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Condition monitoring and fault diagnosis for vane pumps using flow ripple measurement

M Yang, K A Edge, D N Johnston
Department of Mechanical Engineering
University of Bath

ABSTRACT

Vane pumps are simple in principle and can be mass produced inexpensively, making them well suited to the automotive industry. They also have many other applications, such as in the chemical industry and food industry. A common type of damage to a vane pump is cavitation erosion on the side plates. If this damage is not detected in time, it could cause failure of the pump, which depending on the type of system may have safety implications, and in some cases a high cost from lost production whilst the system is shut down. This kind of damage is common on other types of pumps such as gear pumps and piston pumps. So a practical method for fault diagnosis of hydraulic pumps is required which does not necessitate removal of a pump from the working system.

This paper presents a method of detecting and identifying cavitation damage on pump side plates via pump flow ripple. Power steering vane pumps are used for this study, although the principles may also be applicable to other types of vane pump, and indeed to piston and gear pumps. The investigation has been done through measurement and simulation. A numerical model of a vane pump is described, and simulated cavitation damage is introduced into the model. This damage is shown to have a clear effect on the simulated flow ripple. The pump flow ripple has also been measured experimentally using the Secondary Source Method, and artificial damage has been introduced into the pump. The damage is shown to have a clear effect on the measured flow ripple, consistent with the simulation results.

Whilst the secondary source enables the measurement of flow ripple in laboratory conditions, it is generally impracticable for in-situ measurement for condition monitoring. A simplified method for calculation of pump flow ripple from in-situ pump pressure ripple measurements and system impedance is discussed.

1. INTRODUCTION

Condition monitoring for hydraulic pumps has been developed over the last couple of decades. Some of the present methods have been simply transformed from those for mechanical systems. Parameters such as vibration of the pump casing, acoustic noise, temperature and leakage flow have been selected for monitoring purposes [1]. However most of these parameters do not have a direct relation with the pump's condition and cannot necessarily provide an indication of potential damage at an early stage. Some studies have been carried out by researchers on the use of pump pressure ripple for diagnostic purposes [2]. Other researchers [3] used not only pump pressure ripple but also temperature and cylinder motion for condition monitoring. They did identify serious internal leakage and insufficient suction flow of the pumps. However their methods did not have good sensitivity and could not indicate potential damage at an early stage. In addition, the type and location of damage could not be established.

System pressure ripple is very strongly dependent on the system impedance characteristics and on the location of the measurement, as reflections, standing waves and resonances occur. A simple pressure ripple measurement is unlikely to provide clear information about the state of the pump. However pump flow ripple is relatively independent of the system impedance and can be a far clearer indicator of the state of the pump [4]. Unfortunately however, flow ripple is far more difficult to determine and cannot be measured directly. Indirect methods based on pressure ripple measurements, such as the Secondary Source Method (SSM) [4][5][6] need to be used instead.

The main aim of the project was to investigate whether pressure ripple measurements can form a useful indicator for pump fault diagnosis, and to develop suitable, practical, analysis techniques. Tests were performed on a group of balanced vane pumps. The SSM was employed for determining the pumps' flow ripple and source impedance. A simulation model of the pump was also developed. Simulated results were compared with those from the SSM to investigate the validity of the simulation model and to adjust the unknown parameters in the model to get the best match. One of the pumps was then damaged artificially and the same experiments performed on it. This damage was also simulated in the model for comparison.

As the SSM is not suitable for in-situ testing on a real system, another aim of the work was to develop a simplified method that would require minimal instrumentation whilst providing similar information. This project focused on vane pumps, though the technique may be relevant to other types of pump.

2. EXPERIMENTAL RESULTS AND VALIDATION OF SIMULATION MODEL

Flow ripple tests were done on a group of identical pumps using the SSM. The pumps were of the balanced vane type for use in automobile power-assisted steering systems. A simulation model was also developed. This model will be described in more detail in future publications.

The SSM is a precise and efficient method for measuring the source flow ripple and the source impedance of a pump in terms of harmonic spectra. Given these two quantities, the fluid pulsation characteristics of the pump can be described completely [4] [5].

