Condition Monitoring of Aircraft Fuel Pumps using Pressure Ripple Measurements

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ABSTRACT

Gear pumps are used for delivery of high-pressure fuel to aircraft engines. These pumps can suffer from erosion due to cavitation, which eventually causes an increase in leakage and reduced performance. An early warning of excessive wear is desirable, before the performance becomes unacceptable so that replacement can be scheduled conveniently without disrupting the operation of the aircraft.

Pressure ripple and flow ripple measurements were performed on a range of fuel pumps with bearing conditions ranging from good to badly worn. The flow ripple was determined indirectly by analysis of pressure ripple measurements. Results suggest that there is a clear and fairly consistent increase in the pressure ripple and flow ripple measured at the high-pressure outlet port when the bearing is in a worn condition. This increase seems to occur at a wear condition that is not sufficiently bad to worsen the pump performance significantly. This measurement could provide a clear and simple indication of pump wear, at an opportune point in the wear cycle. However whilst these results look promising they are not conclusive, as other differences between the pumps may have affected the results.

Keywords: Fuel pumps, gear pumps, condition monitoring, pressure ripple, flow ripple

1. INTRODUCTION

Pump flow ripple is a key feature of the operation of a hydraulic positive displacement pump, and is closely related to the pump's design and condition. If pump flow ripple can be measured, it can provide very useful information about the state of the pump which may be difficult to obtain by other means. However pump flow ripple cannot be measured directly as conventional flowmeters do not have sufficient bandwidth. Instead, indirect methods need to be used, in which the flow ripple is inferred from pressure ripple measurements.

Testing was performed on a selection of gear pumps used for high-pressure supply of fuel to aircraft engines. Cavitation is the main cause of wear in pumps of this type. In a gear pump, bearing blocks are pushed by fluid pressure against the end faces of the gears, forming a narrow clearance to minimise leakage. Wear mainly occurs on the thrust faces of the bearings, which may eventually cause a leakage path across the gear teeth from the high pressure side to the low pressure side. Wear may also occur on the faces of the gear teeth, though this wasn't considered in this work.

Pump components were interchanged between tests and a range of bearings of differing conditions of wear were included. Pressure ripple was recorded at the inlet and outlet of the gear pump.

The main aim of the investigation was to determine whether pressure ripple or flow ripple could be used as an indicator of pump condition for use in a pump health monitoring system. Secondary aims were to determine whether flow ripple could be determined from pressure ripple measurements, and to determine which quantity (flow ripple, pressure ripple) forms the best indicator.

1.1. The Secondary Source Technique

Pump flow ripple is a key feature of the operation of a pump and it is closely related to the pump's design, wear condition and operating conditions. If it can be measured it is a useful 'signature' of the pump which can be used by the pump designer and system designer, and can potentially be used as for health and condition monitoring [1]. The 'secondary source' method is a method for the indirect determination of pump flow ripple from pressure ripple measurements. It is described in detail by Edge and Johnston [2, 3, 4] and Johnston and Drew [5], and enables the flow ripple and the source impedance of a pump to be measured in terms of harmonic spectra.

The method is based on the measurement of harmonics of pressure ripple at various points along the length of the pipe connected to the port of the pump, and makes use in the analysis of the variations in pressure ripple which occur with distance. The pressure ripple in the pipe can be represented as two waves travelling in opposite directions. The waves add or cancel at different points along the pipe, resulting in different amplitudes, phases and waveforms. By measuring pressure ripple at several different points and by analysing the measurements mathematically, the waves in the two directions can be determined. It is then possible to calculate the pressure ripple and the flow ripple anywhere in that pipeline.

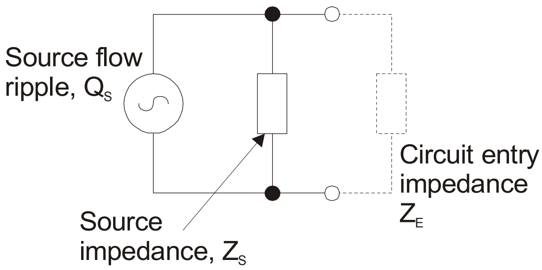

Figure 1 - Norton model of pump

Using the Norton model as shown in Figure 1, the flow ripple at the pump discharge port is defined by the equation:

$$Q_O = Q_S - \frac{P_O}{Z_S} \tag{1}$$

where Q_S is the flow ripple that would be produced by the pump discharging into a circuit of zero entry impedance, and Z_S is the pump source impedance. Q_S is the 'active' component, relating to the pumping action, and Z_S is the 'passive' component related to the resistance, leakage, compressibility and inertance (fluid mass effect) in the delivery passageway. Both of these are pump properties and are not dependent on the circuit.

