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Fault diagnosis of SKF-6205 bearing with modified empirical mode decomposition

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Abstract

Rolling element bearings are broadly used in the rotating machines to support static and dynamic loads. In this research, the advance signal processing techniques are use for processing of bearing fault signals. Experimental validation with genuine vibration signals calculated from bearings with seeded defects on bearing elements. The model-based fault diagnosis method has attempted to diagnose incipient fault detection and classification of bearing with data driven approach. Feature extraction technique has been developed with hybrid signal processing technique based on the band pass filter nature of Empirical mode decomposition (EMD), the resonant frequency bands have owed in specific mono component signals called Intrinsic Mode Functions (IMFs). Synchronized resonant frequency band (SRFB) is obtained on based of orthogonal real wavelet using spectral kurtosis. Biorthogonal 5.5 wavelet, a real wavelet has been selected as a suitable wavelet for WPT based on “Maximum Relative Wavelet Energy” and “Maximum Energy-to-Shannon entropy ratio”. Three, Feature extraction techniques like continuous wavelet transform (CWT), wavelet packet transform (WPT) and modified Hilbert Huang Transforms (HHT) are compared on bases of their classification accuracy with different classification algorithm and filters. Various supervised classifiers have been compared through a common platform of Waikato Environment for Knowledge Analysis (WEKA) and concluded the k- nearest neighbour (KNN) as an effective available classifier for rolling element bearing. Further, asymmetric proximity function based KNN (APF-KNN) has out performs with modified feature selection criteria. Feature extraction through modified HHT and APF-KNN has been future as a most effectual fault classification method. For testing any unknown data, simplified method has been demonstrated, which make the proposed data driven approach more realistic, faster and automated.

Keywords: Ball bearing, HHT, Spectral kurtosis, WPT, Signal Processing

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1. Introduction

Rolling bearings have to be most significant part of rotating machines. Ball bearing is a unique part with multi body dynamics application. In present scenario, condition monitoring of ball bearing has vital role to support overall production cost in process industries like power sector, paper & pulp industries, pharmaceutical & chemical process units. In all such applications, catastrophic failure of any one rotating element may affect the entire process and which will raise the production losses. With advancement in material technology and measurement tools like sensor & data acquition, real time fault diagnosis techniques have improvised with upgradation in digital signal processing techniques. Time based, frequency based and Time-frequency based techniques have significant in vibration measurement and analysis for real time fault diagnosis of ball bearing by (Tandon., 1994).

Dejie et al. (2005) has presented dual application of envelope spectrum analysis technique and Hilbert Transformation for real time fault diagnosis of bearing. Dejie et al. had suggested to transformed raw vibration signal in to time-scale representation with WT (wavelet transformation). Decomposed high scales wavelet co-efficient derived from WT had been evaluated with HT (Hilbert transform). Proposed envelop analysis was evaluated real time bearing condition using (EMD) empirical mode decomposition and HT. Also, data classification accuracy was improved with proposed data mining application.

Tsao et al. (2012) proposed a newel idea using empirical mode decomposition techniques as effective fault diagnosis method for ball bearing diagnosis. Huang et al. (1998) concluded that “a band pass filtering character of decompose signal with EMD include select mono component of signal recognize as IMF”. Optimize IMF selection has proposed by means of EMD with a swept-sine excitation and finished as effective tool for fault diagnosis. Anywhere, specific IMF has chosen with spectrogram.

Various digital signal processing techniques have under research to identify the effective fault diagnosis technique. Conclusion on top of review, disclose different digital signal processing techniques begin from FFT, STFT, wavelet transformation, wavelet packet transformation (WPT), Hilbert Transformation and Hilbert Huang Transformation (HHT). HHT along with Wavelet packet transform was the effective fault diagnosis process for ball bearing. HHT is just right tool for non-linear and non-stationary signals of ball bearing. HHT have also identified some deficiency, a large swing has observed at end of orthogonal representation of intrinsic mode function (IMF) due to curve fitting limitation. Another deficiency observed that first IMF is fail to satisfy definition of mono component but even then, first IMF is considered envelop spectrum. Researchers have considered first two IMF as genuine component and rest are the pseudo-IMF but concept of pseudo-IMF was not available in literature review. In this research, effectiveness of subsequent IMF with different resonant frequency band has been evaluated. Synchronized resonant frequency band (SRFB) is selected with the spectral kurtosis applied with WPT noise reduction technology.

2. Experimental Setup and Data Acquisition

Experimental set up has shown in fig.1. a table top experimental set up was design and installed in Green KSV skill development workshop. To minimize modulation of surrounding noise an appropriate rubber packing has installed between rigid structures & set up. SKF6205 deep groove ball bearing has utilized in current research. Ball bearing mounted on balanced rotor and rotor system drive by a DC motor with external servo controller. A flexible spring type coupler used to reduce misalignment between rotor & motor, if any being there in system. The localized defects of size of 300 X 300 X 20 micron have inserted in ball bearing parts as shown in Fig.3. A localized defect have inserted on Outer race defect (ORD), Inner race defect (IRD) and Ball defect. Vibration data has collected with vibration analyzer shown in Fig. 2. Unidirectional piezoelectric sensors with frequency range of 1-30 kHz and measuring range of +/- 500g with resolution of 0.005 g has utilized to collect data at sampling rate of 20.480 kHz. Calibration of variable speed motor with vibration analyzer has recognized up to resonant frequency of 70 kHz. Post-processor of current analyzer is trouble-free to operate with its GUI interface and MATLAB reliability.