The method is based on the measurement of harmonics of pressure ripple at a series of points along the length of a rigid pipe connected to either the delivery or suction port of the test pump. The pressure ripple that occurs at two or three positions is analyzed to establish the flow ripple. The hydraulic circuit is shown in figure 1. In this work the 'secondary source' was a rotary valve, designed to produce four short-duration flow pulses per revolution [6]. The frequency of the pulses was controlled by the speed of rotation.
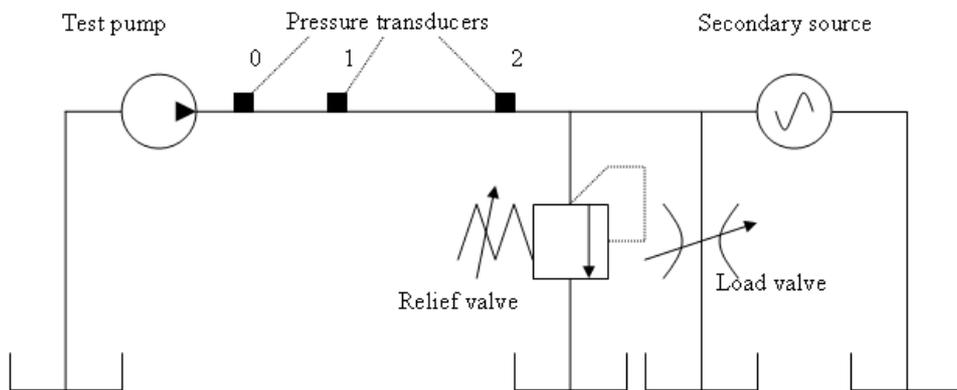

Figure 1 Hydraulic circuit for secondary source method

Tests were performed at speeds of 1000rpm, 1500rpm, and 2000rpm, and pressures of 20bar, 40bar and 60bar. Two examples of experimental flow ripples of one pump and the flow ripple from the simulation model are plotted in Figure 2 and Figure 3. Figure 2 shows excellent agreement between experiment and simulation. The best agreement between experiment and simulation was generally found to occur at lower speeds and pressures. Differences at higher speed and higher delivery pressure might be attributed to limitations in the simulation model, such as in modelling of the leakage transients, or to errors in the analysis for the SSM. To determine the flow ripple in the pump using the SSM, it is necessary to apply a model to the measured source impedance and to make certain assumptions about the nature of the pump's internal passageways, and this can incur errors. In addition the SSM analysis is performed on harmonic measurements up to a certain frequency, and the waveform is reconstructed from this, so the effect of higher frequency components is neglected. The simulated flow ripples are also reconstructed from harmonic frequencies to match the experimental flow ripples.
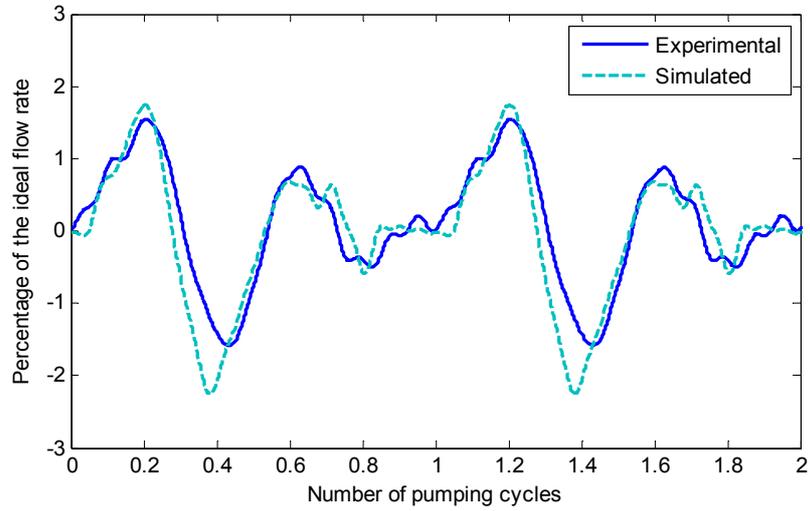
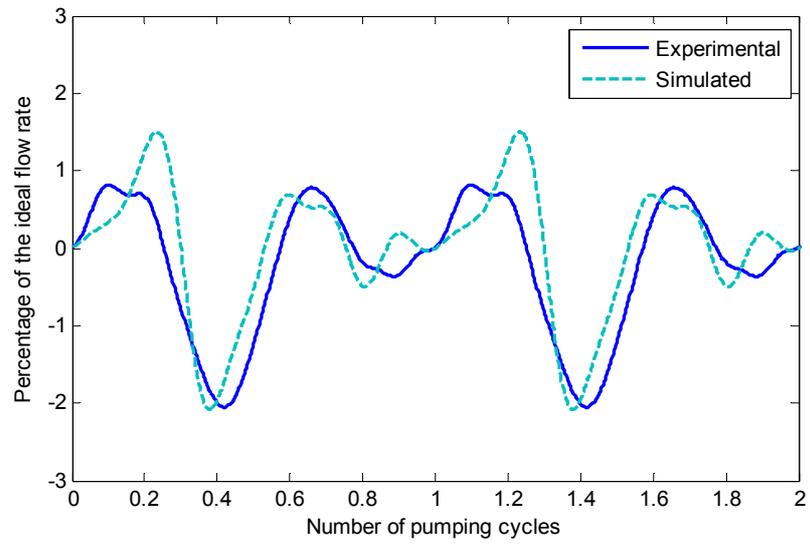**Figure 2 Comparison of simulated and experimental flow ripple at 1000rpm 20bar**

