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# Fault detection in a centrifugal pump using vibration and motor current signature analysis

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**Abstract:** Due to growth of mechanisation and automation, today's industrial systems are becoming more complex. A small breakdown of any non-redundant machine component affects the operation of the entire system. To increase the availability and reliability, automated health monitoring and self-diagnostic capability (SDC) becoming essential to many industrial machineries like pumps, motors, etc. Condition monitoring does not prevent the failure, but it can predict the possibility of future failure by measuring certain machine parameters. Though there are various condition monitoring techniques, vibration analysis and motor current signature analysis (MCSA) are most suitable for detection of faults and abnormalities in machine systems. This work attempts to develop an SDC framework and diagnose the impeller condition of a centrifugal pump using MCSA. Time and frequency domain analyses are done for different impeller conditions of the pump, such as normal impeller and defective impellers. Significant differences are observed and a fault prediction strategy is recommended.

**Keywords:** pump; condition monitoring; vibration analysis; spectrum; FDI; diagnostics.

**Biographical notes:** Amiya Ranjan Mohanty received his PhD in the area of noise control from the University of Kentucky, USA. He is a Professor of Mechanical Engineering at IIT Kharagpur. He was with the Ray W. Herrick Laboratories, Purdue University as a Postdoctoral Fellow. He has worked in the R&D Division of Larsen and Toubro Ltd., Mumbai and Ford Motor Company, Detroit. He has over 50 research publications in refereed journals and equal number of publications in conference. He is recipient of the Chancellor's Award for Outstanding Teaching at the University of Kentucky and the OAP-inbound fellowship of the NUS, Singapore.
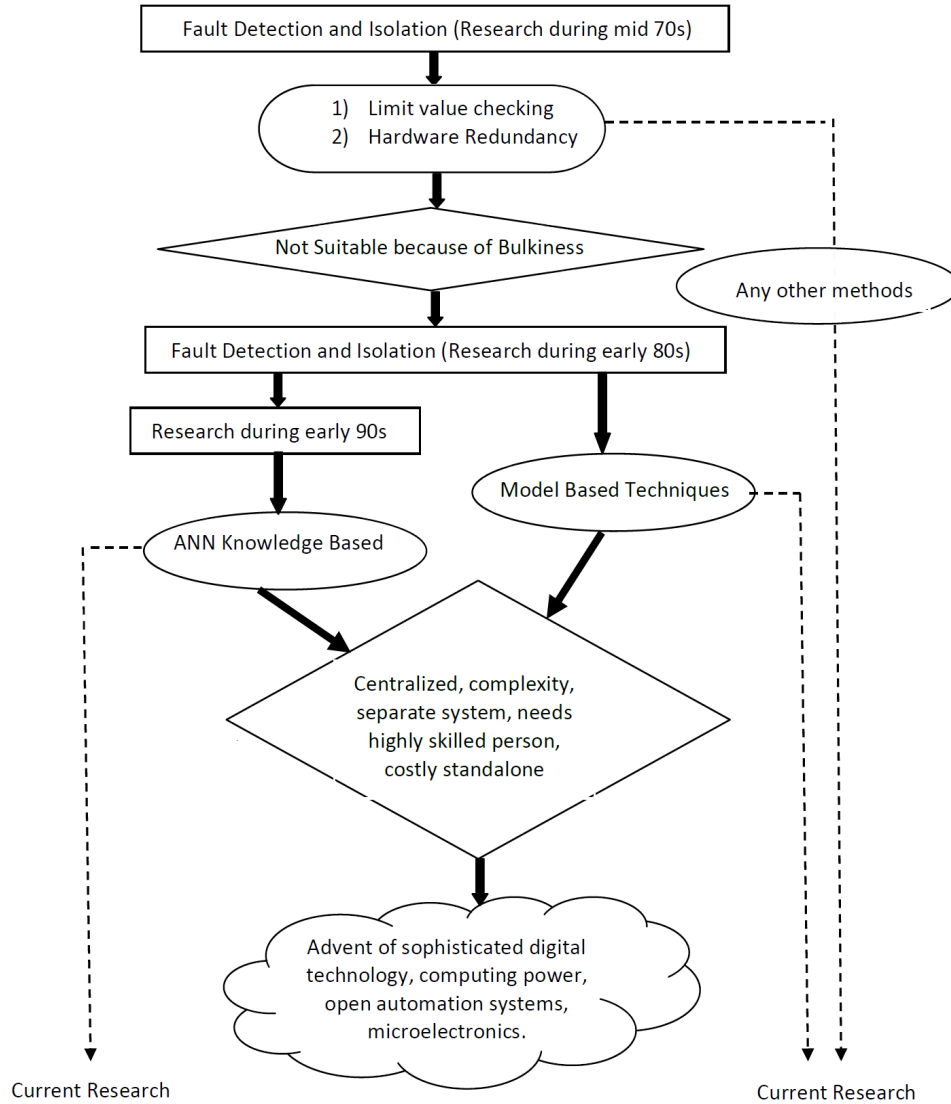
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Nitaigour P. Mahalik has expertise in the field of distributed control, FDI and soft computing. With 20 years of teaching experiences, he has published about 100 papers, 5 books, and 12 chapters. He has supervised five PhD and 30 MS theses/projects. He is the editor and committee members of several journals. He was the recipient of NOS and Brain-Korea fellowships and member of ISTE, ATMAE, ASABE, and ISA.

