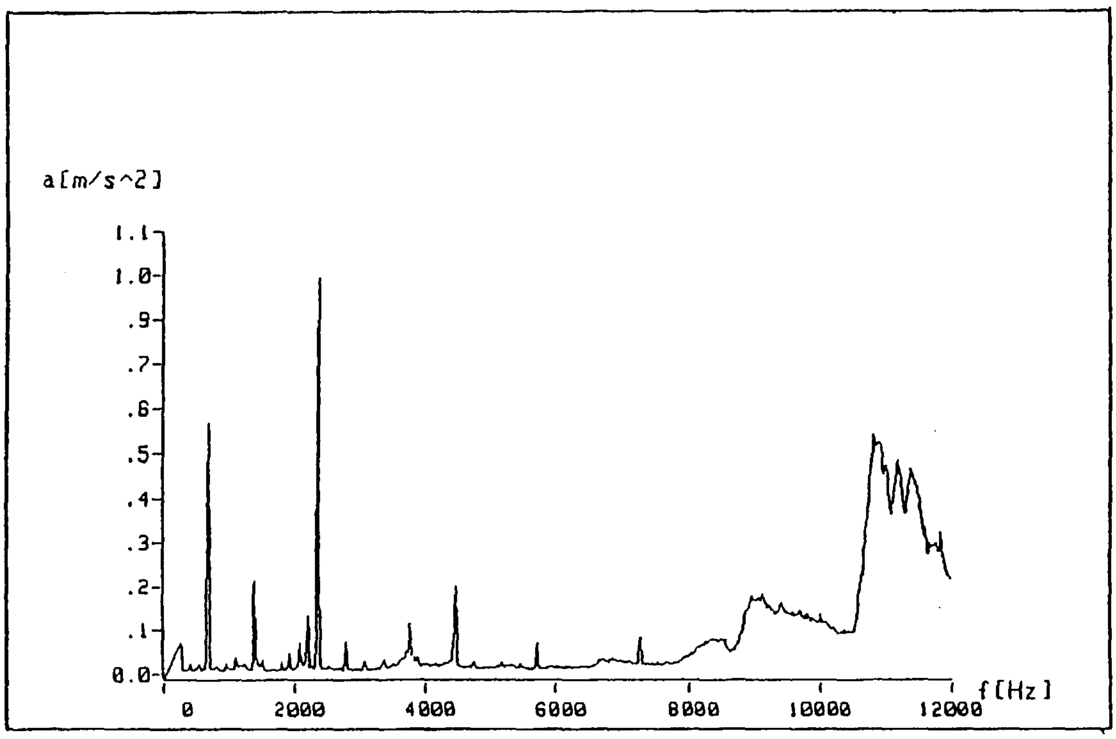
a[m/s^2]
1.1
1.0
.9
.7
.6
.5
.4
.3
.2
.1
0.0
0
2000
4000
6000
8000
10000
12000
f[Hz]