Figure 3 Comparison of simulated and experimental flow ripple at 1500rpm 20bar

3. PUMP DAMAGE

Cavitation is one of the most common causes of damage in a pump. As it was difficult to obtain pumps that had been damaged by real use, artificial damage was introduced in one of the pumps. The damage was intended to imitate that which occurs in a region of the pump side plate which is likely to be subject to cavitation in real machine. Whilst it would be desirable to test a pump with real damage, this artificial damage has the advantage of being more predictable and easier to simulate.

As Figure 4 shows, the damage is a circular indentation drilled on the plate close to one of the relief grooves. The diameter of this indentation was 1.5mm and it was subsequently enlarged to 1.8mm. The depth of the indentation was about 0.5mm. The thickness of the vane was 1.25 mm, so the damage provides a short-duration leakage path as the vane passes over it.

Damage

Figure 4 Photograph of the side plate with artificial cavitation damage
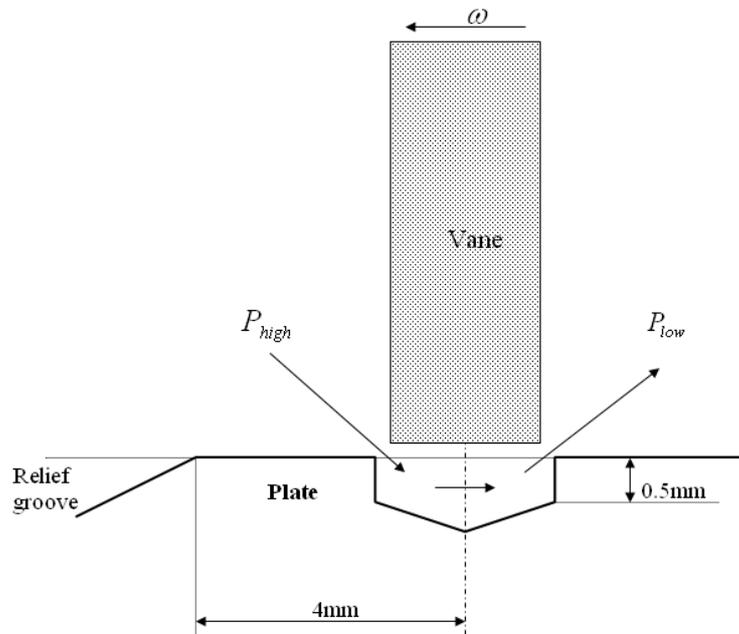
Figure 5 Illustration of the artificial damage