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# 1   Introduction

Next generation industrial systems will require more reliability, availability, safety, and embedded control strategy in response to provide highly customised products. The benefits that have been achieved so far through implementation of condition monitoring are now being significantly extended through the application of new theories, techniques, tools, and methods. Advances in computing tools and techniques have stimulated studies to design as well as realise autonomous machinery systems. Fault detection and isolation (FDI) is the main research topic that fall under the category of condition monitoring (Mohanty and Mahalik, 2007, 2011). Figure 1 (Mahalik et al., 1998) illustrates the progress on condition monitoring methods.

**Figure 1** Progress on FDI



Fault Detection and Isolation (Research during mid 70s)

1) Limit value checking
2) Hardware Redundancy

Not Suitable because of Bulkiness

Any other methods

Fault Detection and Isolation (Research during early 80s)

Research during early 90s

Model Based Techniques

ANN Knowledge Based

Centralized, complexity, separate system, needs highly skilled person, costly standalone

Advent of sophisticated digital technology, computing power, open automation systems, microelectronics.

Current Research

Current Research

*Source:*   Mohanty and Mahalik (2007, 2011)

Centrifugal pumps are used in many process plants including paper mill, chemical industry, mining (Nave, 1989), and so on. Availability and reliability of pumping system is essential in such industries. Often a failure in non-redundant pumping system may bring the entire plant to a standstill. Online continuous monitoring of such machine systems helps to avoid malfunction, damage, wear and can promote the optimal utilisation of component's service cycles as well as its life. Rotary machines like pumps involve continuous analysis of operational point and the detection of problems before the unit or component fails to operate. The detection parameters are vibration analysis, mass unbalance, crack, bearing systems, lubrication, wear, degradation factor and so on.

Common problem in centrifugal pump is its inability to deliver the required flow and head due to wearing out of impeller, unusual vibration and leakage along the shafts. The other problems are loss of lubrication, contamination of oil, noise, leakages from pump casing and motor related problems.

The conditions of component such as pump shaft, bearings, and impellers are monitored by means of vibration measurement which is frequency selective measurement (Scheffer, 2000). The observation also involves monitoring of operating parameters such as flow rate, drive power, RPM, and vane pass frequency (VPF). Vibration analysis technique is a common condition monitoring technique usually used for rotating machines. Some of common machinery defects, like unbalance, bent shaft, eccentricity, misalignment and looseness are easily detected using vibration measurement. But defects, like crack in shaft, gear defects, bearing problems and electrical faults require further analysis of vibration signals. Electrical vibration problems occur due to unequal magnetic forces acting on the rotor or stator. The unequal magnetic force may be due to broken rotor bars, unequal air gap, open or short windings. Generally, the vibration pattern emerging due to above mention electrical problems will be at $1 \times$ RPM and will thus appear similar to unbalance. Some cases, like stator eccentricity and asymmetry air gap shows the vibration peak at twice of supply frequency (Suphattana and Surawatpunya, 2011).

Bearing defects can also be detected using vibration analysis (Rao, 2000). A roll bearing comprises of inner and outer races, a cage and rolling elements. Defects can occur in any component of bearing and will cause high frequency vibration. Using vibration spectrum, Amarnath et al. (2004) identified the amplitude and corresponding frequencies and enable to predict the presence of defect on inner race, outer race and rollers of antifriction bearings. Late stages of journal bearing wear normally display a whole series of running speed harmonics, which can be up to 10 or 20 times of the rotational speed. The FFT spectrum looks very much like that of mechanical looseness. In another study, Jalan and Mohanty (2009) found that the fault condition and location of rotor-bearing system can be detected using model-based technique.

As a general rule, distributed faults such as eccentricity and gear alignment will produce sidebands (SBs) and harmonics that have high amplitude close to the tooth-mesh frequency. Localised faults such as cracked tooth produce SBs that are spread more widely across the spectrum. Wang et al. (2001) have focused the use of vibration frequency analysis for gear fault detection. Kar and Mohanty (2008) have shown the application of multiresolution Fourier transform and wavelet transform to current signature to find out gear faults.