FIG. 5b

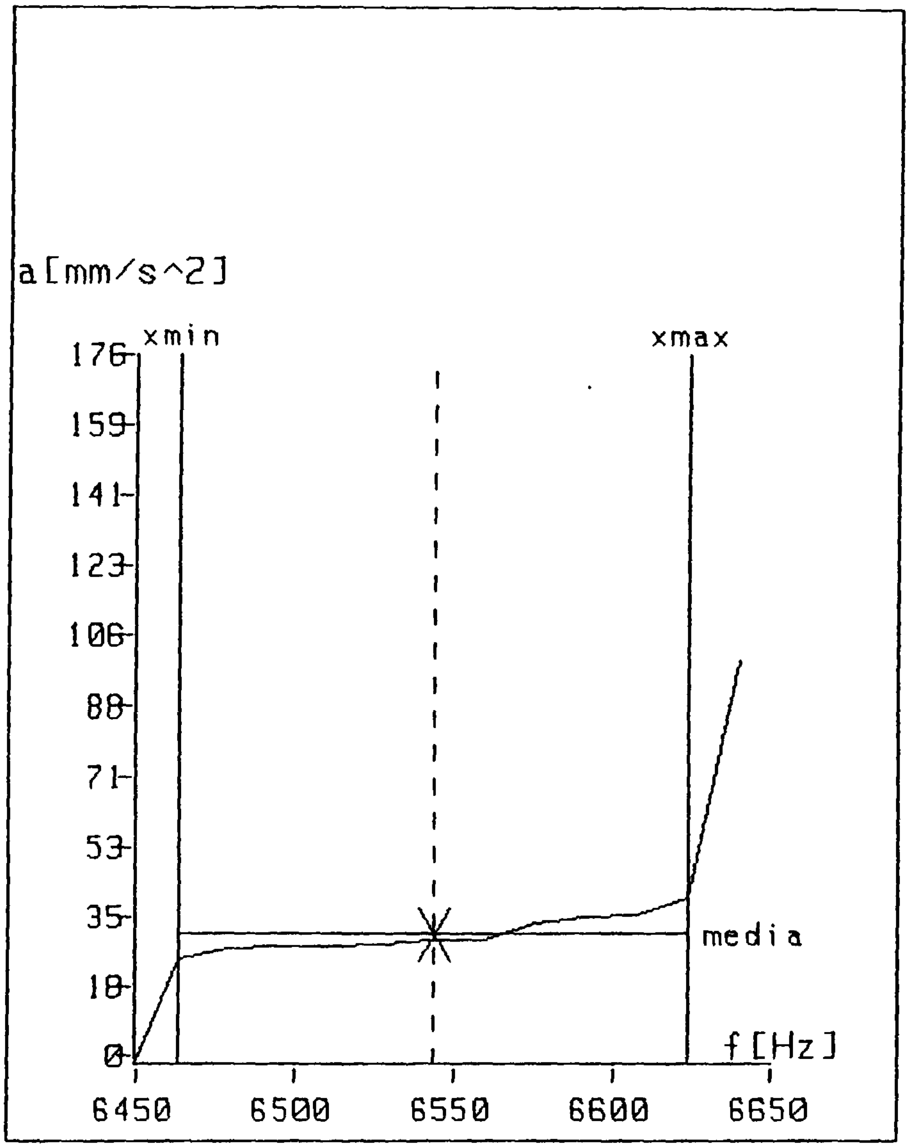
a[mm/s^2]
xmin
xmax
176
159
141
123
106
88
71
53
35
18
0
media
f[Hz]
6450
6500
6550
6600
6650

FIG. 6a

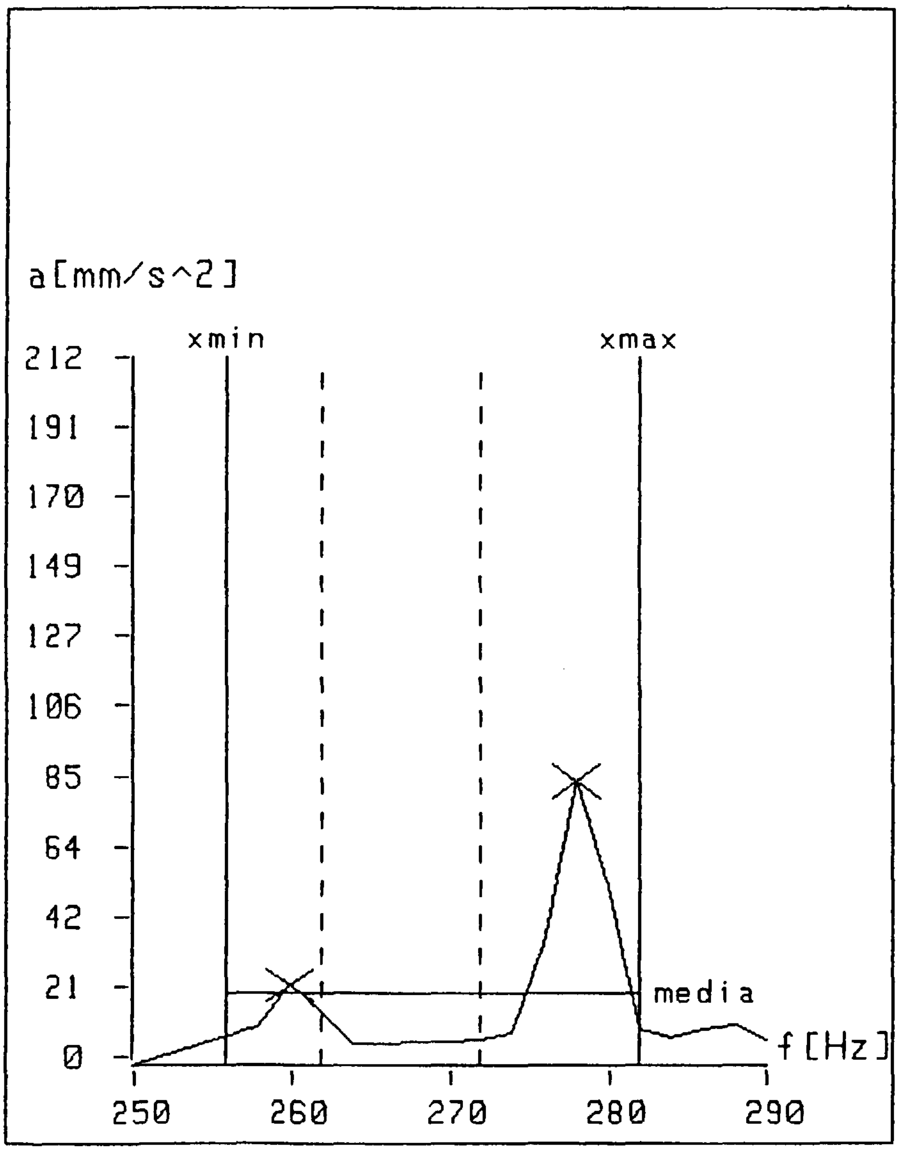
a[mm/s^2]
xmin
xmax
212
191
170
149
127
106
85
64
42
21
0
media
f[Hz]
250
260
270
280
290