Theoretically when the vane passes across the artificial damage, fluid flows from the high pressure chamber (to the left of the vane in figure 5) into the indentation and then to the low pressure chamber (to the right of the vane). This causes a transient drop in delivery flow which would be expected to appear as a negative spike in the flow ripple. Experiments to determine the flow ripple were performed at the same range of speeds and pressures as for the undamaged pumps. The steady flow rate was also measured and showed no noticeable difference after the pump was damaged. Here only flow ripples at two conditions are plotted as results in other conditions show similar trends. Figure 6 shows the measured flow ripples of the undamaged pump and damaged pump at 1000rpm, 20bar and 60bar. Figure 7 shows the simulated flow ripples of the undamaged pump and damaged pump at 1000rpm, 20bar. The x axis on the graphs represents the angular position of the pump rotor relative to a datum angle; one pumping cycle represents one tenth of one complete revolution (the pump has ten vanes). A vane passes across the hole between 0.74 and 0.78 on the x axis, and the next vane passes between 1.74 and 1.78. As only harmonics of pumping frequency were measured, the waveforms for each pumping cycle are identical.
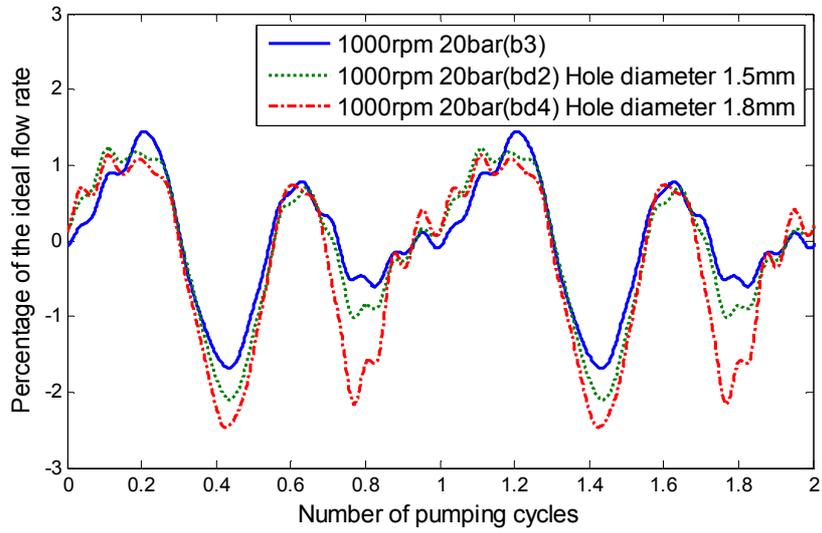
(a) 1000rpm 20bar
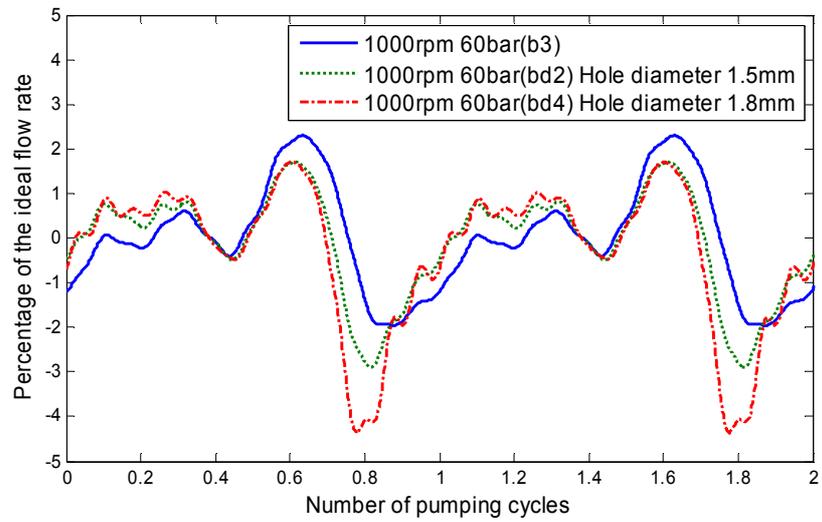
(b) 1000rpm 60bar

Figure 6 Comparison of measured flow ripples of undamaged and damaged pumps
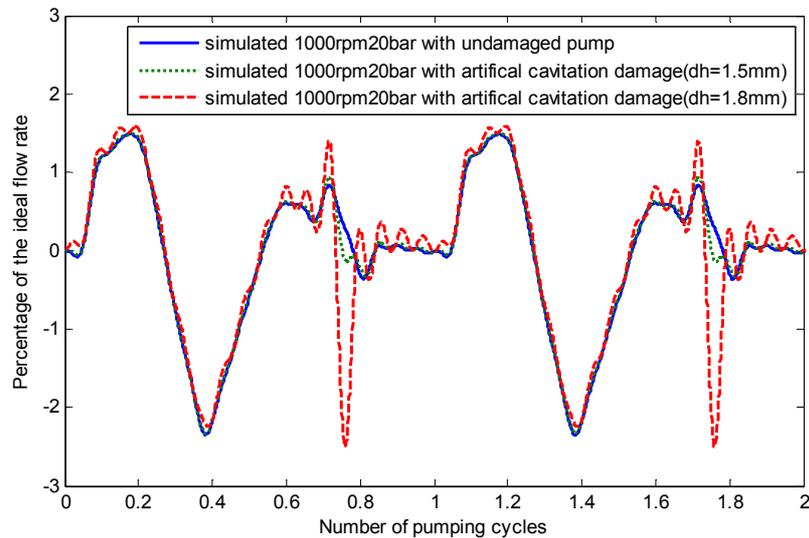
Figure 7 Comparison of simulated flow ripples of undamaged and damaged pumps

