A model-based method for leakage detection of piston pump under variable load condition

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ABSTRACT Hydraulic systems have been widely used in construction machinery, aeronautics, astronautics, automobiles, shipping and other fields. Piston pumps are power source and core component in the hydraulic system. The detection and assessment of leakage fault in piston pumps is challenging because (1) piston pump is always subjected to varying loads and operates at variable speeds, the conventional condition monitoring methods that rely on instantaneous behavior analysis can hardly give reliable prediction to the actual health state of the piston pump; (2) it is not easy to obtain the typical condition monitoring data that can reflect the change of the piston pump in dynamic behavior when it suffers different severity levels of faults under various loading conditions. In order to tackles these issues, a model-based method for leakage detection of piston pump under variable load condition was proposed in this paper. The liquid-solid coupling model of piston pump is developed and verified at first. Then, with the aid of the model, different severity levels of oil leakage faults are simulated. It is found that outlet pressure signals can better indicate the oil leakage of piston pumps in comparison of the casing vibration signals. ‘Sub-harmonics’ will appear in the frequency spectra of outlet pressure signals in the presence of oil leakage fault. Finally, the dynamic responses of the piston pump under different loading and structural health conditions are investigated systematically. The results show that external load can significantly influence the dynamic responses of the piston pump and the gradients of the trend lines of total ‘sub-harmonic’ energy of outlet pressure provide correct prediction to the presence and growth of the oil leakage fault. Based on the investigation results, a reliable oil leakage detection and assessment method is proposed.

INDEX TERMS Piston pump, leakage, liquid-solid coupling model, condition monitoring

I. INTRODUCTION Hydraulic systems have been widely used in construction machinery, aeronautics, astronautics, automobiles, shipping and other fields. Its performance can affect the operation, efficiency and reliability of the overall system [1-2]. Piston pumps are power source and core component in the hydraulic system attributing to their advantages of high rated pressure, high force-to-weight ratio, high efficiency, etc. Due to usually harsh working environment and heavy working loads, piston pumps are prone to failures [3-4]. Failures of piston pumps might cause unexpected machine breakdowns, resulting in economic loss, even worse, catastrophic consequences [5-6]. Relevant statistics show that more than 50 percent of electromechanical equipment defects are related to pumps faults [7]. Therefore, effective and feasible fault diagnosis methods for piston pumps are vital for successful operation of the whole system. Methods can be roughly divided into two categories. They are respectively signal processing-based methods and the artificial intelligence-based methods. As the condition
monitoring signals collected from piston pumps are usually noisy [8, 9], noise cancellation and fault feature extraction are two major tasks in the first category of achievements [10-16]. For example, wavelet package decomposition was adopted in [10] for diagnosing a hydraulic pump based on analyzing the energy distributions of wavelet package coefficients; the empirical mode decomposition was employed in [12] to realize the condition monitoring of a piston pump by analyzing its oil discharge pressure signals; the local mean decomposition was used in [14] to deal with the fault-related modulation issues that were present in the pump vibration signals; a method that combines intermittent chaos and sliding window symbol sequence statistics was proposed in [15] to realize the real time diagnosis of pump faults; a simulation-determined band pass filter is employed in [16] to improve the performance of minimum entropy de-convolution (MED) for the fault diagnosis of axial piston pump bearings; a hybrid method of Walsh transform de-noising and Teager energy operator (TEO) demodulation is proposed in [17] in order to eliminate the heavy background noises, and so on. The methods based on artificial intelligence were implemented through inputting the extracted fault features into artificial intelligence tools, such as neural network [18-21], support vector machine [22], and other kinds of intelligent pattern recognition tools [23-27]. For example, Yan [18] developed a scheme by using improved convolutional neural network. It can be directly used without human intervention, although the operator knows little knowledge about hydraulic pump. Lu [22] used optimized support vector regression (SVR) model to detect faults and estimate the fault sizes of a piston pump. Azadeh [23] provided a correct and timely diagnosis mechanism of pump failures by knowledge acquisition through a fuzzy rule-based inference system which could approximate human reasoning.

