4th Asia Pacific Conference of the Prognostics and Health Management,
Tokyo, Japan, September 11 – 14, 2023 R02-05

Tacholess Instantaneous Speed Estimation Considering the Characteristics of Vibration Harmonics

Jinoh Yoo[1], Jongmin Park[2], Taehyung Kim[3], Jong Moon Ha[4], and Byeng D. Youn[5]

[1,2,3,5]*Department of Mechanical Engineering, Seoul National University, Seoul, 08826, Republic of Korea*
cosmbusi@snu.ac.kr
20jmp02@naver.com
grunth@snu.ac.kr
bdyoun@snu.ac.kr

[4]*Intelligent Wave Engineering Team, Korea Research Institute of Standards and Science (KRISS), Daejeon, 34113, Republic of Korea*
jmha@kriss.re.kr

[5]*OnePredict Inc., Seoul, 06160, Republic of Korea*
bdyoun@onepredict.com

ABSTRACT

Knowledge of instantaneous shaft speed is vital for non-stationary condition monitoring of rotating machinery in real applications. To avoid installing expensive and inconvenient encoders, many researchers have developed instantaneous speed estimation methods by extracting the shaft speed from vibration signals. However, previous methods show limitations due to challenges in vibration signals. Therefore, we propose a novel instantaneous speed estimation method considering the characteristics of vibration harmonics to overcome the difficulties. Multiple harmonic components and their characteristics are utilized to obtain an accurate ridge in the time-frequency representation (TFR). The proposed method is validated and compared with the previous methods using a gear vibration simulated signal and civil aircraft engine dataset. The results show the accuracy and robustness of the proposed method.

1. INTRODUCTION

Vibration-based instantaneous speed estimation acquires the transient speed profile of the rotating machinery in non-stationary operations without an encoder and tachometer. This minimizes the cost and enables condition monitoring of rotating machinery under variable speed conditions. Therefore, this research field has gained a lot of attention over the past decades. But the difficulties in vibration signals hinder the application in real industrial sites. The well-known difficulties in vibration-based speed estimation are low SNR, amplification by resonances, and the presence of multi-components (Peeters, Leclère, Antoni, Lindahl, Donnal, Leeb, and Helsen, 2019). To deal with these problems, recent studies tried to make use of multiple harmonics to improve performance. Leclère, André, and Antoni (2016) considered multiple speed-related components in TFR. Peeters, Antoni, Leclère, Verstraeten, and Helsen (2022) utilized multi-harmonics while applying phase demodulation based on Hilbert transform. They showed better accuracy than previous methods. However, they also reveal weakness when several difficulties exist at the same time. Especially when the extreme noises obscure some low-energy harmonics, the state-of-the-art methods show tremendous error due to those low SNR harmonics.

In this study, a novel vibration-based instantaneous speed estimation is proposed to acquire both accuracy and robustness. The proposed method reflects the characteristics of vibration harmonics when using multiple harmonics. By considering the vibration characteristics, speed-related multi-components with high SNR can be utilized more efficiently to estimate the instantaneous speed.

2. PROPOSED METHOD

Vibration signals acquired from rotating machinery have multi-components. Among them, some harmonic components may have low SNR values. Therefore, it is important to suppress those low-energy harmonics by considering harmonics' characteristics while employing multiple harmonics for speed estimation.

The energy and entropy of harmonic components are the critical characteristics of multi-component signals. The energy of the vibration harmonic can be reflected by using all the energies in the harmonic frequency band as follows:

$$E_i = \sqrt{\int_{f_i}^{f_o} \int_{-\infty}^{\infty} S(t, f) dt df} \tag{1}$$

where $S(t, f)$ is the time-frequency representation of the signal, and $[f_i, f_o]$ is the frequency band of the i^{th} harmonic. The entropy of vibration harmonics can be acquired by using Rényi entropy as follows:

$$H_i = \frac{1}{1-\alpha} \log_2 \int_{f_i}^{f_o} \int_{-\infty}^{\infty} S_n^{\alpha}(t, f) dt df \tag{2}$$

where α is the order of Rényi entropy, $S_n(t, f)$ is the normalized TFR.