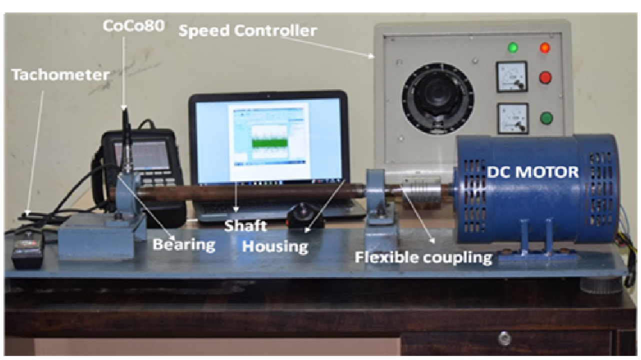

Figure.1. Experimental Set up

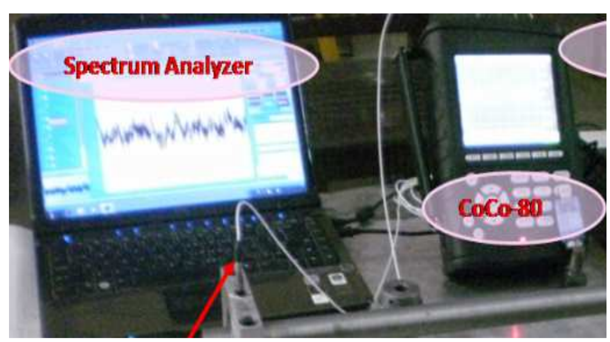

Figure.2. CoCo-80dynamic signal analyzer

Figure.3. Seeded Localized defect on ball bearing

3. Methodology

In this research paper, unique time series data is decaying with wavelet packet using real reverse bi-orthogonal 5.5 wavelet, where choice of R-bio5.5 wavelet was suggested by (Pandya et al., 2013) therefore decompose signal proceed to check spectral kurtosis of every decompose section. Better the kurtosis includes analytic of impulsive responses in that synchronized frequency band. Nowadays, decompose the original time series data in intrinsic fluctuation mode, by means of the empirical mode decomposition and to finish, the envelop spectrum applied to the IMF with resonant frequency band which coordinated with preceding chosen frequency band.

The procedure of assortment of IMF based on synchronized resonant frequency band intended for ball bearing diagnosis was planned stepwise as follow:

- Collect raw vibration signal data, $x(t)$
- Decay signal, Selecting a wavelet & decomposition level J. The entirety decomposition levels (J) can be considered according to the following affiliation:

  $$J \geq \log_2\left(\frac{f_s}{f_c}\right)+1$$

  Wherever, f s is sampling frequency and f c characteristic defect frequency
- Choose the W P T resonant frequency band among maximum kurtosis & get maximum impulse frequency in this band. Spectral Kurtosis effective capability to analyze frequency domain and to indentify concern frequency bands someplace the fault signal can be most excellent detected by Dwyer (1983), Antoni (2006,2007), Randall (2005), Xiao (2015).
- Performing arts band pass filtering with E M D on time series data $x(t)$.
- Optimize I M F and gather set of I M Fs of specific frequency band.
- Pick the I M F with resonant frequency band, which synchronized frequency band obtains with W P T and Spectral kurtosis.
- Process preferred signal to extracting fault features.