All these efforts are quite helpful to improve the condition monitoring of piston pumps, but still not successful enough for engineering application. There are many reasons for this, but the major reasons are

1) The most signal processing-based techniques are based on the analysis of the instantaneous dynamic responses of piston pumps, and then assess the health condition of the piston pumps based on observing the variation tendencies of the fault features over time. However, in the actual operation of piston pump, the load is constantly changing, the measured responses are not only affected by the health condition of the piston pumps, but also influenced by their operational and loading conditions. All these factors are coupled together to take effect on the dynamic responses of the piston pumps. However, their coupling effect was not fully considered in the process of condition monitoring;

2) The reliability and accuracy of the artificial intelligence-based methods are highly dependent on the quality of training. It is well known that a large amount of data, collected under various operational, loading and structural health conditions, are essential for accomplishing the training. However, in practice it is very difficult to obtain so many kinds of data from the piston pumps;

3) In addition, both signal processing-based methods and artificial intelligence-based methods are data-driven methods, which lack in-depth dynamic characteristics analysis of piston pump, especially the dynamic behavior of piston pump when it suffers different severity levels of faults under various loading conditions. The provided physical insight into faults and their respective causes is limited.

As we know, model-based approaches to fault detection can provide deeper insights. Physical models of hydraulic pumps were employed for fault detection and diagnosis by Yu [28], who used a bilinear fault detection observer to detect faults in the fluidic and mechanical domain. An extended Kalman filter is used in [29] for leakage detection in hydraulic pumps. A fault diagnosis method based on a nonlinear unknown input observer is proposed in [30] to realize intelligent hydraulic pump system fault detection. However, due to the complex structure of piston pump and the liquid-solid coupling effect, the accurate mathematical model of piston pump is very difficult to obtain. The recently developed virtual prototyping technology provides an effective tool to overcome this issue. Piston pump manufacturers such as Rexroth [31] and other research institutes [32] have already used the virtual prototype of piston pump for design development and performance improvement.

In order to address these issues and fill the technology gap, a model-based method for leakage detection of piston pump under variable load condition is proposed in this paper. The advantages of method is

1) It can help to understand the essential relations between the faults and their corresponding dynamic responses;

2) It can help to readily obtain the dynamic response data under any desired operational, loading and structural health conditions;

3) It can help to better understand the characteristic features of the faults from the simulated dynamic response signals attributing to the absence of background noise that are often present in practical signals measured from site.

The novelty of this research can be summarized as

1) The liquid-solid coupling model of a seven-piston piston pump is developed in order to investigate the dynamic behavior of the piston pump under various loading and structural health conditions;

2) Instead of using the conventional condition monitoring methods that are based on observing the variation tendencies of the fault features over time, a more effective and reliable oil leakage fault detection and assessment method is developed based on considering
the coupling effect of loading and structural health conditions.

The remaining part of the paper is organized as follows. First of all, the liquid-solid coupling model of a seven-piston piston pump is developed in Section 2 and verified in Section 3. In Section 4, different severity levels of leakage faults are simulated in the liquid-solid coupling model to obtain the dynamic responses of the piston pump under various loading and structural health conditions. Following the analysis of the dynamic responses in different scenarios, a more reliable oil leakage detection and assessment technique is proposed in Section 5. The paper is concluded with a few key remarks in Section 6.

II. Development of the liquid-solid coupling model

The liquid-solid coupling model of a seven-piston piston pump is developed first in this paper for facilitating understanding the dynamic responses of piston pumps under various loading and structural health conditions. The model was built based on the following considerations:

1) Only necessary parts are considered in the model for simplifying the calculation;

2) The assembly clearance and manufacturing tolerance is negligible in model development;

3) The oil film between friction pairs, such as piston and cylinder, swash plate and slipper, cylinder and valve plate, is assume perfect for operation. Therefore, the friction coefficient of the oil film is assumed to be a constant;

4) The fluid oil has constant viscosity under all considered operational conditions.