In the `secondary source' method [2-6], the calculation of Z_S is separated from the calculation of Q_S. This is done by using a secondary source of pressure ripple, connected to the opposite end of the pipeline to the pump as shown in Figure 2. The secondary source is operated at a different speed to the test pump, and the harmonic components of the secondary source are measured. At these frequencies, provided that they do not coincide with harmonic frequencies of the test pump and that spectral leakage is negligible, Q_S can be assumed to be zero. The source impedance can be evaluated using equation (2).

$$Z_S = -\frac{P_O}{Q_O} \tag{2}$$

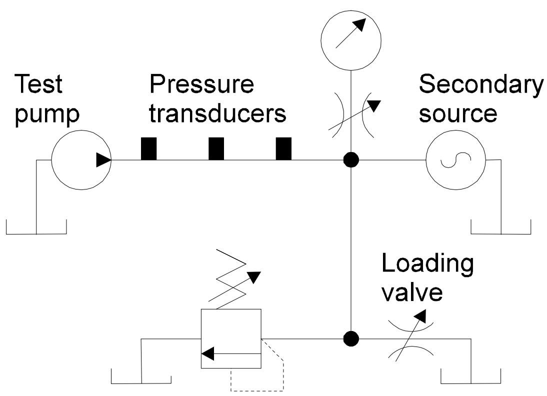

Figure 2 – Test rig for Secondary Source Technique

The pump flow ripple is determined by measuring the harmonic components of the test pump, with the secondary source not operational. The flow ripple Q_S can be determined from Equation (1), provided that Z_S is known at that frequency.

The 'secondary source' technique has been used extensively with oil hydraulic pumps and systems. Prior to this work little or no testing had been done using this method with fuel pumps.

2. TEST RIG DESCRIPTION

The test rig was set up as shown in simplified form in figure 3. The LP centrifugal pump was mounted in the same housing as the HP gear pump. The rig was instrumented to measure the pressure ripple and flow ripple at both low pressure (LP) and high pressure (HP) ports of the high pressure pump simultaneously. The ripple generator was a rotary valve designed to produce short, sharp flow pulses during its rotation [5, 6]. The test rig is shown in figure 4.

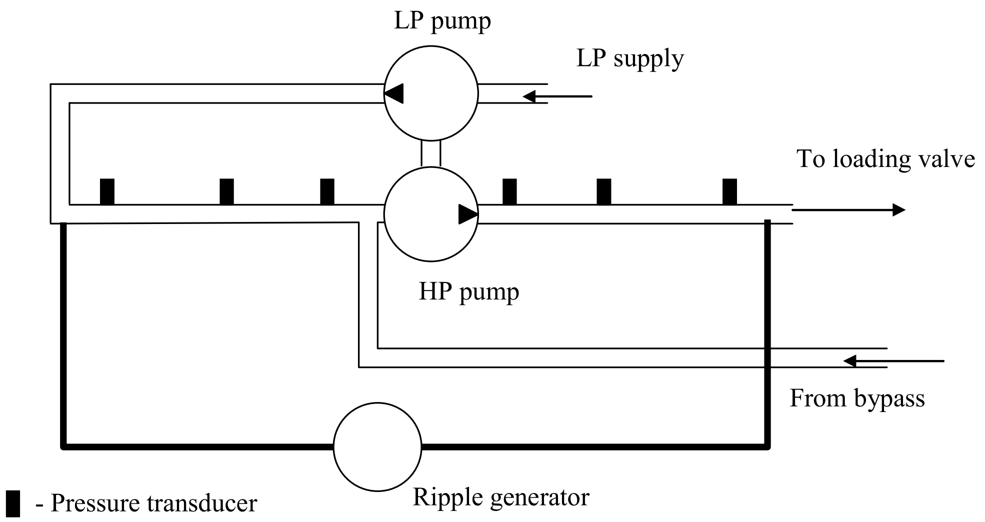

Figure 3 – simplified schematic of part of test rig

2.1 Test Conditions

Tests were performed at pump speeds of 2000 rev/min to 7000 rev/min at 1000 rev/min intervals, and pressures of 200, 600 and 1200 lbf/in^2 (14, 34 and 83 bar). The temperature was between 10°C and 15°C. Tests were repeated at some conditions for checking repeatability. Tests were performed on 12 pump builds; two different pump bodies were used and internal parts were interchanged giving a total of five ‘good’ condition pumps, three ‘worn’ (intermediate condition) pumps and four ‘bad’ (severely worn) pumps. In total over 240 tests were performed.