FIG.6b

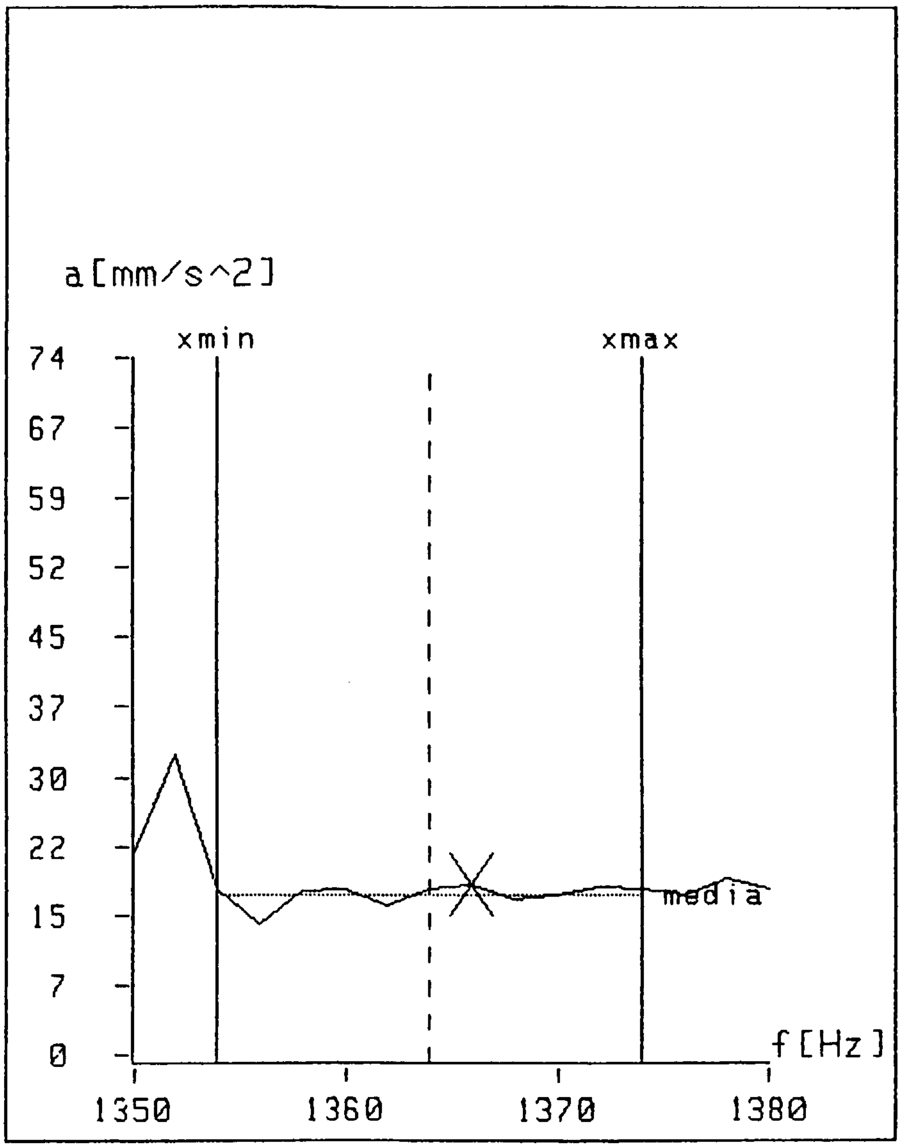
a[mm/s^2]
xmin
xmax
74
67
59
52
45
37
30
22
15
7
0
media
f[Hz]
1350
1360
1370
1380