The 3-D solid model of a seven-piston piston pump is built first in SOLIDWORKS, as shown in Fig.1. The driving shaft is connected to the external power. The cylinder block is supported by a roller bearing, of which the outer-race is mounted on the pump casing. As cylinder block rotates with the driving shaft, the pistons will reciprocate in piston bores, drawing and discharging the fluid through the valve plate installed at the end side.

In order to establish multi-body dynamic model, the 3-D solid model of piston pump was saved as ‘Parasolid’ format file and imported into ADAMS. Then, the joints, loads and drive forces were added. According to the kinematics and dynamics of the piston pump, the joints between different components are listed in Table I. The addition of joints is an important step, including selecting the type of joint, picking component, defining location and picking geometry feature. Here is an example of addition process of planar joint between slipper and swash plate. First, the planar joint was selected. Then, the bodies of slipper and swash plate were picked. Furthermore, the center point of the contact surface between slipper and swash plate was used as the location point of the planar joint. Last, the geometry feature of the planar joint was defined based on the selected location point. The multi-body dynamics model of the piston pump was shown in Fig.2.

Dynamic response of some key components in piston pump should be obtained by flexible body analysis. The 3-D model of the components which need to be flexible were saved as ‘Parasolid’ format files and imported into ANSYS. After the flexible process, including setting material parameter, selecting unit type, meshing grid, defining rigid area, etc., the flexible models could be obtained and saved as modal neutral files (MNF). The flexible models of shell and cap in the piston pump were shown in Fig.2. Furthermore, the modal neutral files (MNF) were imported into ADMAS/flex module and the flexible models replaced their corresponding models. The rigid-flexible coupling model of the piston pump could be finally obtained.
Subsequently, the hydraulic model of the piston pump is established in software AMESIM. The hydraulic model starts with single piston model, as shown in Fig. 4. It includes the flow model, movement model and valve plate model. It can be seen that the low pressure oil is sucked to the piston bore when the piston moves to the right. When the piston moves to the left, the piston charges the high pressure oil out to drive loads. This model also includes three types of leakage, i.e. leakage between piston and cylinder \(q_{c1}\), leakage between slipper and swash plate \(q_{c2}\), and leakage between cylinder and valve plate \(q_{c3}\). Then, replicate the assembled single piston hydraulic model for seven times to achieve the hydraulic model of the whole seven-piston piston pump. At each time of replication, the initial phase of the model will be shifted by a constant phase angle of \(\frac{2\pi}{7}\) to differentiate the initial positions of the pistons in different piston bores. The resultant hydraulic model of the whole piston pump is shown in Fig.5.

To enable the rigid-flexible coupling model and the hydraulic model to work synchronously in simulating the operation of a seven-piston piston pump, it is necessary to define the coupling variables between the two models. To ease the understanding of the cooperation of these two models in the simulation process, a work diagram is illustrated in Fig.6. During the co-simulation process, the dynamics simulation was done in ADMAS at first and the kinematics parameters of seven pistons, such as displacement, velocity, and acceleration, were imported through ADAMS/Controls module. Then in AMESIM, the kinematics parameters were loaded by ‘import ADAMS model’ module and hydraulic pressures in seven piston bores could be obtained through hydraulic system simulation. At last, the hydraulic pressures in seven piston bores were transmitted to ADAMS and co-simulation was finished.
FIGURE 7. The movement diagram of the piston in a piston pump

Take point A as the initial position of the piston ball, after the cylinder block rotates an angle $\phi$ its new position can be updated by using the following equations

\[
\begin{align*}
    x &= -R\cos\phi \tan\gamma \\
    y &= R\cos\phi \\
    z &= R\sin\phi
\end{align*}
\]

(1)

where $\gamma$ indicates the tilt angle of swash plate, and $R$ represents its radius.

From (1), it is noticed that the piston exhibits two types of motions. One is the linear reciprocating motion in the direction of x-axis, another is the rotational motion in the direction perpendicular to the x-axis. The velocity and acceleration of the linear motion of the piston are

\[
\begin{align*}
    v_1 &= \omega R \tan \gamma \sin \phi \\
    a_1 &= \omega^2 R \tan \gamma \cos \phi
\end{align*}
\]

(2)

(3)

The instantaneous quantity of flow in a single piston chamber is

\[
q_i = \frac{\pi}{4} d^2 v_1 = \frac{\pi}{4} d^2 \omega R \tan \gamma \sin \phi
\]

(4)

where $d$ denotes the diameter of the piston bore.