## 1.1  Review on signature analysis

Motor current signature analysis (MCSA) can be used as condition monitoring of pump and other machineries, where use of vibration sensor is difficult due to insufficient space and unusual environmental condition, like submersible pump operating at depth of 100 metres and a pump in nuclear power plant, etc. The 'MCSA' was first used for fault diagnosis by Thomson et al. (1987) and then by Kliman et al. (1988). Using MCSA they were able to detect the broken rotor bar and air gap eccentricity in a three phase induction motor. Choudhury and Rahman (1992) were able to estimate the speed of submersible induction motor from input voltage and current data. Thomson and Reith (1994) studied

the effect of speed oscillations on current spectrum also experimentally they found that when speed fluctuates, SBs are observed around the running speed in frequency domain. They showed that due to misalignment SBs are observed and when misalignment increases height of SBs increases. In another paper, Nandi (2005) has described how the various faults of electrical motor can be detected by current analysis. Casada (1994) studied about the degradation of pump's performance by using vibration, pressure pulsation and motor power measurement and observed that the motor power instability appears to provide some more useful insight into general hydraulic instability of the pump. Casada (1996) has also detected a pump specific operational problem by motor current analysis and where the detection of a partial load operation caused by strainer clogging using MCSA was achieved. In another investigation, Kenull et al. (2003) detect the speed of submersible motor by current analysis. Not only in motor but also in gear box cases, MCSA can be used to detect the faults. Mohanty and Kar (2006) were able to find out to detect in gear box using modulation of motor current waveform. It is observed from above literature survey that previous researchers have used vibration analysis and MCSA to diagnosis the defects of machineries, motor of the pump, etc. But the diagnosis of damaged/broken impellers using vibration and MCSA has not received much attention. The objective of present work is fault detection of the impeller in a centrifugal pump using vibration analysis and MCSA. In the following section, the experimental procedures are described followed by the results and discussion.

## 2    Experimental details

Specification of the impellers used in pump is made of brass; with external diameter 100 mm; width 10 mm; vane length 25 mm and number of vanes are 24. The diameter of impeller hub is 13 mm. The experimental work has been performed in the following sequence:

1    a centrifugal pump is run with 24 vanes brass impellers at various conditions (of impeller like non-defective, one vane removed, two vanes removed, three vanes removed)

2    vibration signal and motor current signals are recorded during operation/working condition and the data is analysed using a signal analyser (B&K pulse system).

### 2.1    Experimental procedure

The accelerometer (PCB 353B33) was placed on the casing of the pump close to the bearing (as shown in Figure 2) to measure the vibration. Hall effect sensor (Tektronix A621, as shown in Figure 3) was kept around the phase terminal of motor current to measure the instantaneous motor current. The centrifugal pump (0.75 kW, 1,450 RPM, 240 V, make-Crompton Greaves, as shown in Figure 2) was operated under different working conditions of impeller like normal impeller (all vanes present), one vane broken impeller, two vanes broken impeller, three vanes broken impeller (as shown from Figures 4 to 8) sequentially.

Multiple number of experiments were conducted (i.e., two experiments were for each impeller condition for repetition) in order to critically evaluate the validation of the procedure. The experiments were performed over a period of six months. For each experiment, current and vibration signal data were collected. For each of the signal data the following were recorded:

1    recording data for a duration of 10 s

2    time domain data for 4 s (at sampling frequency 4,096 Hz) for both current and vibration signal

3    fast Fourier transform (FFT) spectrum up to 1.6 kHz (at 6,400 resolution) for both current and vibration signal.

Using the time domain data, RMS and peak value were calculated and analysed. FFT algorithms were developed, realised and tested for the analysis of both vibration and current. Also, analyses were done for getting the rotating speed (in RPS) of pump, VPF, SBs around VPF and their respective amplitude (in dB).

**Figure 2**    Accelerometer mounted on a pump (see online version for colours)



**Figure 3**    Hall effect sensor (see online version for colours)

**Figure 4** Normal impeller (see online version for colours)



**Figure 5** Broken impeller (one vane missing) (see online version for colours)



**Figure 6** Broken impeller (two vane missing) (see online version for colours)



**Figure 7** Broken impeller (three vane missing) (see online version for colours)

**Figure 8**   Broken impeller inside casing of the centrifugal pump (see online version for colours)



## 3   Results and discussions

Four different sets of data were obtained from each experiment. The result of each set is presented as follows. The following results were taken at the full flow rate of the pump (i.e., 0.0018 m$^3$/s).

### 3.1   Time domain analysis of vibration signals

The time domain data of the vibration signal is used to find out the RMS and peak value of the vibration of each case and was compared for different impellers (as shown in Table 1).

**Table 1**       Peak value and RMS value of vibration signal for different impellers

| Impeller type | Peak (m/s$^2$) | RMS (m/s$^2$) |
|---|---|---|
| Normal | 9.82 | 2.78 |
| Defective (1 vane) | 11.62 | 4.07 |
| Defective (2 vane) | 14.66 | 4.70 |
| Defective (3 vane) | 17.29 | 5.41 |

From Table 1, it is observed that the peak values of the vibration signal increase as the severity of the defect of impellers increase. Since the severity of defect increases, the flow excitation is more at the instance when the broken vane passes the particular point, i.e., inlet of the casing. Due to that, vibration amplitude increases and peak value of vibration signal increases. It is also observed that the RMS value of vibration signal increases as the severity of the defect of impellers increases. RMS value shows the energy contents of the signal. Obviously due to broken impeller, the degree of unbalance increases and vibration energy increases accordingly.