TFR-based instantaneous speed estimation utilize the ridge which is related to shaft speed. Therefore, the crucial part is to build more precise ridge. In the proposed method, multiple harmonics having more energy and less entropy are preferred to be used for speed estimation. First, by using the concept of the multi-order probabilistic approach (MOPA) method researched by Leclère et al. (2016), a probability density function of instantaneous speed (Ω_t) for each harmonic is defined:

$$[\Omega_t \mid \beta_i] \propto S(t, [f_i, f_o]) \tag{3}$$

where β_i denotes the i^{th} harmonic component. Then, the more accurate ridge is obtained by considering multiple harmonic components with the vibration characteristics by following equation:

$$[\Omega_t] \propto \prod_i [\Omega_t \mid \beta_i]^{c_i} \tag{4}$$

where c_i is the proposed coefficient reflecting characteristics of i^{th} harmonics as follows:

$$c_i = g(E_i, H_i) = \frac{E_i}{n} \tag{5}$$

$$n = 2^{H_i - \min_{\forall i}(H_i)} \tag{6}$$

where n is the complexity or the number of components of i^{th} harmonic in TFR calculated by Rényi entropy (Sucic, Saulig, and Boashash 2011). Locating E_i in the numerator enables to reflect the importance of the harmonic energy. However, overlapping of adjacent harmonics or extreme noise in the given frequency range may overemphasize the energy value. Therefore, the number of components is used for denominator to release the overemphasizing problem. Thus, the proposed coefficient allows to focus on the high energy harmonics while multiple harmonics are used.

3. CASE STUDY

The gear vibration simulated signal compares the performance of the proposed method and previous methods. The simulated signal is composed of 10,000 samples, and the sampling frequency is 5,000Hz. To add the problems for speed estimation, white Gaussian noise with very low SNR is applied. The speed change is getting bigger in the profile. Furthermore, similar to the real gear vibration signal, the simulated signal has multiple harmonics of shaft frequency and gear mesh frequency (GMF), and the energy of higher harmonics are lower. The spectrogram of the simulated signal is shown in Fig. 1.

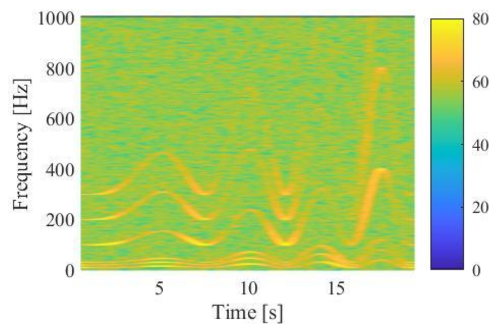

Fig. 1 Spectrogram of the gear vibration simulated signal

For comparison, single harmonic phase demodulation (SHD) and multi-order probabilistic approach (MOPA) are used. For MOPA and the proposed method, every three harmonics of shaft and gear mesh frequency are applied. Fig. 2 shows the estimation results of each method with the encoder profile. The SHD method shows the worst result among them. Because the SHD method uses only a single harmonic and is based on the Hilbert transform, it is vulnerable to the presence of adjacent harmonics occurring by large speed changes. The MOPA method shows much better results than SHD throughout the whole time by using multiple harmonics. However, MOPA shows large errors for 15s and 18.5s. Because the MOPA method treats all the harmonics equally, the higher harmonics with low energies hinder the accurate estimation. The estimation result obtained by the proposed method follows the encoder profile best.

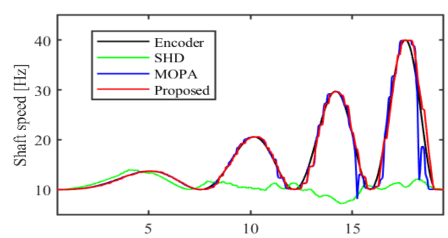

Fig. 2 Estimated instantaneous speed profiles of each method for the gear vibration simulated signal

Fig. 3 displays the mean and median absolute error for each method. SHD shows the worst result. MOPA acquires better results for both errors than SHD. The proposed method reduces the Mean absolute error significantly compared to the MOPA. However, the median absolute error is slightly lower for MOPA than the proposed method. This is because of the smoothing process in the MOPA. In the proposed method, the smoothing process is not employed because of the overfitting issue (Peng, Smith, Randall, Peng, and Mechefske, 2021). Thus, this case study shows the effectiveness of the proposed method for speed estimation.