The total instantaneous flow in the discharge area of the piston pump is the sum of the flow quantities in all pistons bores, i.e.

\[
q = \sum_{i=1}^{n} \frac{\pi}{4} d^2 \omega R \tan \gamma \sin \phi = \frac{n \pi}{4} d^2 \omega R \tan \gamma \sum \sin \phi
\]

(5)

For a piston pump with $n$ pistons, the difference of the phase angles of the adjacent pistons will be

\[
\beta = \frac{\pi}{n}
\]

(6)

As the piston pump considered in this paper has odd number of pistons, (5) can be rewritten as

\[
q_p = \begin{cases} 
\frac{\pi}{4} d^2 \omega R \tan \gamma \frac{\cos(\phi - \frac{\beta}{2})}{2 \sin \frac{\phi}{2}}, & \phi \in [0, \frac{\beta}{2}] \\
\frac{\pi}{4} d^2 \omega R \tan \gamma \frac{\cos(\phi + \frac{\beta}{2})}{2 \sin \frac{\phi}{2}}, & \phi \in [\frac{\beta}{2}, \beta]
\end{cases}
\]

(7)

Obviously, the instantaneous flow quantity of the piston pump is a periodic function with the frequency of $\frac{n}{2\pi}$. Its maximum, minimum, and average values are

\[
\begin{align*}
    q_{\text{max}} &= \frac{\pi}{4} d^2 \omega R \tan \gamma \frac{1}{2 \sin \frac{\phi}{2}} \\
    q_{\text{min}} &= \frac{\pi}{4} d^2 \omega R \tan \gamma \frac{\cos \phi}{2 \sin \frac{\phi}{2}} \\
    q_{\text{ave}} &= \frac{n}{4} d^2 \omega R \tan \gamma
\end{align*}
\]

(8)

(9)

(10)

The frequency of the pulsation of the flow will be

\[
f_q = \frac{n \omega}{60}
\]

(11)

Then, with the aid of these equations the velocity, acceleration and flow of the seven-piston piston pump can be calculated. The calculation results will be used to verify the accuracy of the liquid-solid coupling model developed in Section 2.

Assume the rotational speed of the input shaft is $\omega = 1500$ rev/min, the geometric parameters of the piston pump are listed in Table I, the velocity and acceleration of the motion of the piston and the total flow of the piston pump are calculated by using equations (2), (3) and (7) and the liquid-solid coupling model developed in Section 2. The calculation results are shown in Fig.8. Where, ‘theoretical results’ refer to the results obtained from the mathematical equations, while ‘simulation results’ represent those obtained from the liquid-solid coupling model. Meanwhile, the values of the maximum velocity and the maximum acceleration of piston motion and the total flow of the piston pump obtained from both approaches are also listed in Table III for facilitating comparison.

<table>
<thead>
<tr>
<th>Parameters of the Piston Pump</th>
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<tbody>
<tr>
<td>Radius of swash plate $R$</td>
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<tr>
<td>Diameter of piston chamber $d$</td>
</tr>
<tr>
<td>Piston number $n$</td>
</tr>
<tr>
<td>Tilt angle of swash plate $\gamma$</td>
</tr>
<tr>
<td>Speed of input shaft $\omega$</td>
</tr>
<tr>
<td>Value</td>
</tr>
</tbody>
</table>