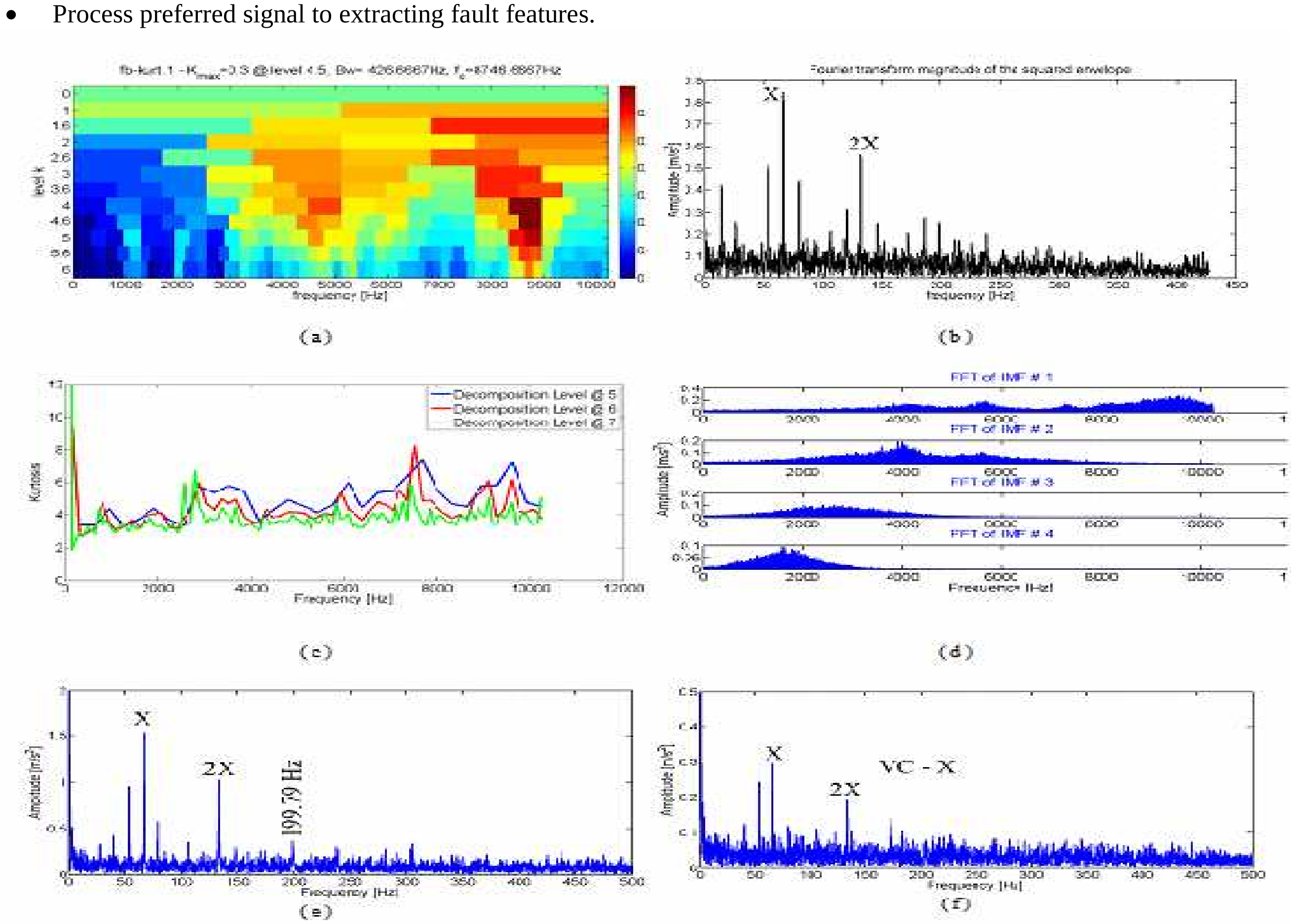

Figure.4 Healthy bearing at 4000 RPM (a) STFT envelop spectrum (b) FFT Plot (c) selection of SRFB with spectral kurtosis (d) Fourier spectrum of first four I M Fs (e) FFT of I M F1 (f) FFT of I M F3

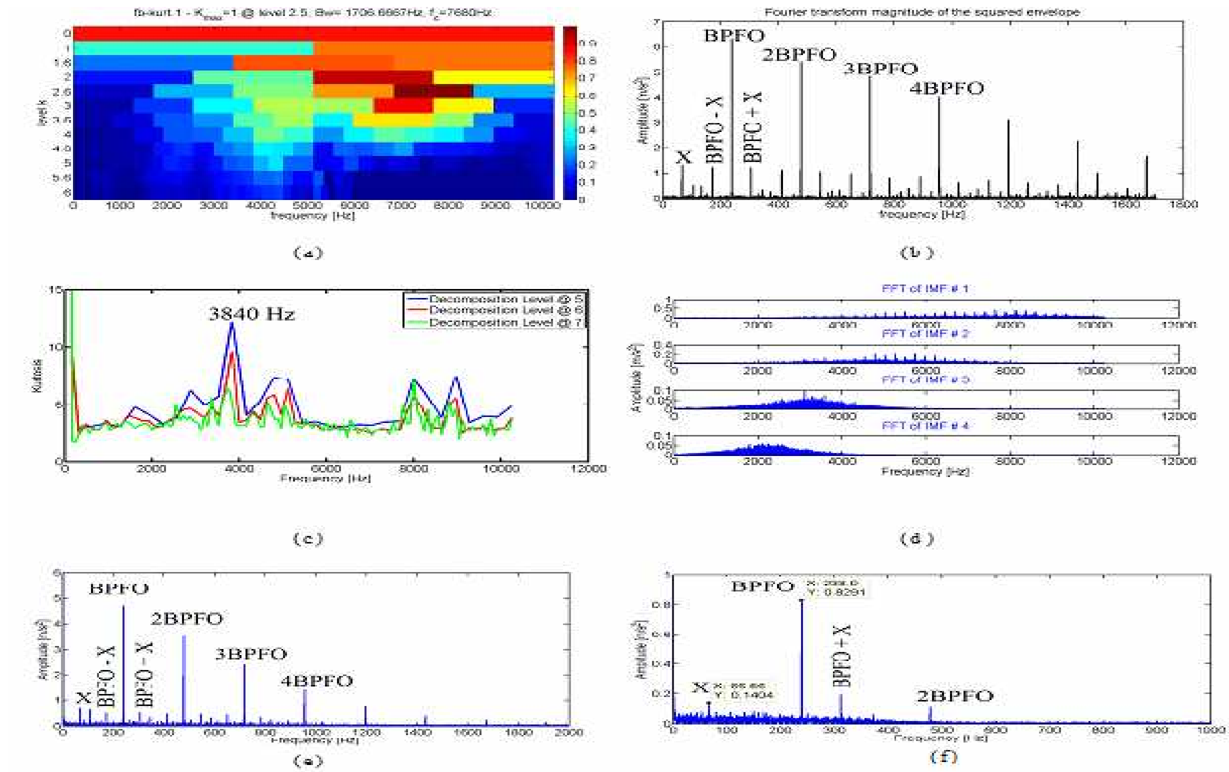

Figure.5 Ball Bearing outer race defect at 4000 RPM (a) STFT envelop spectrum (b) FFT Plot (c) selection of SRFB with spectral kurtosis (d) Fourier spectrum of first four I M Fs (e) FFT of I M F1 (f) FFT of I M F3