FIG. 6c

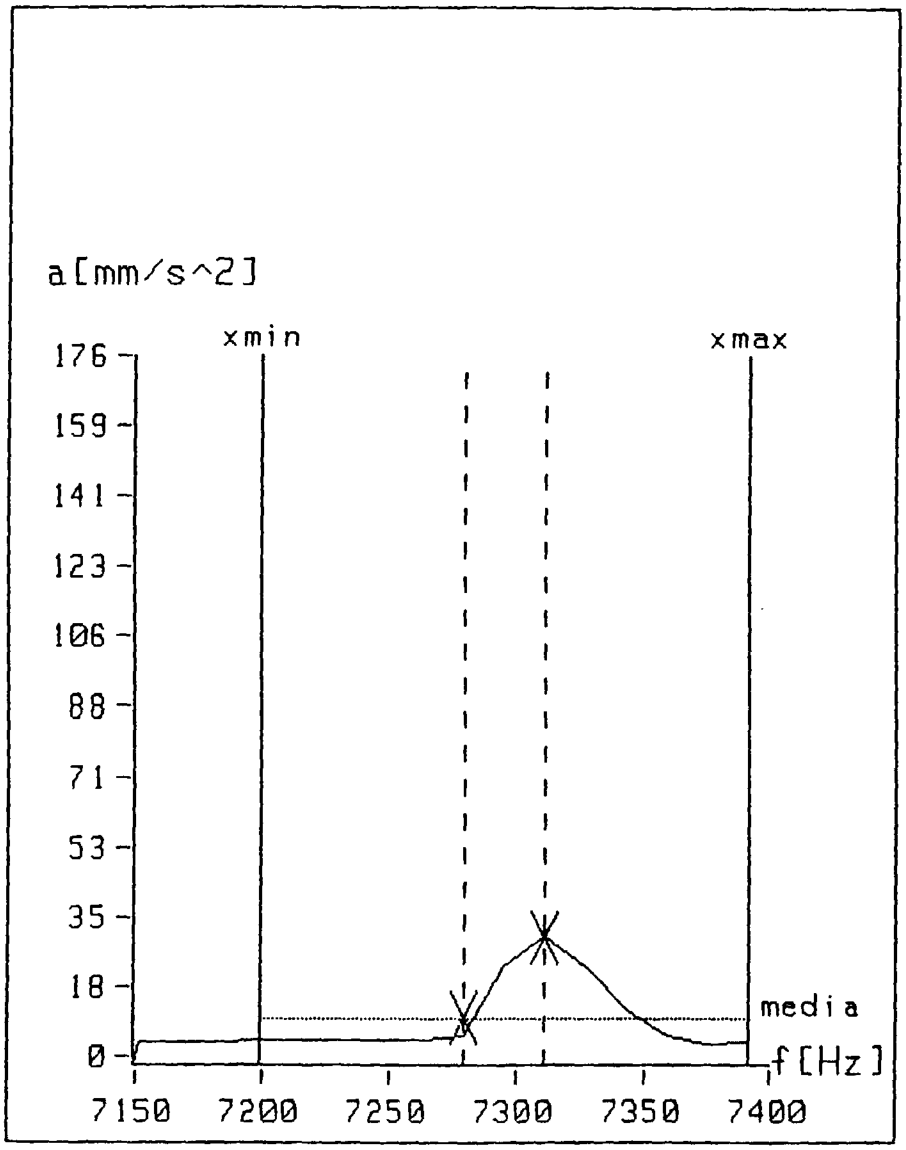
a[mm/s^2]
xmin
xmax
176
159
141
123
106
88
71
53
35
18
0
media
f[Hz]
7150
7200
7250
7300
7350
7400