To have a clear view of the change of flow ripple caused by the artificial damage, the flow ripple of the undamaged pump was subtracted from the flow ripple of the damaged pump. This was done for both experimental results and simulation results. Here only results at 1000rpm (Figure 8 and Figure 9) are shown as at higher speed the results are not as clear as those at 1000rpm. Figure 8 shows that the effect of the damage is to produce a relatively clear drop in the flow when a vane passes the location of the damage. The size of this drop in flow increases with pressure. This is as would be expected, and shows that the measured flow ripple gives a clear indication of the detailed dynamic behaviour of the pump. There is also a small effect on the flow at other points in the cycle. This may be a real effect but is more likely to be due to limitations in the measurement technique, such as source impedance modelling errors.

Figure 9 shows the difference in the simulated flow ripple between the undamaged and damaged pump. Here the damage gives a very clear pulse in the flow. For a more direct comparison between simulation and experiment, the simulation results were Fourier transformed and the spectrum truncated to the same number of harmonics as the measurements. The ripple in the results is entirely due to this truncation.

These results indicate pump fault diagnosis might best be done at relatively low speeds and higher pressures, as the clearest variations were apparent at these conditions.
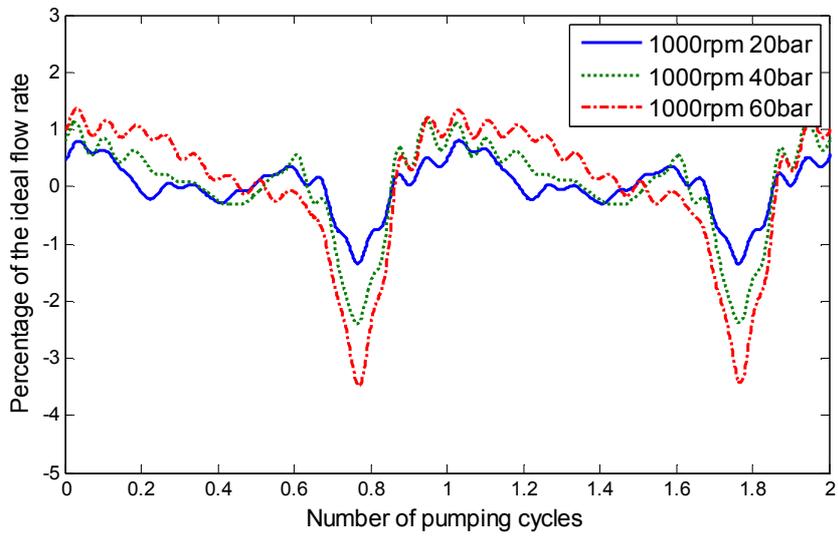
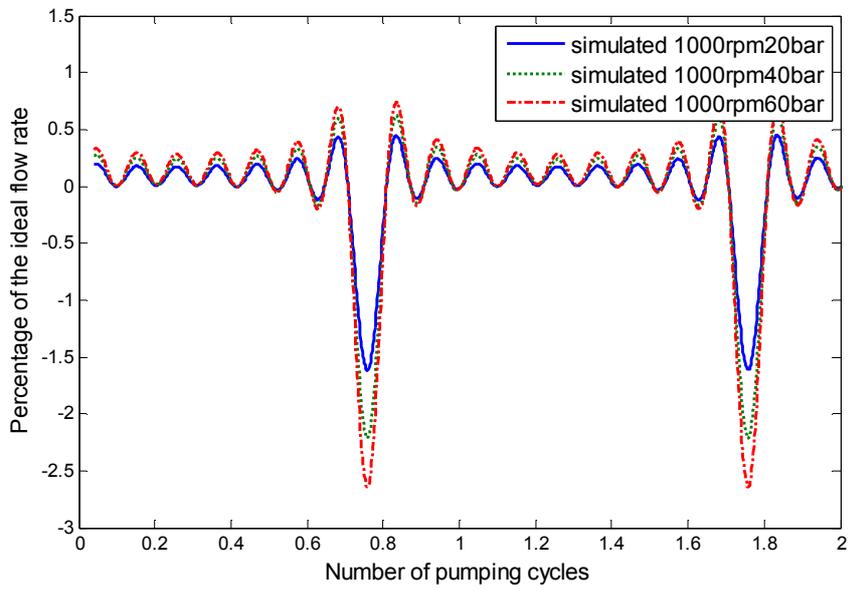**Figure 8 Transient leakage flow caused by the artificial damage (1.8mm) at 1000rpm**