TABLE II

FIGURE 8. Comparison of the theoretical and simulation calculation results


From Fig.8, it is noticed that the oscillations of both the velocity and acceleration of the reciprocating motion of the piston and total flow obtained from the liquid-solid coupling model are not stable until 0.2s. This is because in the calculations, the rotational speed of the input shaft is set to gradually increase from 0 to 1500rev/min within 0.2s. From Table 2, it is found that the relative errors of the maximum velocity, the maximum acceleration and the total flow are 0.05%, 0.07% and 5.18%, respectively. The differences are so small and ignorable. Thus, it can be concluded that the liquid-solid coupling model developed in Section 2 can accurately simulate the operation of the piston pumps. In particular, it is noticed from Fig.7 that the total flow obtained from the model is slightly smaller than that derived from the equations. This is because clearance always exists between the piston and piston bore, which will lead to minor oil leakage. This has been well considered by the model by setting an appropriate value of clearance (e.g. 0.005 mm in this paper). However, it is unlikely to reflect this phenomenon by using the mathematical equations. Inspired by this, different severity levels of oil leakage faults were readily simulated through assigning different clearance values to the model. In addition, the mathematical equations are only able to describe the flow, they are unable to describe the dynamic responses (e.g. vibration and oil pressure) of an operating piston pump. Thus, the liquid-solid coupling model is superior to the mathematical equations from this point of view. This explains why the modelling research conducted in this paper is based on a fluid-solid coupling model rather than based on mathematical equations.

The instantaneous flows and pressures in individual piston bores are also calculated for checking the correctness of the model. The results are shown in Fig.9. From Fig.9a, the piston pump’s two working stages, i.e. oil discharge and oil suction, can be clearly observed. The former is characterized by the flow flux oscillating in the form of a sinusoidal signal; the latter is characterized by zero flux of flow. The switch from oil suction to oil discharge is indicated by a reverse pulsation of the flow. The cycle of oil discharge and oil suction is 0.04 s, which corresponds to the rotational speed of the input shaft 1500rev/min. It can be seen from Fig.9b that high pressure and low pressure alternately appear in individual piston bore, corresponding to the two working states of piston pump. The high pressure has a certain pulse around the set load pressure 23.5Mpa. There is a phase difference which match the theoretical analysis well between the seven pistons.

![Instantaneous flows and pressures in individual piston bores](image-url)
IV. Fault simulation and dynamic response analysis

With the aid of the liquid-solid coupling model, different severity levels of oil leakage faults in the seven-piston piston pump are simulated in this section in order to achieve an in-depth understanding of the dynamic responses of the piston pump under different loading and structural health conditions. Herein, the dynamic responses of the piston pump will be indicated by the oil pressure in piston bore and the vibrations of the piston pump in three mutual-perpendicular directions, x, y, and z. Where, x indicates axial axis, y and z refer to vertical and horizontal directions, respectively. The vibration sensor in the model will be mounted on the outer casing of the piston pump. In the research, three different severity levels of oil leakage faults were simulated in one of the seven piston bores by setting the clearance to be 0.005 mm, 0.1 mm and 0.2 mm, respectively. As the clearance of 0.005 mm is quite small and ignorable, it is used to simulate the normal condition. The clearance values of 0.1 mm and 0.2 mm are set to simulate the slight and serious oil leakage faults, respectively. When the load pressure is 23.5 MPa and the rotational speed of the input shaft is 1500 rev/min, the flow and oil pressure in individual piston bore and those at the outlet of the piston pump are calculated. The results are shown in Fig.11, where the calculation results obtained in the three fault simulation scenarios are displayed in the same plot for easing comparison.

In theory, the oil leakage fault due to the worn of piston and piston bore will not change the frequency of flow pulsation in the defective piston bore, however it will reduce the amplitude of flow pulsation. Moreover, the more serious the leakage, the more the flow pulsation amplitude will be reduced. From Fig.11a, such a phenomenon can be perceived although not very clearly. From Fig.11b, it is found that the effect of oil leakage fault can be more clearly observed from the oil pressure in individual piston bore. The oil pressure waveforms show a clear declining tendency in the presence of oil leakage. Moreover, the more serious the oil leakage, the more the oil pressure will decrease. But in the actual engineering application, due to the difficulty of measuring...
the instantaneous flow and oil pressure in individual piston bores, it is more feasible to realize the detection and assessment of the oil leakage fault through investigating the outlet flow signal and outlet oil pressure signal. Considering oil pressure is relatively easier to measure and the pressure sensor is easy to install in practice, the outlet oil pressure signals are further analyzed in the following research.