FIG. 6d

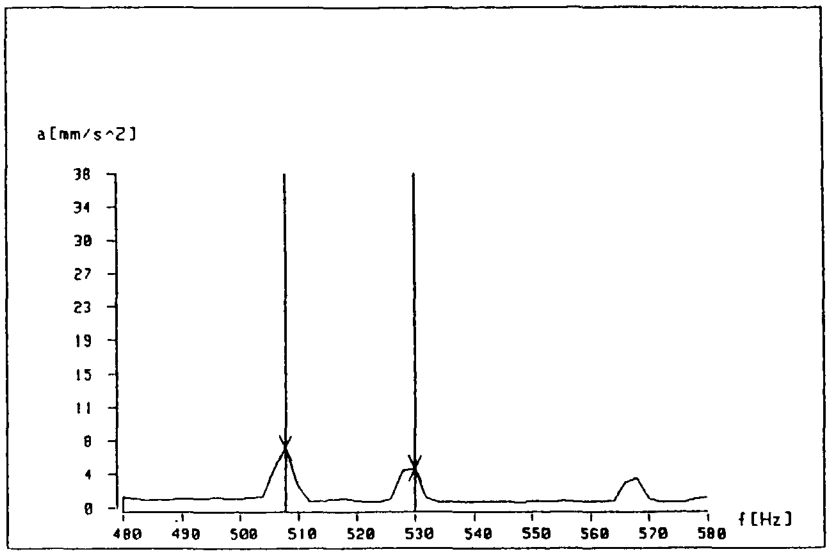

FIG. 7a

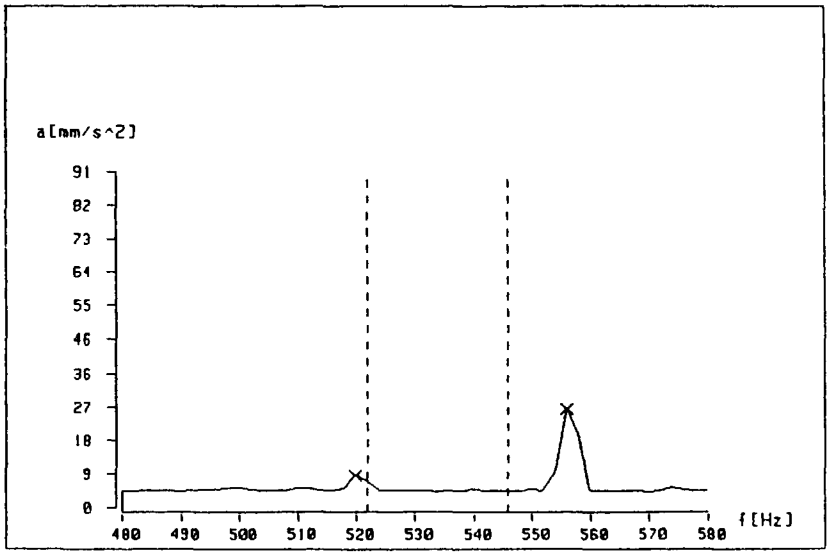

FIG. 7b

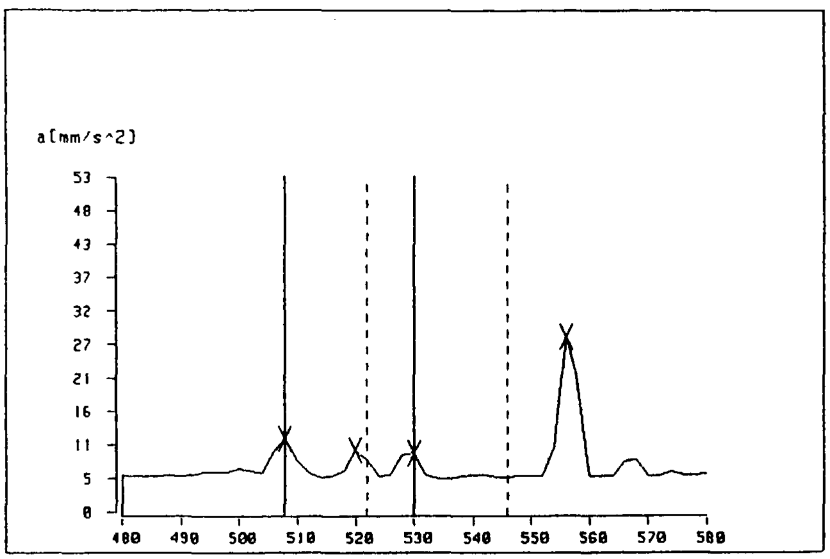

FIG. 7c