2.2 Steady Flow Results

Before each test a flow check was performed on each pump to provide a quantitative means of comparison. These tests were done at a range of speeds and pressures. Figure 5 shows the flowrate at 7000 rev/min plotted against nominal bearing condition. The flowrate is normalised relative to the average flowrate for ‘good’ condition. The flow rates for ‘good’ condition are very closely spaced. There is a small drop in flowrate (about 4%) and increased variation for the ‘worn’ condition, but a much larger drop in flowrate (15% to 30%) for the ‘bad’ condition.

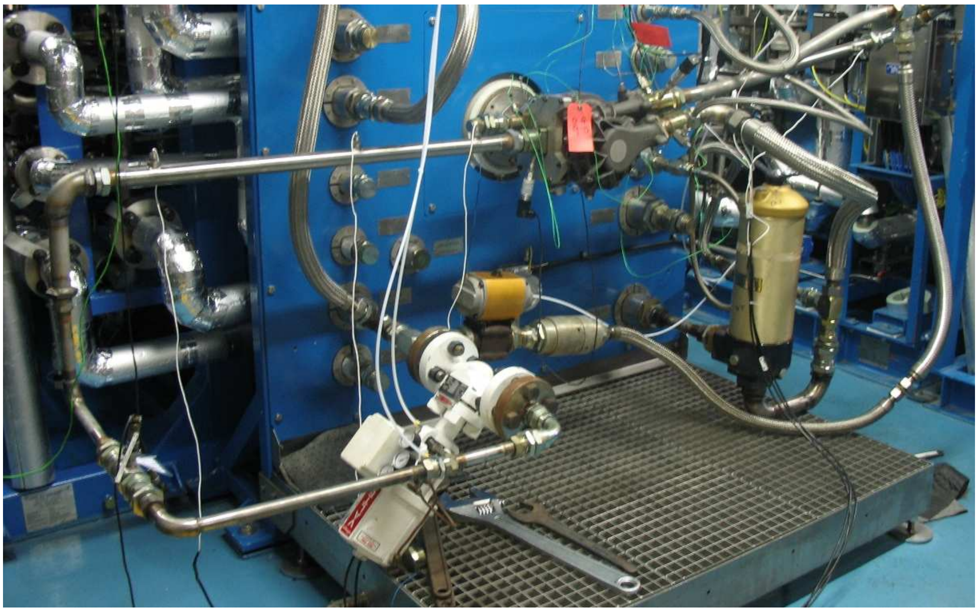

Figure 4 Photograph of test rig (ripple generator not included)

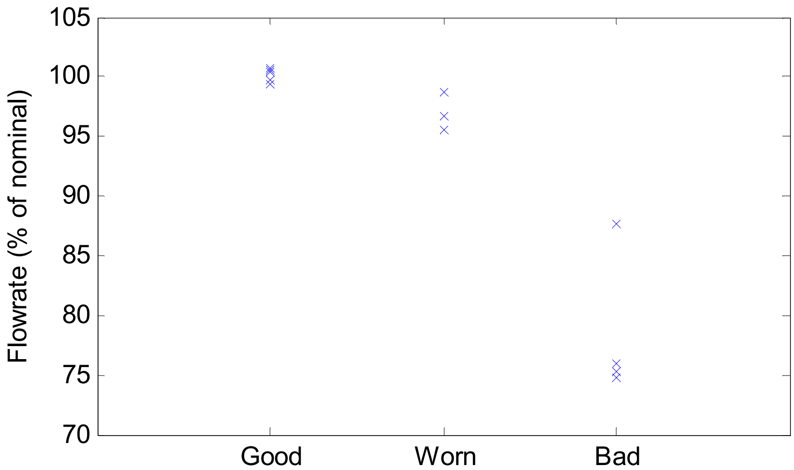

Figure 5 - Measured flowrate at 7000 rev/min vs. bearing condition

2.3 Ripple test procedure

Pressure ripple data were acquired from all six piezoresistive pressure transducers synchronously, along with a shaft reference pulse signal (one pulse per revolution) at 30 kHz per channel in a 1 second burst. The measurements were analysed using the FBN software [6] to obtain the harmonic amplitudes and phases at all multiples of shaft frequency up to 5000 Hz. These harmonic values were then processed using the FBN software to determine the pump's outlet flow ripple. The speed of sound and bulk modulus of the fluid were also determined [7]. The flow ripple was evaluated in the form of 'anechoic flow ripple' [5, 6], representing the flow ripple that would be produced in an infinitely long tube. The flow ripple was evaluated as a harmonic spectrum, waveform and overall r.m.s. (root-mean-square) amplitude. The flow ripple analysis was only performed at the outlet port as it was found not to be possible to obtain reliable results from the inlet port data.