From Fig.11c, it is interestingly found that the oil leakage occurring in one piston bore significantly influences the outlet pressure of the piston pump. It is seen that the time waveform of the outlet pressure is deformed by the oil leakage fault. Moreover, the more serious the oil leakage, the more the time waveform of the outlet pressure will be changed. Moreover, based on Fig.11c, it can be predicted that outlet pressure will be reduced more when multiple pistons and piston bores are worn.

Frequency spectra of the outlet pressure are calculated by using the Fast Fourier Transforms (FFT) and the corresponding results are shown in Fig.12.

From Fig.12, the fundamental frequency, 175 Hz, is clearly observed from all three frequency spectra in spite of the health state of the piston pump. Additionally, it is interestingly found that in the presence of the oil leakage fault, \( n - 1 \) number of ‘sub-harmonics’ are present below the operational frequency 175 Hz. Their frequencies are \( i \times (\text{operational frequency}/n) \) ( \( i = 1,2,\ldots,n - 1 \) ). Moreover, the more serious the oil leakage, the more significant these ‘sub-harmonics’ will tend to be. However, they cannot be clearly observed when the oil leakage is absent.

Furthermore, the vibration behaviors of the piston pump before and after the presence of the oil leakage faults are investigated. The casing vibrations of the piston pump in three directions \( x, y \) and \( z \) are calculated. The calculation results and the corresponding frequency spectra are shown in Fig.13.

![Figure 12: Frequency spectra of the outlet oil pressure signals](image-url)

![Figure 13: Vibration and FFT spectra for piston pump](image-url)
V. Detection and assessment of leakage fault

The findings in Section IV provide important clues for detecting and assessing the oil leakage fault in piston pumps. But it is worth noting that all dynamic responses described in Section IV are obtained when the piston pump is subjected to constant external load, i.e. 23.5 MPa. However, in reality the piston pump is often subjected to varying loads, which can affect its dynamic responses as well and thus increase the difficulty of oil leakage detection. To address this issue, further research is conducted in this section by considering varying loading conditions. In the research, considering the difficulty of using the developed model to simulate continuously varying loads, a few discrete constant loads, i.e., 5, 10, 15 and 23.5 MPa, are considered to enable the research. This measure is acceptable because the load undertaken by the piston pump often changes slowly over time. When we use a very high sampling frequency to collect the response signals of the pump, the change of pump load during the short sampling period is small and ignorable, thus can be regarded as constant.

The time waveforms of the outlet pressure signals obtained under different loading conditions are shown in Figs. 14.

Inspired by the phenomenon observed from Fig. 12, the total energy $E_{sub}$ of the ‘sub-harmonics’ below the operation frequency of the piston pump is calculated by

$$E_{sub} = \sum_{i=1}^{n} A(i\omega)$$  \hspace{1cm} (13)

where $A(*)$ indicates the magnitude of the subharmonic component at frequency ‘*’.

The values of $E_{sub}$ are calculated and its results obtained in different loading and structural health scenarios are listed in Table IV.

![FIGURE 13 Vibration behaviors in three directions](image)

From Fig. 13, it is found that in contrast to the influences of the fault on flow and oil pressure, its influence on casing vibrations is little, although the pump’s vibrations in the three directions seem to decrease a little bit but not obvious when oil leakage happens. This is because when the oil leakage fault occurs, the damping of the system in the three directions may show a little increase. But anyway, it can be concluded that the oil leakage fault of the piston pump can be better indicated by outlet oil flow and outlet oil pressure rather than by the casing vibrations.

Finally, the following key information can be obtained from the above calculation results. They provide important clues for detecting and assessing the oil leakage fault in piston pumps:

1) The outlet oil pressure signals will be deformed in the presence of oil leakage fault. Moreover, the more serious the leakage, the more the signals will be changed. ‘Sub-harmonics’ will be present blew the operational frequency of the piston pump when oil leakage occurs. Moreover, the more serious the fault, the more significant these ‘sub-harmonics’ will tend to be.