## 3.2 Frequency domain analysis of vibration signals

From the vibration spectra it has been observed that the first high peak was at 24.75 Hz (52 dB) which happens to be the rotational speed (RPS) of the pump. This measurement was verified by an optical tachometer which indicated a rotational speed of 1,485 RPM. Also, the presence of VPF (i.e., RPS × No. of vanes) was observed in the vibration spectra. Their corresponding amplitudes (in dB) and their SBs (at VPF ± RPS) for different impellers were noticed. The observations of vibration spectra (as shown in Figures 9 to 12) for different impellers are summarised in Table 2.

**Figure 9** Vibration spectra of the normal impeller (see online version for colours)
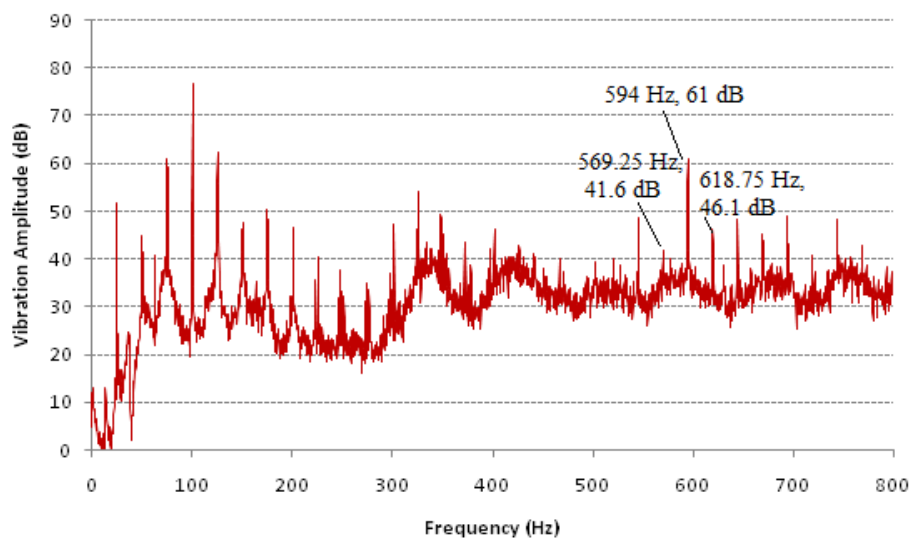


**Figure 10** Vibration spectra of the defective impeller (with one vane missing) (see online version for colours)
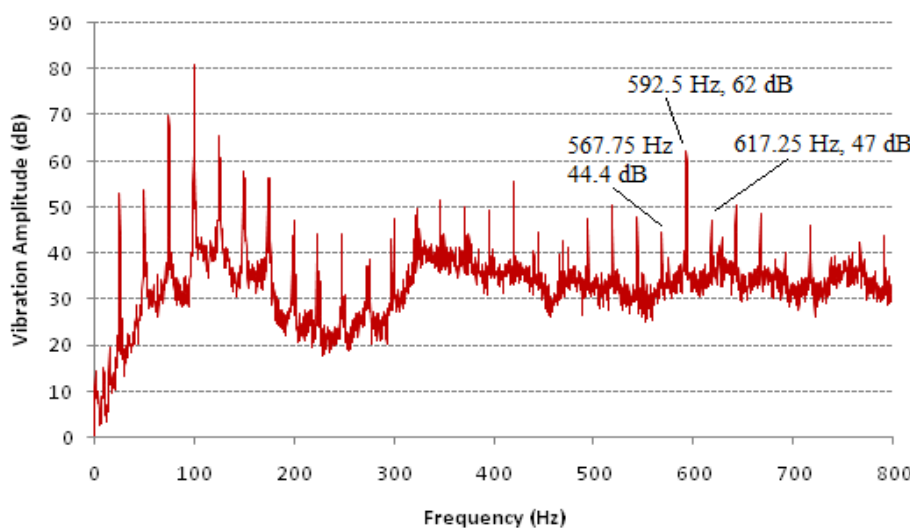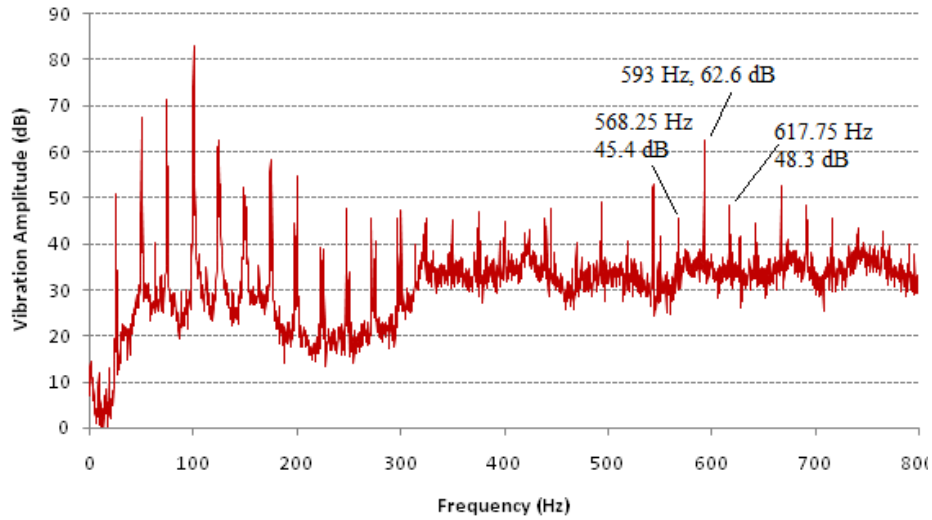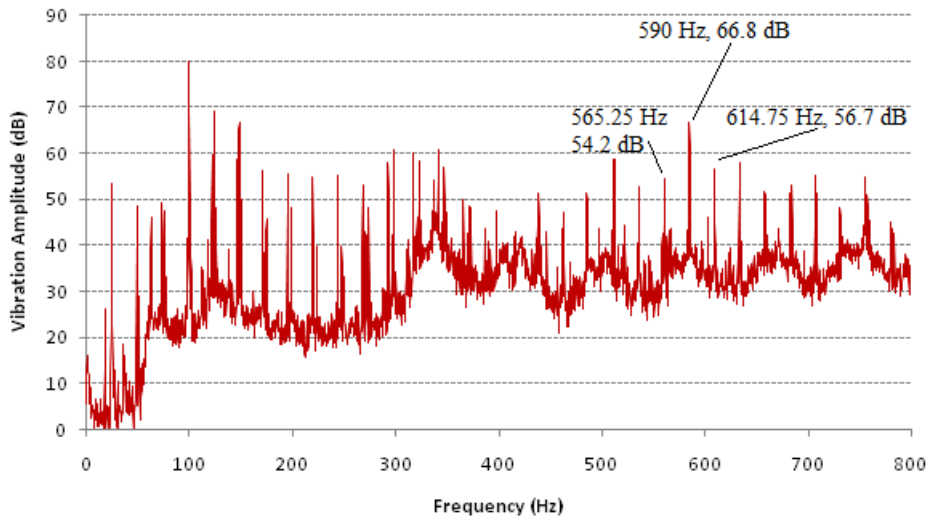
**Figure 11**   Vibration spectra of the defective impeller (with two vanes missing) (see online version for colours)