The flow ripple was determined using previously measured source impedance data in equation (1). Because of test rig limitations it was not possible to use the ripple generator for all of the pumps that were tested. For this reason the same impedance data were used for all pumps and it was assumed that the source impedance was the same for all pumps. This is an approximation as the impedance may change slightly as the fluid properties, pump compliance and leakage paths may change slightly with speed, pressure and temperature. However experience has shown that variations in impedance are usually small. The impedance that was used is shown in figure 6. This was obtained from a pump with 'good' bearings at 3000 rev/min and 600 lbf/in^2 (41 bar). This is It is a mainly capacitive characteristic with a negative phase and amplitude decreasing with frequency, but more complex effects are apparent at higher frequencies.

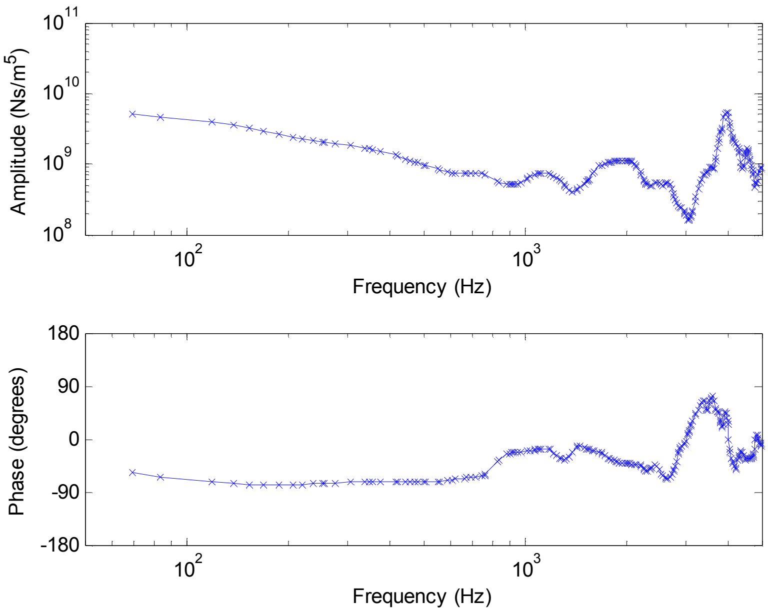

Figure 6 - Impedance data

3. RIPPLE TEST RESULTS AND DISCUSSION

Some representative flow ripple results for pumps with 'good', 'worn' and 'bad' bearings are shown in figures 7-9 (this is a small selection as about 240 tests were performed). Here amplitude spectra and waveforms are plotted. The spectra show dominant peaks at multiples of 12 orders, these being the pumping harmonics as there are 12 gear teeth. The other harmonics are small and may be considered as background noise. The 12th order (first pumping harmonic) is the strongest in all cases.

Whilst there are differences for different conditions and different pump builds, the waveforms generally conform to the shape expected for a gear pump [8], somewhat similar to a rectified sine wave but with some pressure dependent ‘spikiness’. The waveform amplitudes can be seen to be greater for the ‘worn’ and ‘bad’ bearings than for the ‘good’ bearings. In most cases the amplitude increases with pressure.