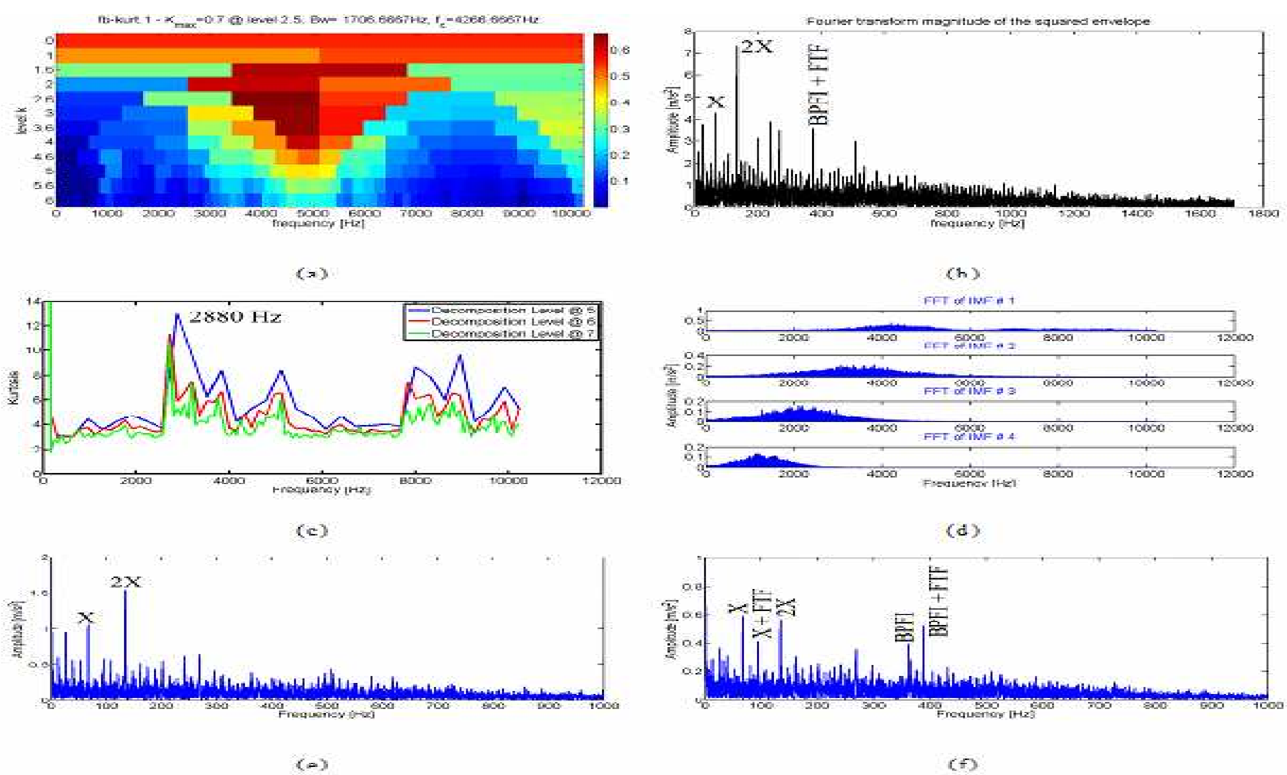

Figure.6 Ball bearing with inner race defect at 4000 RPM (a) STFT envelop spectrum (b) FFT Plot (c) selection of SRFB with spectral kurtosis (d) Fourier spectrum of first four I M Fs (e) FFT of I M F1 (f) FFT of I M F2

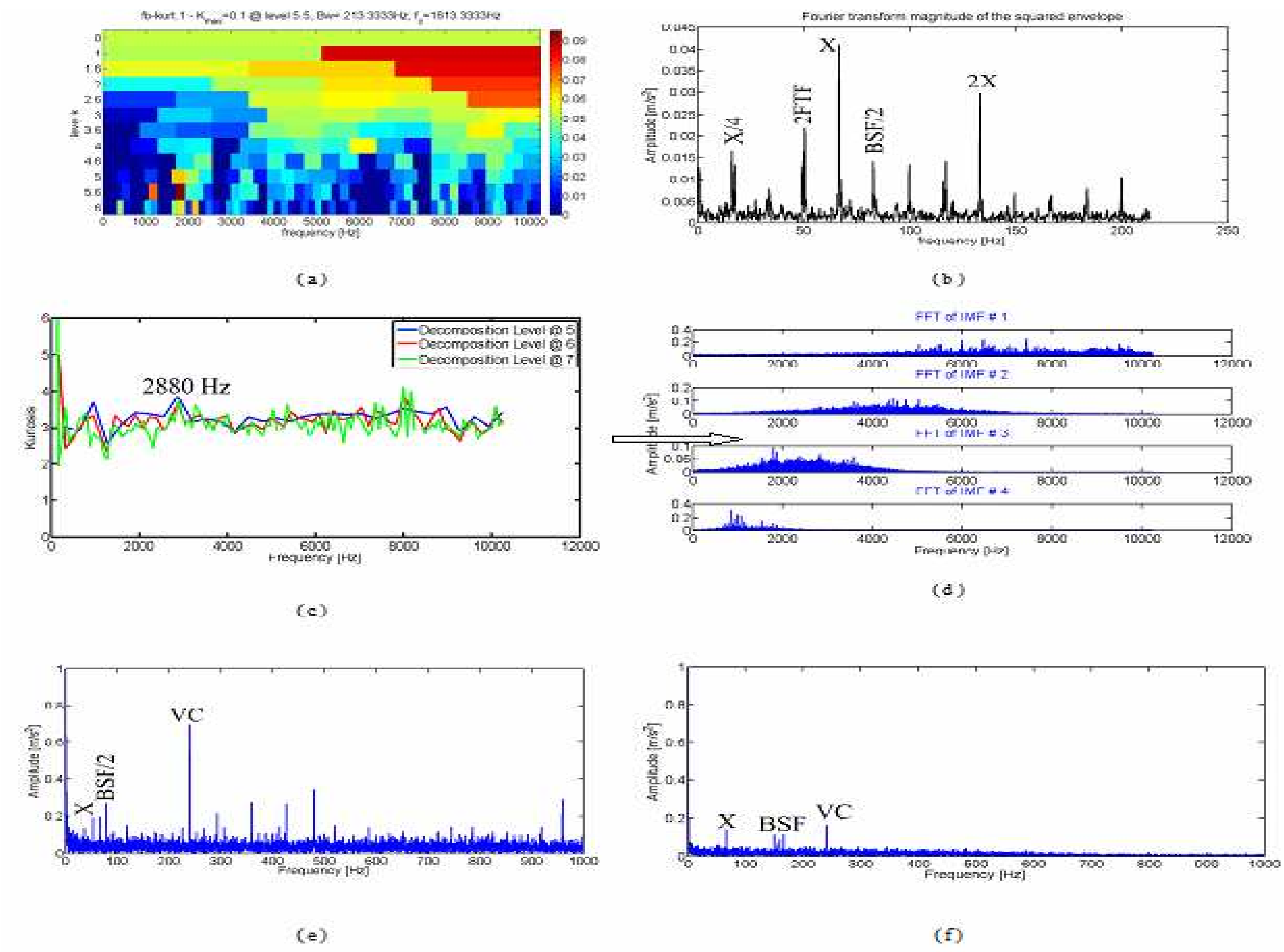

Figure.7 Ball bearing with ball defect at 4000 RPM (a) STFT envelop spectrum (b) FFT Plot (c) selection of SRFB with spectral kurtosis (d) Fourier spectrum of first four I M Fs (e) FFT of I M F1 (f) FFT of I M F3