**Figure 12**   Vibration spectra of the defective impeller (with three vanes missing) (see online version for colours)



From Table 2, it is observed that when the severity of the defect increases, height of SBs increases and the difference between the dB values of VPF and SBs decreases. Like as the severity of the rotor bar fault increases, the height of SB's peak increases (Thomson and Fenger, 2001). As vane/vanes of impeller of pump has/have been broken, the momentary torque exerted between two consecutive normal vanes (in between whose, vane has been broken) rises. Due to that, the amplitude of force as well as vibration at (VPF ± RPS) increases. So, the peak height at (VPF ± RPS) also increases.

**Table 2** Features of vibration spectra for various impeller cases

| Impeller type | VPF and its amplitude | | LSB and its amplitude | | RSB and its amplitude | | Difference between amplitude of VPF and LSB (dB) | Difference between amplitude of VPF and RSB (dB) |
|---|---|---|---|---|---|---|---|---|
| | VPF (Hz) | Amplitude (dB) | LSB (Hz) | Amplitude (dB) | RSB (Hz) | Amplitude (dB) | VPF (Hz) | Amplitude (dB) |
| Normal | 594 | 61.0 | 569.25 | 41.6 | 618.75 | 46.1 | 19.4 | 14.9 |
| Defective (1 vane) | 592.5 | 62.0 | 567.75 | 44.4 | 617.25 | 47.0 | 17.6 | 15 |
| Defective (2 vane) | 593 | 62.6 | 568.25 | 45.4 | 617.75 | 48.3 | 17.2 | 14.3 |
| Defective (3 vane) | 590 | 66.8 | 565.25 | 54.2 | 614.75 | 56.7 | 12.6 | 10.1 |

Notes: Left side band (LSB) is VPF − rotating speed
Right side band (RSB) is VPF + rotating speed

## 3.3   *Time domain analysis of current signals*

It has been used to demodulate current spectrum for different impellers to find out the VPF and respective amplitude.

From Figures 13 to 16, the VPFs and their respective amplitudes are summarised in Table 3. It is observed that when the severity of the defect increases, then the amplitude of the demodulated current signal at VPF increases.