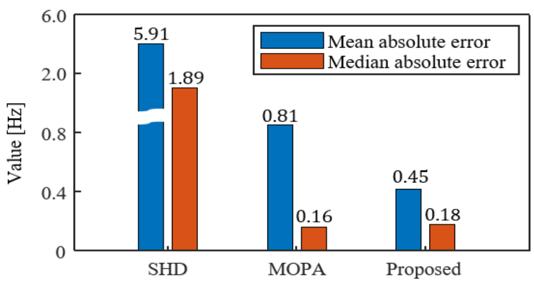

Fig. 3 Mean and median absolute errors of the results for each method on the gear vibration simulated signal

For more verification, the proposed method is demonstrated by the popular civil aircraft engine data provided by the Safran contest Conference Surveillance 8, Roanne, France (Antoni., Griffaton, André, Avendaño-Valencia, Bonnardot, Cardona-Morales, Castellanos-Dominguez, Daga, Leclère, Vicuña, Acuña, Ompusunggu, and Sierra-Alonso, 2017). The objective of the data is to estimate the instantaneous speed of the high-pressure (HP) shaft in the aircraft engine as shown in Fig. 4 and Fig. 5.

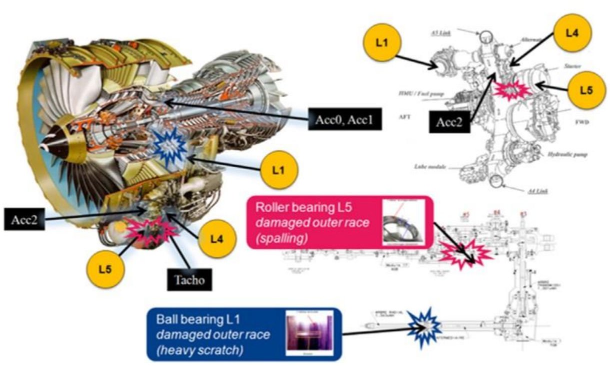

Fig. 4 Overview of the aircraft engine and the gearbox

Fig. 6 shows the estimation results of MOPA and the proposed method. For both methods, 15 harmonics of the HP shaft and the radial drive shaft (RDS) are used for speed estimation. The MOPA method shows inaccurate results around 160s leading to a large mean absolute error value of 0.0792. However, the proposed method correctly estimates and yields a much lower mean absolute error value of 0.0391.

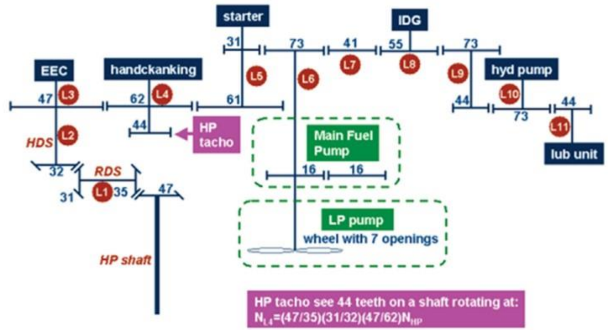

Fig. 5 Kinematics of the gearbox in the aircraft engine

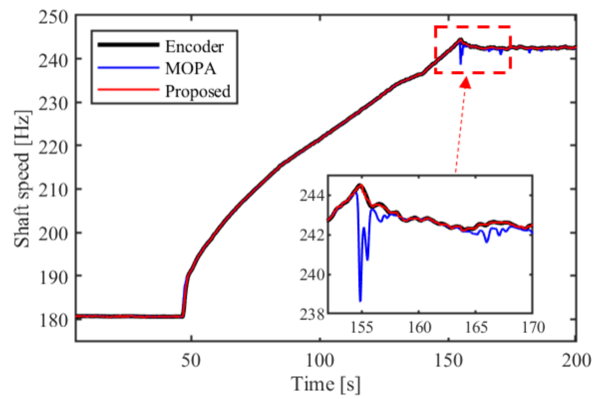

Fig. 6 Estimated instantaneous speed profiles of each method for the Surveillance 8 aircraft engine data

4. CONCLUSION

In this study, a novel tacholess instantaneous speed estimation method is developed by considering the characteristics of vibration harmonics. The proposed coefficient reflects the energy and entropy of the harmonics to utilize the high SNR harmonics and minimize using low energy harmonics. The simulated vibration signal and the civil aircraft engine dataset validate the proposed method. The comparative results demonstrate that the proposed method has better performance.

ACKNOWLEDGEMENT

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea Government (MSIT) (No. 2020R1A2C3003644).