4. Results and Discussion

Inner race defect faults come in load zone inside a rebellion & engender low frequency vibration reply as compared to same size of outer race defect fault, still it should not produce several impulses once inner race defect fault is absent of load zone. BPFI is modulated with rotor spinning frequency generally. In case of defective rolling element, two times BSF can be produced, because the fault strikes both races during each revolution of the ball. The RMS value of the frequency generated is not very high because the ball is not always in the load zone when the fault strikes the race. This frequency usually passes through more mechanical interfaces and may not be measurable in some cases. B P F I is normally modulated by way of rotating frequencies & B S F resultant in age group of elementary train frequency which is modulated additional frequencies such as B P F I, B S F and rotating component frequency. This modulation generates numeral of side bands something like the characteristic fault frequency (C D F) or some time it's not easy to recognize the C D F of low down frequency.

Experimental response is obtained on various speed and different bearing conditions like healthy bearings, outer race defect fault, inner race defect fault and ball defect fault, inside this section, the conventional envelope analysis in the midst of fast kurto-gram is worn to notice various bearing faults, & the diagnosis recital is compared & discussed by way of 6205 bearing at 4000 rpm.

4.1 Healthy Bearing

In this work, results & conversation arranged first to healthy bearing. Fig. 4(a), show fast kurto-gram among decomposition level 4.5, show far above the ground non-stationary responses approximately carrier frequency of 8476.66 Hz. which maximize the kurtosis, is (fc, B W), so as to frequency band [8263.33 Hz – 8690 Hz]. Envelope analysis shows significant peak at X (66.67 Hz) and 2X (133 Hz) are observed in fig. 4 (b). Fig. 4 (c) shows the spectral kurtosis at three decomposition levels, selection of three decomposition levels depends on concern CDF at 4000 rpm and with 20.4 KHz sampling frequency. E M D course of action computed waveform spectrum of 16 I M Fs out of individuals first four Fourier spectrum of I M Fs shown in fig. 4 (d)., Maximum

SK is observed in the higher frequency range at around 8000 Hz and above, where IMF1 is synchronized with this frequency range. But, IMF1 is not satisfied the definition of mono component and end of IMF1 has large swing due to curve fitting limitation as reported by Peng (2002). In this scenario, second higher frequency band is observed at 3000 Hz and concern envelope spectrum proposed concept shows the significant peaks at X (66.67 Hz), 2X (133 Hz) and (1/2*VC+X) (187 Hz) are observed in fig.4(e). Now comparing the envelope spectrum of fast kurto-gram & proposed concept, it's clearly observed the modulation of rotating frequency have reduced with less sideband in envelope spectrum of proposed concept and clearly show the experimental set up is rotating with minor misalignment which results in unbalance rotating frequency at X and 2X. Another peak at 175 Hz (VC - X) clearly show the interaction of varying compliances and rotating frequency indicate healthy bearing condition.

4.2 Outer Race Defects

Outer race defect fault is put in the load zone & it's executing stationary signals. Inside of bearing among outer race defect fault, both fast kurto-gram & planned concept shows significant and visible responses. Fig. 5 (a), show fast kurto-gram amid decomposition level 2.5, shown high stationary response just about carrier frequency of 7680 Hz. Which maximizes the kurtosis, (fc, BW), with the intention of frequency band [6826 Hz – 8533 Hz]. at this point, a characteristic defect frequency (B P F O) is 239 Hz. intended for rotational frequency of 66.67 Hz. Envelope analysis among fast kurto-gram obtain, the responses next to B P F O & it's harmonic seeing that shown in Fig. 5 (b)., Fig. 5 (c) represent the spectral kurtosis at 3rd level of decomposition, which show the maximum kurtosis at 3840 Hz & decomposition level 5 of W P T matching resonant frequency band [3680 Hz–4000 Hz]. E M D process computed wave form spectrum of 16 I M Fs elsewhere of those first four Fourier spectrums of I M Fs shown in Fig. 5 (d). Nowadays, the Fourier spectrum synchronized through resonant frequency band is I M F3. Established HHT envelope analysis based on I M F1 still during I M F1 cover a ample frequency range at high frequency region & not make happy the mono component description. Fig. 5 (e) & (f) represents envelope spectrum of I M F1 and I M F3 in that order, judgment without a doubt indicate reduction in sideband in envelope spectrum with IMF3 in Fig. 5 (f). These reductions are not because of amplitude reduction but also demodulation of signal at appropriate low frequency synchronized resonant band. Envelope spectrum with fast kurto-gram, conventional Hilbert Huang Spectrum and proposed concept are observed significant peak at BPFO and its harmonics. All three methods are effectively diagnosing the bearing with outer race fault.