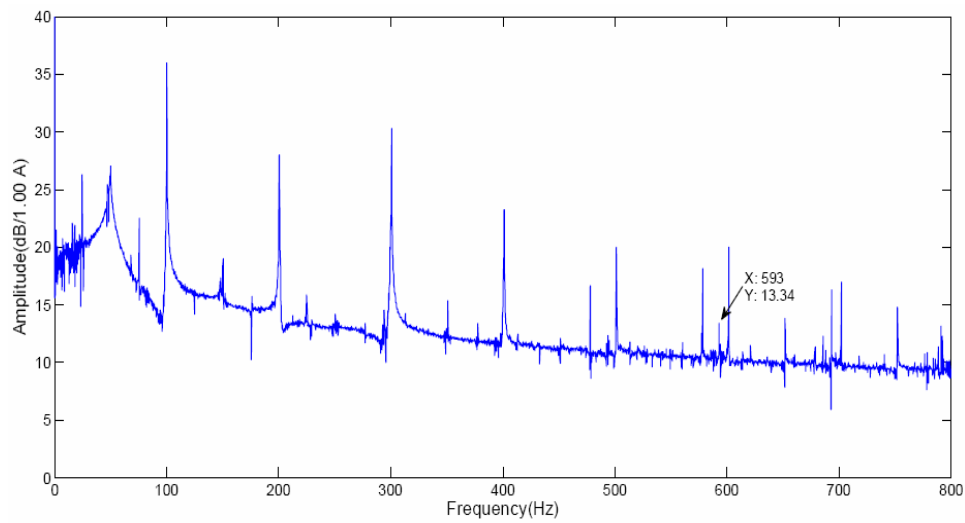**Figure 13**   Demodulated current spectra of the normal impeller (see online version for colours)



**Figure 14**   Demodulated current spectra of the defective impeller (with one vane missing) (see online version for colours)
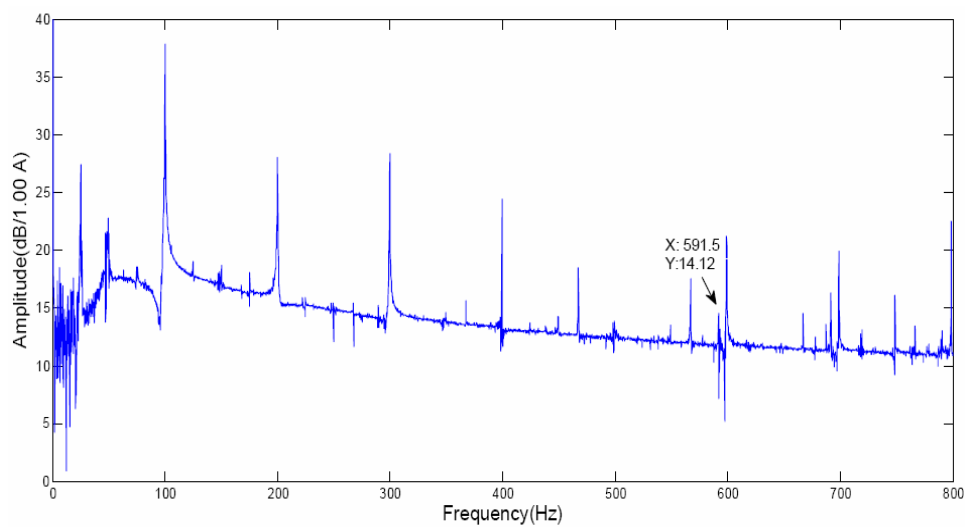
**Figure 15** Demodulated current spectra of the defective impeller (with two vanes missing) (see online version for colours)
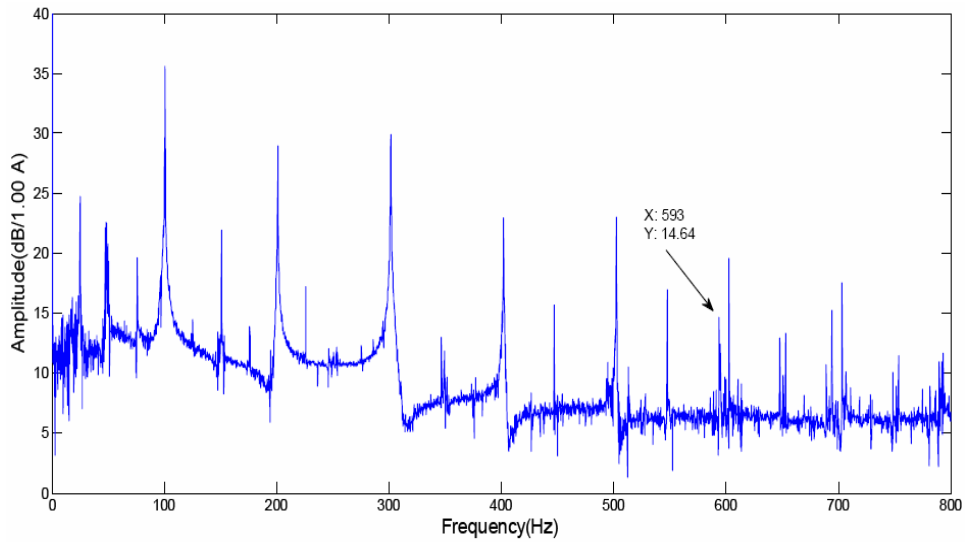