2) In comparison of oil pressure signals, the casing vibrations are not good indicators of the oil leakage fault. But the vibration signals do decrease a little bit in the presence of the fault. Moreover, the more serious the leakage, the more the vibration signals will reduce.
From Table 4, it is found that with the increase of the external load, the value of $E_{sub}$ increases regardless of the health condition of the piston pump. Meanwhile, the value of $E_{sub}$ increases also with the further deterioration of the oil leakage fault. Apparently, both the external loads and the structural health condition of the piston pump are coupled together to take effect on the value of $E_{sub}$. This rises the difficulty of fault detection inevitably. To explore a solution for this issue, the data listed in Table 4 are reorganised and shown together in Fig.16, where the data obtained in different structural health scenarios are indicated by different kinds of marks.

From Fig.15, it is clearly seen that the value of $E_{sub}$ does increase with the increase of external load. However, it shows different increasing tendencies against the external load when the piston pump is in different health states. In other words, the more serious the leakage fault, the more quickly the value of $E_{sub}$ will increase with the increasing load. This suggests that the gradient of the increasing tendency curve of $E_{sub}$ against the external load can be used as a reliable indicator of the oil leakage fault. To calculate the gradient, the trend lines of the data obtained in different scenarios are calculated. They are mathematically expressed by the following equations:

\[
\begin{align*}
  y &= 25241x - 9287.6 & \text{for normal condition} \\
  y &= 52913x - 40515 & \text{for slight fault} \\
  y &= 113252x - 90581 & \text{for serious fault}
\end{align*}
\]  

From (14), it is seen that the gradients of the trend lines are 25241 for normal, 52913 for slight fault and 113252 for serious fault, respectively. Indeed, the more serious the fault, the larger the gradient value of the trend line will tend to be.

Through the above analysis, a model-based method for leakage detection of piston pump under variable load condition could be proposed, as shown in Fig.16. The steps are as follows:

1) Collect the outlet pressure signal within a short period (for example, one second);
2) Divide the collected pressure signal into equal segments (for example, four segments);
3) Calculate the frequency spectra of each segmentation signal using FFT;
4) Calculate the energy $E_{sub}$ of the ‘sub-harmonics’ of each segmentation signal according equation 13;
5) Calculate the gradient of the trend lines of $E_{sub}$;
6) Detect and assess oil leak occurrence based on the gradient.

Attributing to this fault detection and assessment method is based on investigating the oil pressure signals collected under a wide range of external loading conditions rather than based on observing the instantaneous response of the pump, the condition monitoring result derived from this method will be more reliable.

**VI. Conclusions**

In order to achieve a more reliable technique for detecting and assessing the oil leakage fault occurring in piston pumps, in-depth analysis of the dynamic responses of the piston pumps is conducted based on the liquid-solid coupling model of a seven-piston piston pump. From the research described above, the following conclusions can be drawn:

1) In comparison of the casing vibration signals, outlet oil pressure signals can better indicate the oil leakage fault of piston pumps. Outlet oil pressure signal will be deformed in the presence of oil leakage fault. Moreover, the more serious the leakage, the more the signal will be changed.
2) Under the presence of oil leakage fault, ‘sub-harmonics’ will appear in the frequency spectra of outlet oil pressure signals. Moreover, the more serious the fault, the more significant these ‘sub-harmonics’ will tend to be;
3) External load can significantly influence the dynamic responses of the piston pump. This increases the difficulty of fault detection. However, it is found that the gradients of the trend lines of total subharmonic energy of outlet oil pressure provide correct prediction to the presence and growth of the oil leakage fault.

**FIGURE 15.** The total sub-harmonic energy $E_{sub}$ in different scenarios

**FIGURE 16.** Fault diagnosis procedure
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4) A model-based method for leakage detection of piston pump under variable load condition is proposed. Attributing to the calculation of gradients is based on the investigation of the dynamic responses of the piston pump over a wide range of external loads rather than based on the instantaneous responses of the piston pump, the fault detection and assessment results derived from gradient is true and reliable.

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