4.3 Inner Race Defects

Fig. 6 (a), represent fast kurto-gram among decomposition level 2.5, show high non-stationary response around carrier frequency of 4266.67 Hz. which maximize kurtosis are [fc, BW], with the intention of frequency band [3413.33 Hz–5119 Hz]. at this time, a attribute defect frequency (BPFI) is 361 Hz intended for rotational frequency 66.67 Hz. Envelope spectrum analysis through fast kurto-gram be recorded significant peak at X, 2X & additional peaks recorded at 214 Hz, 227 Hz, 390 Hz (B P F I + F T F) & 513.23 Hz. seeing that in Fig. 6 (b). Fig. 6 (c) represent the spectral kurtosis at 3 decomposition level, which shown the maximum kurtosis at 2880 Hz & decomposition level 5 of W P T ensuing resonant frequency band is [2720 Hz- 3040 Hz]. E M D process is computed wave form spectrum of 18 I M Fs elsewhere first 4 Fourier spectra of I M Fs shown in Fig. 5.24(d). At this moment, Fourier spectrum synchronized resonant frequency bands is I M F2. Established HHT envelope analysis is based on I M F1 even during I M F1 wrap a broad frequency range at high frequency region & not make happy the mono component definition. Fig. 6 (e) & (f) represent the envelope spectrum of I M F1 & I M F2 in that order, judgment noticeably designate the helpfulness of projected concept. Envelope spectrum amid I M F2 represent the significant & clear peaks at X, 2 X, B P F I (361.24 Hz) & B P F I + F T F (385.72 Hz), even as envelope spectrum of I M F1 represent the momentous peaks at X & 2X. Supplementary peaks are pragmatic as side bands next to 254 Hz, 278 Hz. Fault diagnosis of inner race defect is the most difficult diagnosis due to non stationary nature of signal as defect is continuously changes its position with rotation of shaft. Proposed concept has diagnosed inner race defect more effectively with resonant frequency band of IMF2 as compare to STFT based fast kurto-gram amid resonant frequency band next to [3413.33 Hz -5119 Hz] & deprived resolutions in the midst of I M F1 envelope spectrum next to high frequency region & also meager curve fitting limitation of 1 intrinsic function.

4.4 Rolling Element Defect/Ball Defects

Rolling element defect is executing non-stationary signal with of low frequency, which could be difficult to demodulate from interfering signals. Fig. 7 (a), represents fast kurto-gram among decomposition level 5.5, & shows high non-stationary responses approximately carrier frequency of 1813.33 Hz. which maximize kurtosis [fc, BW], with the aim of frequency band [1706.66 Hz – 1919 Hz]. at this time, a characteristic defect fault frequency (B S F) is 157 Hz meant for rotational frequency of 66.67 Hz. Envelope spectrum analysis through fast kurto-gram, represent in the same normalize magnitude give no such momentous peaks, but make bigger view observed the significant peaks at X, 2 X & its harmonic in addition to extra peak are recorded next to 2 F T F(50 Hz) , B S F/2 (81 Hz) & modulated signal peaks represent in Fig. 7 (b). Fig. 7 (c) shows the spectral kurtosis next to 3 decomposition level, which represent the highest kurtosis by the side of 2880 Hz. & at decomposition level 7 of W P T matching resonant frequency band is [2800 Hz -2960 Hz]. E M D modus operandi is computed wave form spectrum of 18 I M Fs away from home first four Fourier spectrum of I M Fs are represent in Fig. 7 (d). Currently, the Fourier spectrum synchronized by way of resonant frequency bands is I M F3. Established HHT envelope analysis is based on I M F1 represent envelope spectrum as Fig. 7(e). The significant peaks are observed at VC (239 Hz), 361 Hz and weak response are observed at X (66.7 Hz) and BSF/2 (78.54 Hz) So it's difficult to diagnose the bearing condition, modulation of FTF frequency is also represented as additional side band in spectrum. While the proposed concept shows the clear peak at VC (239.5 Hz), X (66.67 Hz) and dense multiple side band are observed around BSF (157 Hz) with selected IMF3 represent in Fig. 7 (f), which obviously shown the usefulness of planned conception for fault diagnosis of ball bearings.

5. Conclusion

Inside this research paper, data acquisition has been done through developed experimental set up at institute. The localized defect spall is considered on different rolling element component. First, signal processing technique has been modified with hybrid method of HHT and WPT for incipient fault diagnosis. Anywhere synchronized resonant frequency band is chosen among maximum kurtosis at different decompose sub-band and corresponding intrinsic frequency band will select for fault diagnosis. The real time application on bearing among outer defect, inner defect, ball defect & healthy bearing has been tested. The result obtained with proposed hybrid method shows its effectiveness over STFT based fast kurto-gram as well. Thus SRFB with HHT and WPT has recognized as an effective fault diagnosis tool. To be more precise on fault diagnosis, multiple fault diagnosis techniques have been applied depending on importance for component or processes. Seeing that bearing is an exclusive multi body dynamic mechanism through various non-linearity has diversified responses, therefore difficult to make a diagnosis fault condition with advance signal processing techniques barely. Consequently, data driven clever system has necessary to re-validating embryonic fault diagnosis of rolling bearing by the side of signal processing technique.

I M F elected based on S R F B & after that statistical features extracted beginning preferred I M F for data mining algorithm. Data acquisition of vibration signals carried out of speed range of 1000 to 8000 rpm next to intermission of 1000 rpm. To make data more sensible five sets of data to be acquired for every class of bearing. Total five classes of bearings are measured.180 data samples to be obtained for the 5 bearing conditions (H B, O R D, I R D, B D & C D). For every sample, total 18 features are extracted to symbolize the characteristic in sequence contained in the sample, wherever 9 feature for horizontal & 9 for vertical response.