Figure 9 Simulated transient leakage caused by the artificial damage (1.8mm) at 1000rpm

4. FAULT DIAGNOSIS

So far, cavitation damage could be distinguished 'intuitively' from the flow ripple of a damaged pump. However, the Secondary Source Method for measuring pump source flow ripple is rather complicated, time consuming and expensive from the average customers' points of view, and not practicable as an in-situ method for production pumps in real use. Also it is necessary for an experienced person to analyse the results and interpret them to identify faults. Therefore a method is desired which makes pump fault diagnosis economical, easy to operate, and which interprets the results automatically to give a clear indication of the existence and type of faults.

The idea to be considered here is to use the pressure ripple and overall system impedance (including pump source impedance) to determine the source flow ripple of the damaged pump. This will be called the 'deduced flow' method (DFM). The flow chart is shown in Figure 10.
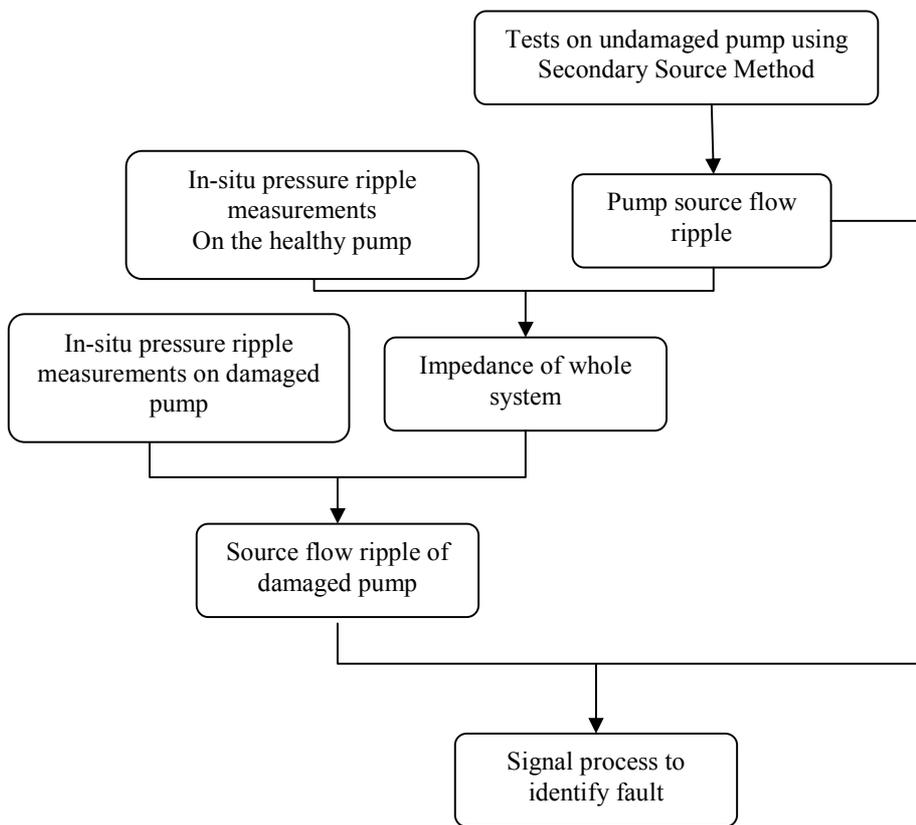