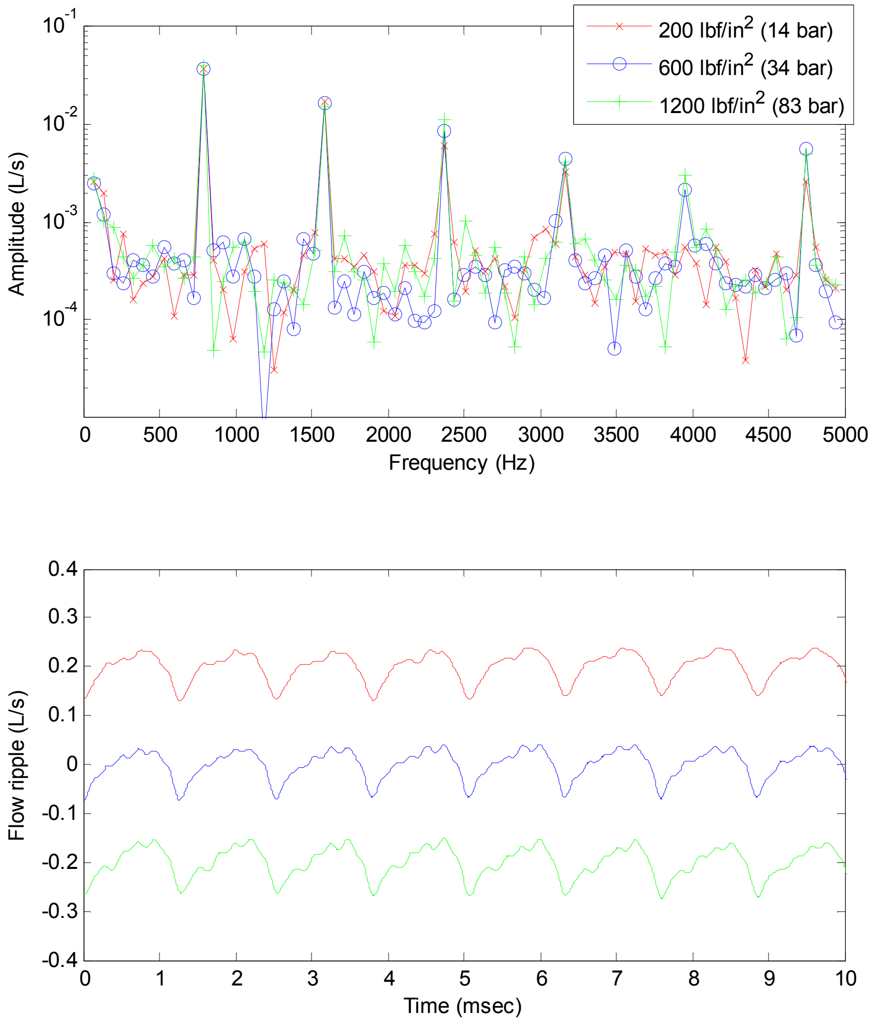

Figure 7 - Typical measured flow ripples, ‘good’ bearings, 4000 rev/min

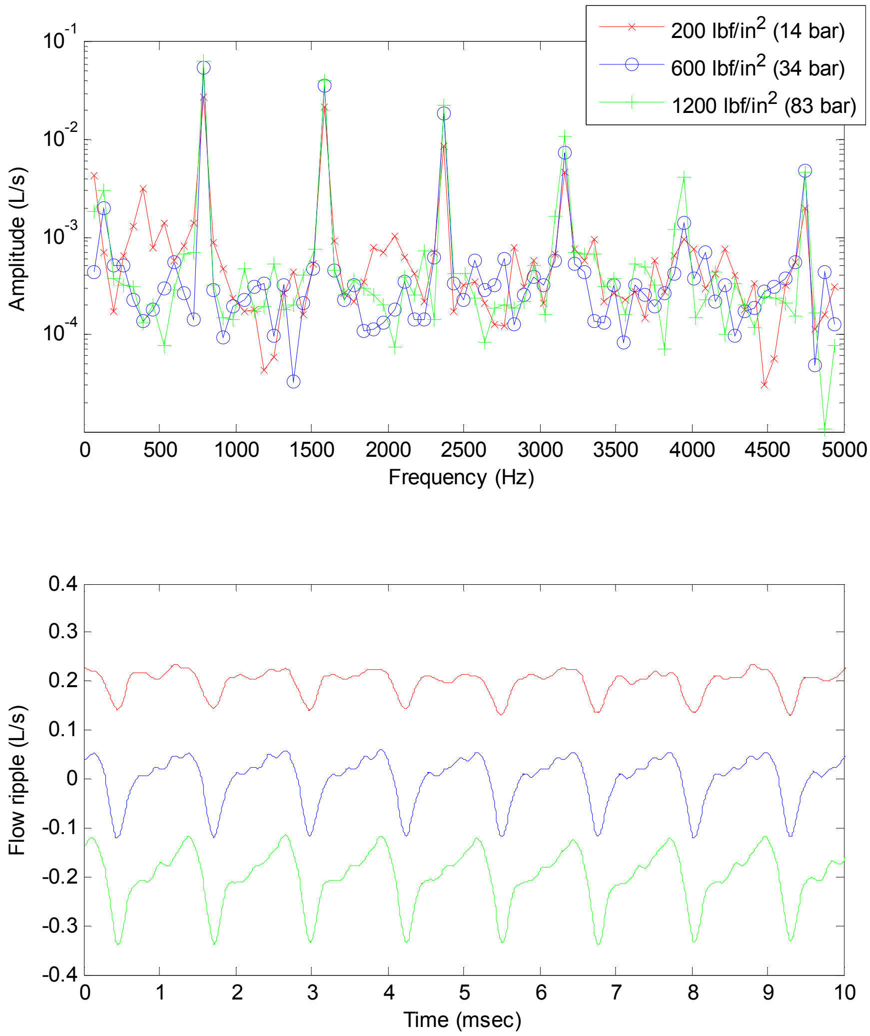

Figure 8 - Typical measured flow ripples, ‘worn’ bearings, 4000 rev/min

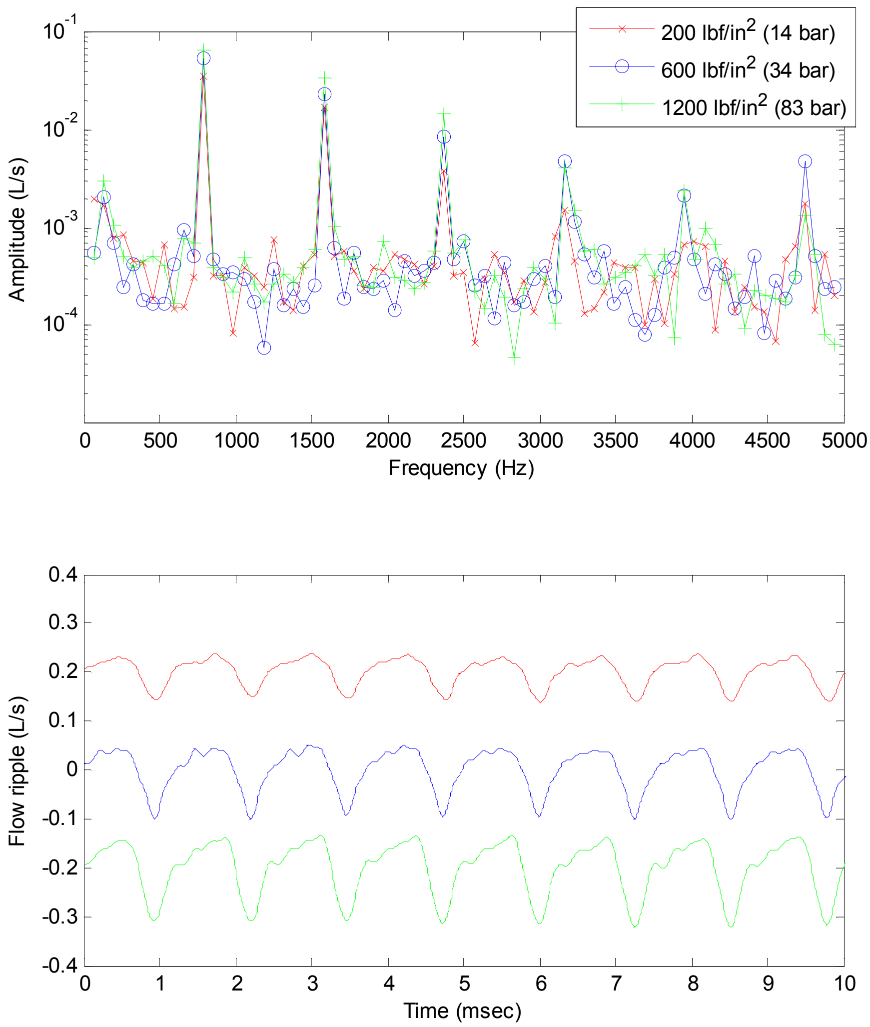

Figure 9 - Typical measured flow ripples, 'bad' bearings, 4000 rev/min

Repeatability was found to be good, as differences between the first and repeat tests at 3000rpm were negligible.

For pump health monitoring, a simple indicator of pump health is required, preferably a single-figure quantity. Various single-figure quantities were considered, including:

1. r.m.s. flow ripple, high pressure (delivery) port;
2. Peak-peak flow ripple, high pressure port;
3. r.m.s. pressure ripple at transducer nearest to pump, high pressure port;
4. First (pumping frequency) harmonic amplitude of flow ripple, high pressure port;

5. First (pumping frequency) harmonic amplitude of pressure ripple, high pressure port;
6. r.m.s. pressure ripple at transducer nearest to pump, low pressure (inlet) port;
7. First (pumping frequency) harmonic amplitude of pressure ripple, low pressure port.

The most consistent trends were found to occur with quantities 1, 3, 4 and 5 above. Similar trends occur for these four different quantities. This suggests that the extra complexity involved in measuring flow ripple may not be necessary as a simple pressure ripple measurement may be sufficient.