Further, comparison of feature extraction techniques are compared along with 8 different classifiers associated with 8 different filters for ball bearing fault diagnosis reported by means of investigational vibration signal analysis. primary, real wavelet is preferred for W P T based assortment criteria of maximum relative wavelet energy & maximum energy to entropy ratio criteria. Assortment of wavelet for C W T considered from previous investigator (Rafiee et al., 2010; kanakar et al., 2011(a)). Intrinsic feature data set is prepared throughout progression of E M D. Data mining algorithms spanned a broad diversity of classifiers counting Bayesian, regression based methods, meta-analysis, clustering, and tree based approaches are chosen on basis of their presentation in the respective data mining approaches for fault categorization of rolling element bearing. The W E K A default setting of parameters was used for each algorithm to keep away from unfairness and over fitting. Based on top of facts
Subsequent conclusions are drawn.

- **Signal Processing Technique:**

Reverse biorthgonal (5.5) wavelet is one of efficient real wavelet intended for fault identification of rolling element bearing. The proposed concept of synchronized resonant frequency band (SRFB) is providing an edition edge to EMD as an effectual incipient fault identification tool. Due to curve proper restraint at the conclusion of IMF1 broad swing is reported and second, IMF1 is not full fill mono component definition. But even then, IMF1 is generally considered for Envelop analysis follows by HHT. IMF1 is considered as real IMF and others are pseudo-IMF but no such explanations are reported in literature. Here, effectiveness of IMF2 and IMF3 has been justified with experimental verifications.

Wen et al. (2012)., has shown STFT based IMF selection concept where, conventional envelop analysis approach is require to examine all frequency band. But, proposed SRFB based concept is decomposing the signal in time-frequency domain with WPT and impulsive characteristic in decompose frequency band identified with spectral kurtosis. Thus in proposed SRFB concept, evaluation of all decomposed intrinsic frequency band are not require to evaluate. So, the proposed method can conclude as easier and can apply for real time fault detection and diagnosis.

- **Data Mining& Expert System:**

To get better the categorization accuracy, customized KNN algorithm is projected based on asymmetric proximity function (APF) in simple method , information is bound for as of test point to preparation data set & therefore more sensible information at local level obtain among APF. Condition of fine art cataloging can be achieved by storing 36 instant through 18 features in one class and parallel classification accuracy is obtained by means of optimized 8 features. Suitable value of K plays a significant roll in presentation of KNN as finished by former researchers (Mitra et al., 2002). In this research paper customized KNN consider $k=\sqrt{n}$, wherever n is the number of data worn for preparation reason for each class (bearing condition) and value of k will be adjacent odd number. Investigational outcome obviously shows that proposed APF-KNN algorithm among optimize feature has out-perform the KNN algorithm through 100% without compromising classification time and computational memory obligation.

Vertical response are more effective then horizontal response, as out of 8 optimize features, 6 features are from vertical responses. Significant of vertical response is revalidated here with data mining tool, that were reported by earlier researcher with numerical simulation and experiment of rolling element bearing (Fukata et al., 1985;Harsha, 2006(b); Cao and Xao, 2008;). Authors revalidated that WPT is outperform as compared to CWT (Nikoloau and Antoniadis, 2002(b)) with these results. Authors also revalidate EMD as an effective feature extraction method. Adaptive characteristic of EMD has evaluated the frequency with differentiation and not with convolution.

Investigational outcome obviously shows that APF-KNN algorithm among instant based (re-sample) filter has out-perform the rest of algorithms with 100% classification accuracy devoid of compromising classification time and computational memory requirement. APF-KNN is customized instantaneous based algorithm, which hypothetically necessitate more classification time and computational memory but together the draw backs are approximately unimportant in our scenario for the reason that of moderate amount of data sets.

More than most, these work concluded EMD as better feature extraction technique and APF-KNN as most effective available data mining algorithm. This information may elaborated with some more experiment in working conditions, which certainly lead industries for real application of intelligent system in automation.

References

Antoni, J. 2006, the spectral kurtosis: a useful tool for characterizing non- stationary signals, *Mechanical Systems and* ***Signal*** *Processing*, Vol. 20, No. 2, pp. 282-307. https://doi.org/10.1016/j.ymssp.2004.09.001

Antoni, J. 2007, Fast computation of the kurtogram for the detection of transient faults, *Mechanical Systems and Signal Processing*, Vol. 21, pp. 108–124. https://doi.org/10.1016/j.ymssp.2005.12.002

Cao, M. and Xiao, A., (2008). A comprehensive dynamic model of double-row spherical roller bearing-model development and case studies on surface defects, preloads, and radial clearance, *Mechanical Systems and Signal Processing*, Vol. 22, pp.467-489. https://doi.org/10.1016/j.ymssp.2007.07.007

Darji A., Darji P.H., Pandya D.H., 2019, Fault Diagnosis of Ball Bearing with WPT and Supervised Machine Learning Techniques. In: Tanveer M., Pachori R. (eds) Machine Intelligence and Signal Analysis. *Advances in Intelligent Systems and Computing*, Vol.748. Springer, Singapore. https://doi.org/10.1007/978-981-13-0923-6_25

Darji A. A., Darji P. H., and Pandya D. H., 2020. Envelope spectrum analysis with modified EMD for fault diagnosis of rolling element bearing. In:Reliability and Risk Assessment in Engineering. *Lecture Notes in Mechanical Engineering*. Springer, Singapore. https://doi.org/10.1007/978-981-15-3746-2_8

Dejie Y., Junsheng C. and Yang Y. (2005).Application of EMD method and Hilbert spectrum to the fault diagnosis of roller bearings, *Mechanical Systems and Signal Processing*, Vol. 19, pp.259–270. https://doi.org/10.1016/S0888-3270(03)00099-2

Dwyer, R.F. 1983, A technique for improving detection and estimation of signals contaminated by under ice noise, *Journal of the Acoustical Society of America*, Vol. 74, No. 1, pp.124-30. https://doi.org/10.1121/1.2019597

Fukata, S., Gad, E.H., Kondou, T., Ayabe, T. and Tamura, H., 1985, On the radial vibration of ball bearings: computer simulation. *Bulletin of JSME*, Vol. 28, No. 239, pp.899-904. https://doi.org/10.1299/jsme1958.28.899