**Figure 16** Demodulated current spectra of the defective impeller (with three vanes missing) (see online version for colours)
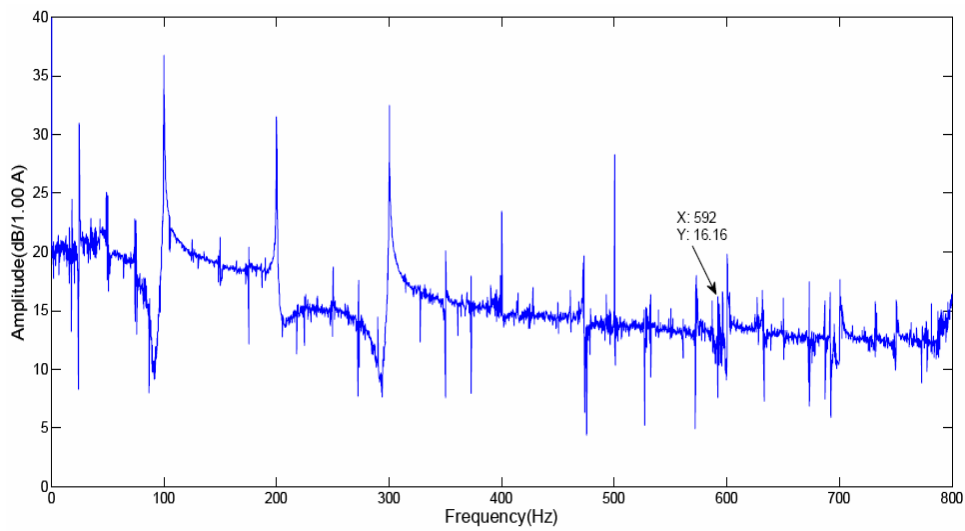


**Table 3** Summary of the observations for the demodulated current spectra

| Impeller type | VPF (in Hz) | Amplitude (in dB) |
|---|---|---|
| Normal | 593 | 13.34 |
| Defective (1 vane) | 591.5 | 14.12 |
| Defective (2 vane) | 593 | 14.64 |
| Defective (3 vane) | 592 | 16.16 |

## 3.4   *Frequency domain analysis of current signals*

From the current spectrum (as shown in Figure 17), it was observed that the second (and highest) peak gives the supply frequency (in this case 50 Hz).

**Figure 17**   Current spectrum (see online version for colours)
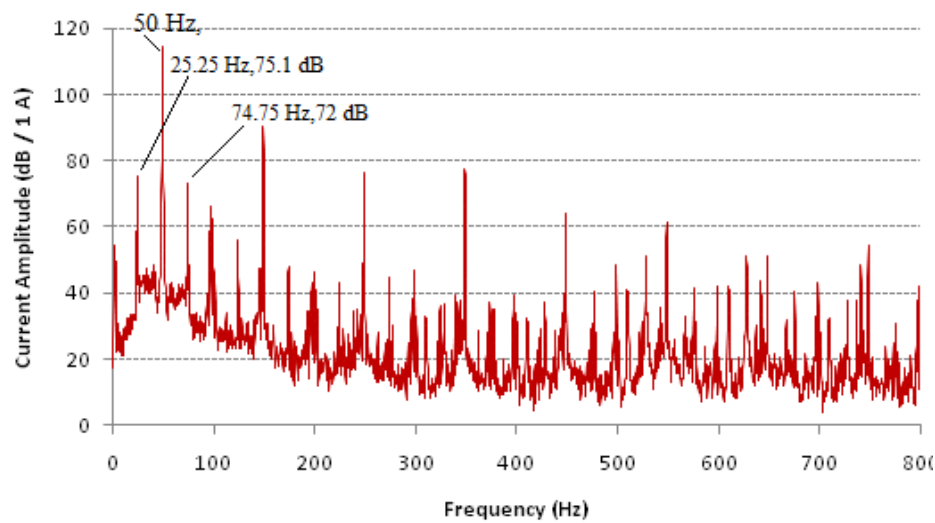


Also, the current spectrum has been used to find out the rotating speed (RPS). From the current spectrum, it was observed that peaks are at supply frequency (50 Hz) and two SBs at $50 \pm$ RPS. These are at 25.25 Hz (75.1 dB) and 74.25 Hz (72 dB) respectively. The SBs occur because of the modulation of the current, due to variation in the air gap between stator and rotor during rotation of motor shaft. Since the rotational vibration which in turn varies the magnetic conductance and due to that instantaneous current signal is modulated. When it is demodulated in frequency domain, it shows as SBs around supply frequency.

## 4   Conclusions

FDI in rotating machineries was introduced. Recent development in FDI has been defined in terms of condition monitoring. A step forward to condition monitoring is self-diagnostic capability (SDC). There are several approaches to SDC. In this paper we have considered FFT-based signature analysis of vibration and current of an exemplar centrifugal pump. After conducting this study on the condition monitoring of the centrifugal pump, the following conclusions are drawn

1 From the vibration spectrum, when the severity of the defect increases, height of SB increases and the difference between the amplitudes (dB) of VPF and SBs decreases.