Figure 10 Flow chart of vane pump fault diagnosis with the Deduced Flow Method

The technique would first require the flow ripple to be measured using the SSM. The pump would then be installed where it is needed to be used. The only modifications required to its working system are that a pressure transducer needs to be fitted near the pump delivery, and a shaft position measurement is needed (a single pulse per revolution is sufficient). The shaft position measurement is needed to determine the shaft speed accurately and to establish a timing reference point for the waveform so that one waveform can be subtracted from another. The pressure ripple measured using this transducer needs to be Fourier transformed and the amplitudes and phases of the harmonics of pumping frequency determined. The system impedance at a particular frequency can then be determined from a measurement from this transducer and from the previously measured source flow ripple using equation 1. The source impedance of the damaged pump is assumed to be the same as that of the undamaged pump, since experiments show that there is very little difference in source impedance after the pump is damaged.

$$\text{System impedance} = \frac{\text{Pump out let pressure ripple}}{\text{Pump source flow ripple}} \tag{1}$$

For an initial study in laboratory conditions, all the in-situ measurements were done in the same SSM circuit using one of the SSM pressure transducers. In practice, they would be done in a different circuit.

First, a test was run on an undamaged pump using the SSM at 1000rpm and 60bar to determine the pump flow ripple. The harmonic amplitudes and phases of the pump outlet pressure ripple were determined, using the pressure transducer closest to the pump. The impedance of the whole system including the pump source impedance was then calculated in the frequency domain using equation 1.

Subsequently, the undamaged pump was removed and replaced with the damaged pump (with 1.5mm indentation diameter). The damaged pump was also run at 1000rpm, 60bar. The harmonic components of the pressure ripple of this damaged pump were again measured by the transducer closest to the pump. The flow ripple of this damaged pump was then calculated by equation (1). The result is shown in Figure 11, comparing the flow ripple determined using the DFM in this way with that determined using the SSM directly on the damaged pump. It can be seen that there are only minor differences between the two flow ripples. However, at the lower pressures of 20bar and 40bar, there was more difference in the flow ripples determined by the SSM and the DFM, perhaps due to different fluid air content and temperatures in the different tests. Regardless of this experimental error the calculated flow ripple is acceptably close to the one given by the SSM.
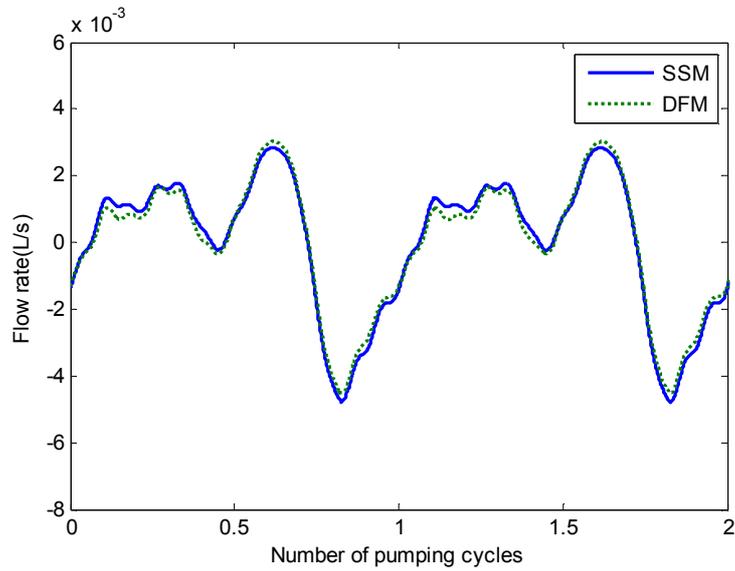
Figure 11 Comparison of flow ripples from the SSM and the Deduced Method at 1000rpm, 60bar (damaged pump with 1.5mm indentation diameter)
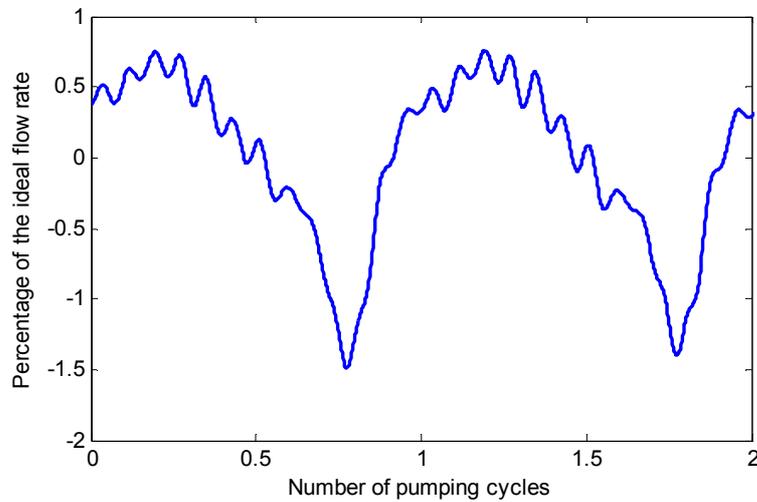