Harsha, S.P. 2005. Nonlinear dynamic response of a balanced rotor supported on rolling element bearing, *Mechanical Systems and Signal Processing*, Vol. 19, No. 3, pp. 551–578. https://doi.org/10.1016/j.mechmachtheory.2005.09.003

Huang N., Shen Z., Long S., Wu M., Shih H., Zheng Q., Yen N. C., Tung C. and Liu H., 1998, The empirical mode decomposition and the Hilbert spectrum for nonlinear and non-stationary time series analysis, *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences*, Vol. 454, pp. 903–95. https://doi.org/10.1098/rspa.1998.0193

Junsheng C., Dejie Y. and Yu Y. 2005. Time-energy density analysis based on wavelet transform, *NDT & E International*, Vol. 38 pp. 569–572. https://doi.org/10.1016/j.ndteint.2005.02.002

Mitra, P., Murthy, C.A. and Pal, S.K., 2002, Density-based multi scale data condensation. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, Vol. 24, No. 6, pp.734-747. https://doi.org/10.1109/TPAMI.2002.1008381

Nikoloau, N.G. and Antoniadis, I.A., (2002(b)). Rolling element bearing fault diagnosis using wavelet packets, NDT & E International, Vol. 35, pp.197-205. https://doi.org/10.1016/S0963-8695(01)00044-5

Pandya, D.H. & Upadhyay, S.H. & Harsha, S.P. 2012. ANN based fault diagnosis of rolling element bearing using time-frequency domain feature, *International Journal of Engineering Science & Technology*, Vol. 4, No. 6, pp. 2878-2886.

Pandya, D.H., Upadhyay, S.H. and Harsha, S.P. 2013. Fault diagnosis of rolling element bearing with intrinsic mode function of acoustic emission data using APF-KNN, *Expert Systems with Applications*, Vol. 40, No. 10, pp.4137-4145. https://doi.org/10.1016/j.eswa.2013.01.033

Pandya D.H., Upadhyay S.H. and Harsha S.P., 2015, Fault diagnosis of high-speed rolling element bearings using wavelet packet transform, *International Journal of Signal and Imaging Systems Engineering*, Vol. 8, No. 6, pp.390–401. https://doi.org/10.1504/IJSISE.2015.072922

Randall, R. B. 2005, Applications of spectral kurtosis in machine diagnostics and prognostics, *Key Engineering Materials*, Vol. 293 pp. 21-30. https://doi.org/10.4028/www.scientific.net/KEM.293-294.21

Parmar U., Pandya D.H. 2020, Selection of mother wavelet for fault detection of cylindrical bearing, *Vibration and Acoustics Research Journal*, Vol. 2, No.1. pp. 1-26. https://doi.org/10.13140/RG.2.2.11094.57928

Peng Z. K., P. W. Tse and F. L. Chu, (2005). A comparison study of improved hilbert–hung transform and wavelet transform: application to fault diagnosis for rolling bearing, *Mechanical Systems and Signal Processing*, Vol. 19, No. 2, pp. 974–88. https://doi.org/10.1016/j.ymssp.2004.01.006

Peng Z., Chu F. and He Y., 2002, Vibration signal analysis and feature extraction based on reassigned wavelet scalogram, *Journal of Sound and Vibration*, Vol. 253, pp.1087–1100. https://doi.org/10.1006/jsvi.2001.4085

Rafiee, J., Rafiee, M.A. and Tse, P.W., 2010. Application of mother wavelet functions for automatic gear and bearing fault diagnosis, *Expert Systems with Applications*, Vol. 37, No. 6, pp.4568-4579. https://doi.org/10.1016/j.eswa.2009.12.051

Rai V.K. and Mohanty A.R. 2007, Bearing fault diagnosis using FFT of intrinsic mode functions in Hilbert–Huang transform, *Mechanical Systems and Signal Processing*, Vol. 21, No. 6, pp.2607–615. https://doi.org/10.1016/j.ymssp.2006.12.004

Sheen Y.T., 2010. An envelope analysis based on the resonance modes of the mechanical system for the bearing defect diagnosis, *Measurement*, Vol. 43, pp. 912–934. https://doi.org/10.1016/j.measurement.2010.03.011

Sheen Y. T., 2007, An impulse-response extracting method from the modulated signal in a roller bearing, *Measurement*, Vol. 40, pp. 868–875. https://doi.org/10.1016/j.measurement.2006.11.020

Sheen, Y.T. 2004. A complex filter for vibration signal demodulation in bearing defect diagnosis, *Journal of Sound and Vibration*, Vol. 276, No. (1-2), pp.105-119. https://doi.org/10.1016/j.jsv.2003.08.007

Tandon N., 1994, A comparison of some vibration parameters for the condition monitoring of rolling element bearings, *Measurement*, Vol. 12, No. 3, pp. 285-289. https://doi.org/10.1016/0263-2241(94)90033-7

Tsao W.C., Li Y., Le D. and Pan, M. 2012, An insight concept to select appropriate IMFs for envelope analysis of bearing fault diagnosis, *Measurement*, Vol. 45, No. 6, pp. 1489-1498. https://doi.org/10.1016/j.measurement.2012.02.030

Xiao Y., Ding E. and Chen C. 2015, A novel characteristic frequency bands extraction method for automatic bearing fault diagnosis based on hilbert huang transform, *Sensors*, Vol. 15, No. 11, pp. 27869-93. https://doi.org/10.3390/s151127869

Yadav H. K. and Pandya D.H., 2017. Non-linear dynamic analysis of cylindrical roller bearing, 11th International Symposium on Plasticity and Impact Mechanics, *IMPLAST, Procedia Engineering*, Vol. 173, pp. 1878–1885.

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