The r.m.s. pressure ripple at the high pressure port is plotted alone against bearing condition in figure 10. Only the cases that showed clear trends are shown here. There is a clear increase in amplitude from 'good' to 'worn' bearings, but there is also some variation between pumps with 'good' bearings in particular.

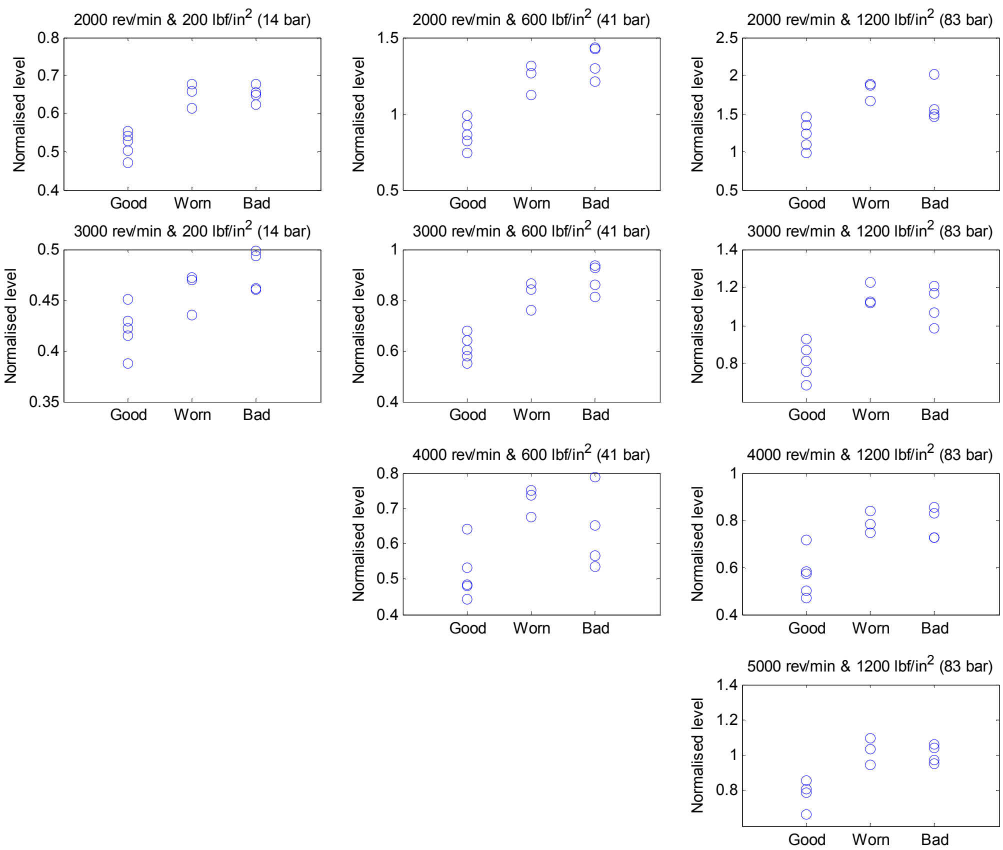

Figure 10 - HP r.m.s. pressure ripple vs. bearing condition

The pressure ripple is simple to measure, far more so than the flow ripple. Just one pressure transducer would be needed, situated near the pump HP port. This would need to be a suitable high-frequency type such as a piezoelectric or piezoresistive type. Digital Fast-Fourier Transform (FFT) processing would be required if the amplitude of the first pumping harmonic was required; FFT processing might not be needed for the r.m.s. level.

The ripple level has been shown to increase significantly in the 'worn' condition, whilst figure 5 shows that the flowrate has reduced only very slightly at that condition. This suggests that the ripple level is very sensitive to wear in the bearings, and may be because wear in the bridging area near to the gear meshing point gives rise to a leakage path that opens and closes as the gear teeth pass. This may result in a small but cyclic leakage flow that increases the pump's flow ripple and hence the pressure ripple. Thus the ripple is likely to provide a good early warning of wear, before the pump performance itself starts to degrade.

The ripple levels depend strongly on speed and pressure, so it is important that comparisons are made at similar conditions. The trends appear to be clearest at relatively low speeds and high pressures.

It should be noted that the results here were obtained from different pump builds. Different pump bodies and gears were used for different runs, so the trends observed here may not be entirely due to the different bearings. In a real health monitoring situation, the degradation of one particular pump build over time would be monitored. This might give more consistent results as the arbitrary differences between individual components within each pump build would be eliminated.