REFERENCES

Peeters, C., Leclère, Q., Antoni, J., Lindahl, P., Donnal, J., Leeb, S., & Helsen, J. (2019). Review and comparison of tacholess instantaneous speed estimation on experimental vibration data. *Mechanical Systems and Signal Processing*, 129, 407-436. doi: 10.1016/j.ymssp.2019.02.031

Leclère, Q., André, H., & Antoni, J. (2016). A multi-order probabilistic approach for Instantaneous Angular Speed tracking *debriefing of the CMMNO'14 diagnosis contest*. *Mechanical Systems and Signal Processing*, 81, 375-386. doi: 10.1016/j.ymssp.2016.02.053

Peeters, C., Antoni, J., Leclère, A. (2016). Multi-harmonic phase demodulation method for instantaneous angular speed estimation using harmonic weighting. *Mechanical Systems and Signal Processing*, 167. doi: 10.1016/j.ymssp.2021.108533

Sucic, V., Saulig, N., Boashash, B., (2011). Estimating the number of components of a multicomponent nonstationary signal using the short-term time-frequency Rényi entropy. *EURASIP J. Adv. Signal Process*, 125. doi: 10.1186/1687-6180-2011-125

Peng. D., Smith. W.A., Randall R.B., Peng. Z., Mechefske C.K., (2021). Speed estimation in planetary gearboxes: A method for reducing impulsive noise. *Mechanical Systems and Signal Processing*, 159. doi: 10.1016/j.ymssp.2021.107786

Antoni. J., Griffaton. J., André. H., Avendaño-Valencia. L.D., Bonnardot. F., Cardona-Morales. O., Castellanos-Dominguez. G., Daga. A.P., Leclère. Q., Vicuña. C.M., Acuña D.Q., Ompusunggu A.P., and Sierra-Alonso. E.F., (2017). Feedback on the Surveillance 8 challenge: Vibration-based diagnosis of a Safran aircraft engine. *Mechanical Systems and Signal Processing*, 97, 112-144. doi: 10.1016/j.ymssp.2017.01.037

BIOGRAPHIES

Jinoh Yoo received the B.S. degree in mechanical engineering from Yonsei University, Seoul, Republic of Korea, in 2021. He is currently pursuing the Ph.D. degree in the Department of Mechanical Engineering at Seoul National University, Seoul, Republic of Korea. His current research interests include prognostics and health management for gearboxes and industrial robots using signal processing and deep learning. He received awards including 1st place in 2022 PHM Society Data Challenge Competiton and 2nd place in 2023 IEEE International Conference on Prognostics and Health Management.

Jongmin Park received the B.S. degree from Seoul National University, Seoul, South Korea, in 2017, where he is currently pursuing the Ph.D. degree in the Department of Mechanical Engineering at Seoul National University. His current research interests include prognostics and health management for rolling element bearings and gas insulated switchgear. He received awards including the PHM Asia Pacific Data Challenge Winner, in 2017 and 2019, and 1st place in 2022 PHM Society Data Challenge Competiton.

Taehyung Kim received the B.S. degree from Seoul National University, Seoul, Republic of Korea, in 2021. He is currently pursuing the Ph.D. degree in the Department of Mechanical Engineering at Seoul National University, Seoul, Republic of Korea. His current research interests include prognostics and health management for gearboxes and industrial robots using vibration signal. He received a 2nd place award in 2023 IEEE International Conference on Prognostics and Health Management.

Jong Moon Ha received the Ph.D. degree from Seoul National University, Seoul, South Korea, in 2017. He is currently a Senior Research Scientist with the Korea Research Institute of Standards and Science (KRISS), Daejoen, South Korea. His research interest includes prognostics and health management for rotating systems. He received three international competition awards including the IEEE PHM Data Challenge Competition Winner, in 2014, and the PHM Society Data Challage Competition Winner, in 2015 and 2019.

Byeng D. Youn is the Full Professor of Mechanical Engineering at Seoul National University (SNU) and the founder and CEO of OnePredict, Inc. (onepredict.com). Prof. Youn received the B.S. degree in mechanical engineering from Inha University, Incheon, South Korea, in 1996, the M.S. degree in mechanical engineering from Korea Advanced Institute of Science & Technology, Daejeon, South Korea, in 1998, and the Ph.D. degree in mechanical engineering from the University of Iowa, Iowa City, IA, USA, in 2001. His current research includes prognostics and health management (PHM), engineering design under uncertainty, and energy harvester design. His dedication and efforts in research have garnered substantive peer recognition, resulting in many notable awards including the Commendation of Prime Minister (2019), the Shin Yang Academic Award from Seoul National University (2017), the IEEE PHM Competition Winner (2014), the PHM Society Data Challenge Winners (2014, 2015, 2017, 2019), the Best Paper Award of ICMR2019 (2019), the PHMAP 2019 PHM Data Challenge Competition 3rd Place Winners (2019), the Front Cover and Featured Article of Journal of Applied Physics (2020), the Industrial AI Hackathon Factory Hack Korea 2021 Winners (2020), among others.