2 From the current spectrum, it was observed that the second (and highest) peak gives the supply frequency (in this case 50 Hz). Also, the current spectrum has been used to find out the running speed (RPS).

3 The RMS value of vibration signal increases as the severity of the defect of impellers increases.

4 Peak value of the vibration signal increases as the severity of the defect of impellers increases; and it was also inferred that the VPF can be found out by plotting the demodulated current spectrum.

## References

Amarnath, M., Shrinidhi, R., Ramachandra, A. and Kandagal, S.B. (2004) 'Prediction of defects in antifriction bearings usingvibration signal analysis', *IE(I) Journal-MC*, July, Vol. 85, pp.88–92.

Casada, D.A. (1994) 'Detection of pump degradation', Presented at *22nd Water Reactor Safety Information Meeting*, Bethesda, Maryland, 24–26 October.

Casada, D.A. (1996) 'Using the motors to monitor pump condition', *4th NRC/ASME Symposium on Value and Pump Testing*, Washington, DC/USA, pp.1–20.

Choudhury, M.A. and Rahman, M.A. (1992) 'Determination of operating condition of submersible induction motors', *IEEE Transaction on Industry Application*, May/June, Vol. 28, No. 3, pp.680–684.

Jalan, A.K. and Mohanty, A.R. (2009) 'Model based fault diagnosis of rotor-bearing system for misalignment and unbalance under steady-state condition', *Journal of Sound and Vibration*, Vol. 327, Nos. 3–5, pp.604–622.

Kar, C. and Mohanty, A.R. (2008) 'Vibration and current transient monitoring for gearbox fault detection using multiresolution Fourier transform', *Journal of Sound and Vibration*, Vol. 311, Nos. 1–2, pp.109–132.

Kenull, T., Canders, W.R. and Kosyna, G. (2003) 'Formation of self-excited vibration in wet motors and their influence on the motor current', *European Transaction on Electrical Power*, March/April, Vol. 13, No. 2, pp.119–125.

Kliman, G.B., Koegl, R.A., Stein, J., Endicot, R.D. and Madden, M.W. (1988) 'Non-invasive detection of broken rotor bars in operating induction motors', *IEEE Transaction on Energy Conversion*, December, Vol. 3, No. 4, pp.873–879.

Mahalik, N.P., Moore, P.R. and Pu, J. (1998) 'Fault detection in the technical process using field bus', *Journal of the Institutions of Engineers*, India, Vol. 79, pp.5–11.

Mohanty, A.R. and Kar, C. (2006) 'Fault detection in a multistage gearbox by demodulation of motor current waveform', *IEEE Transaction on Industrial Electronics*, August, Vol. 53, No. 4, pp.1285–1297.

Mohanty, S. and Mahalik, N.P. (2007) 'Fault detection in sensors using multiresolution decomposition method', *International Journal of Intelligent Systems*, Vol. 2, No. 4, pp.416–426, Inderscience Publications.

Mohanty, S. and Mahalik, N.P. (2011) 'Some studies on fault detection and isolation in actuating systems', *IEEE International Conference on Process Automation, Control and Computing, PACC 2011*, July, Coimbatore, India.

Nandi, S. (2005) 'Condition monitoring and fault diagnosis of electrical motors – a review', *IEEE Transaction on Energy Conversion*, December, Vol. 20, No. 4, pp.719–728.

Nave, M.L. (1989) 'Consideration for application of electrical submersible pumps for underground coalmine dewatering', *IEEE Transaction on Industrial Application*, September/October, Vol. 25, No. 5, pp.846–850.

Rao, J.S. (2000) *Vibratory Condition Monitoring of Machine*, Narosa Publishing house, New Delhi.

Scheffer, C. (2004) *Practical Machinery Vibration Analysis and Predictive Maintenance*, Elsevier, Burlington.

Suphattana, C. and Surawatpunya, K. (2011) 'Vibration analysis and improvement for unbalance electromagnetic flux with air gap of AC induction motor' [online] http://www.aesieap0910.org/upload/File/PDF/4-chnical%20Sessions/TS25/TS2501/TS2501_FP.pdf (accessed 20 October 2011).

Thomson, W.T. and Fenger, M. (2001) 'Current signature analysis to detect induction motor faults', *IEEE Industry Application Magazine*, July/August, pp.26–34.

Thomson, W.T. and Reith, D.L. (1994) 'Online current monitoring to detect purely mechanical problems in three phase induction motor drives', *International Conference on Condition Monitoring*, Swansea/UK, pp.761–772.

Thomson, W.T., Chalmers, S.J. and Rankin, D. (1987) 'An online computer based condition monitoring system for rotor fault diagnosis in 3-phase induction motors', *Turbo Machinery International*, November/December, Vol. 28, pp.17–23.

Wang, W.Q., Ismail, F. and Golnaraghi, M.F. (2001) 'Assessment of gear damage monitoring techniques using vibration measurements', *Mechanical Systems and Signal Processing*, Vol. 15, No. 5, pp.905–922.