4. HEALTH MONITORING

4.1 Requirements for Health Monitoring

The health monitoring system should provide an indication of pump wear and damage, at a time before the pump performance (flow and pressure) degrades below a satisfactory level, such that the pump can be scheduled for repair or replacement at a convenient time and place. It should require a minimum of additional components and instrumentation.

The flow test results (figure 5) suggest that the pumps with 'worn' bearings have a slight decrease in flowrate, but still operate satisfactorily. This level of wear might be a suitable point at which the health monitoring system identifies that maintenance is needed, whilst still allowing time to schedule the maintenance to occur at a convenient time and not requiring immediate emergency maintenance.

These results suggest that HP port pressure ripple amplitude would suit these requirements, as it requires a minimum of instrumentation (one transducer) and appears to provide a clear difference between 'good' condition bearings and 'worn' condition bearings. The results suggest that a large increase in the ripple level occurs before the pump performance degrades significantly.

The clearest indication of wear appears to occur at relatively low speeds and high pressures. Unfortunately these are conditions that do not occur during regular service. The lowest pump speed in service is generally over 4000 rev/min, which is the idle condition, at which pressures are low. Consideration would have to be given to this constraint in developing a health monitoring system.

The 'secondary source' technique is too complex and intrusive to be used in-situ. However it could be used as a pre-installation test to determine the pump and system characteristics. From this the overall system transfer function relating system pressure ripple to pump flow ripple could be determined. The flow ripple could then be estimated from a single pressure ripple measurement during in-flight operation. However these results suggest that this may not be necessary in this case; the pressure ripple amplitude can be used directly as a diagnostic signal.

4.2 Possible Algorithm for Health Monitoring

The speed and pressure ranges should be divided into a number of 'bins' corresponding to conditions that occur during normal flight, and to conditions that give the clearest trends (from these tests, these conditions appear to be mainly at 2000-4000 rev/min). Each bin would be for a specific speed and pressure range (and possibly fuel temperature range and/or flight phase). The bins would not need to cover all possible conditions; if the engine was operating outside of the range of the bins then no monitoring would take place at that time; the monitoring would continue when the conditions returned to within one of the bins.

It would first be necessary to establish baseline levels for a pump in 'good' condition. From when the pump is first installed, the ripple should be measured continuously and the ripple level determined (by FFT or other processing) at regular intervals. The level should be stored in the relevant 'bin' using a low-pass filter or moving average to avoid sudden changes and anomalies. After a certain 'running-in' period the level in each 'bin' should settle to a roughly constant level. The level in each bin may then be taken as the reference level.

After the reference levels have been determined, health monitoring can then begin. The ripple level would be monitored at regular intervals. If the conditions fall into one of the range of one of the bins, the ratio X between the ripple level and the reference level for that bin would be calculated. A low-pass filter or moving average would then be applied to this ratio, to give a smoothed value and avoid anomalies, $\widetilde{X}$ say. Ratios from all bins would feed into one $\widetilde{X}$ value.

- If $\widetilde{X} \approx 1$, this indicates that the pump is still in good condition.
- If $\widetilde{X}$ exceeds a certain threshold (maybe 1.5) this indicates that the pump has worn.

The threshold would need to be set to a suitable value. If it was too low false alarms may occur, whilst if it was too high the monitoring may be too insensitive. The same applies to the time-constant for the low pass filtering or time-span of the moving averages.

Further work, and data for a pump through its life cycle from new to worn, are needed to develop and validate this algorithm.

5. CONCLUSIONS

The measured pressure ripple amplitude was found to be significantly greater for pumps with moderately worn bearings than with good bearings. At these moderately worn conditions there was found to be only a small reduction in delivery flowrate. This suggests that the pressure ripple amplitude might provide a simple and useful early warning of pump degradation, giving a clear indication at a time before the pump performance degrades significantly and allowing a suitable time window for maintenance to be scheduled after the indication occurs. Pressure ripple would be relatively simple to measure and process, and the monitoring would be automatic.

Flow ripple was measured successfully, and the measured flow ripple waveforms showed the expected characteristic shape, similar to a rectified sine wave. Similar trends were observed for the flow ripple and the pressure ripple in relation to pump wear. However the pressure ripple is much easier to determine and therefore preferable as an indicator.

However the results so far are not totally conclusive, as several components were changed between tests and some of the variations in ripple amplitude may have been due to other factors such as differences in pump bodies. To develop this method further, it would be beneficial to perform endurance testing on a pump instrumented with a pressure transducer, through the life of the pump from new through to a worn condition. Ideally the pump would be cycled through a representative range of conditions to simulate flight cycles.

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