Figure 12 Change in flow ripple due to damage at 1000rpm, 60bar

The flow ripple of the damaged pump established by the DFM was subtracted from the flow ripple of the undamaged pump measured by the SSM. The result is shown in Figure 12.

The cyclic increase in the leakage flow due to the damage is clearly apparent in Figure 12. However for automated condition monitoring, it is desirable that the signal should be monitored automatically, and a warning produced when the signal exceeds a certain threshold. This should be sufficiently tolerant of normal variations to avoid 'false alarms'.

A simple fault detection algorithm was tried, based on the peak value of the difference between the flow ripple at the current time (determined using the DFM) and the original flow ripple of the undamaged pump (determined using the SSM). The average value of this difference in the period between one tenth of a pumping cycle before and after the peak was determined. If this was greater than a certain threshold this was taken to be an indication of side-plate damage. The threshold was taken to be 0.7% of the ideal mean flow rate.

This algorithm was found to give a positive indication of wear for the results shown in figure 12. It was also tested on measurements on an undamaged pump, and correctly gave a negative indication. However, individual pumps, even of the same type, may have different flow ripple characteristics due to manufacturing variation. To improve the method and to establish its robustness, more tests on other pumps of the same type are required.

5. DISCUSSION AND CONCLUSION

The simulation of vane pump flow ripple shows good correlation with experimental results at low speed and low pressure such as 1000rpm, 20bar and 1500rpm, 20bar. At these two conditions, the simulated flow ripples are nearly identical to the flow ripples produced by the SSM. However the simulation model does not show good accuracy at high speed and high pressure. There might be some additional leakage flow effects not properly modelled in the simulation. Further enhancement of the model is required to achieve more accurate flow ripple predictions.

The Deduced Flow Method (DFM) provides a means of obtaining the pump flow ripple in-situ under normal operating conditions whilst the pump is in service. It relies on the system impedance not changing appreciably between the calibration phase and the in-service monitoring. This may be difficult to achieve in practice. It also depends on a flow ripple measurement having been taken using the SSM or a similar measurement technique. In practice it is likely that the flow ripple measurement using the SSM would only be performed on a small number of pumps of a particular type, rather than every single pump. This could cause significant errors on the test results if pumps vary appreciably due to manufacturing factors.

The method is likely to be sensitive to variations in test conditions. The temperature and air content of the fluid may have an important influence. Significant variations in the results were observed at lower pressures, at which entrained air is likely to have a significant effect on the system impedance as well as the pump flow ripple.

Another drawback of this method is the uncertainty of the type of damage. If cavitation damage occurs, this method can detect it. Other types of damage may have different effects on the flow ripple, or may have effects that are indistinguishable from cavitation damage. Also other system faults, such as reduced pump inlet pressure, may affect the flow ripple. A good detection algorithm should be able to distinguish, with reasonable probability, between different types of damage and faults.

Further work is needed to test the DFM method under more realistic conditions, that is, using a more practical and realistic working system rather than the SSM system, with real pump damage, and with a wider range of pumps. Whilst only initial results are shown here, they look promising. Compared to this method, it is unlikely that a simple and direct pressure ripple measurement would provide sufficiently clear information for meaningful diagnosis.

Whilst the method has been applied to a vane pump for power assisted steering system, it may not be suited to such pumps because of their low cost. The added expense of a pressure transducer and signal processing is unlikely to be cost effective for a production vehicle. However the method may be more suited to higher cost pumps such as aerospace pumps or industrial pumps.

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