Kinetik: Game Technology, Information System, Computer Network, Computing, Electronics, and Control
Journal homepage: http://kinetik.umm.ac.id
ISSN: 2503-2267
Vol. 7, No. 2, May, Pp. 129-136

Hybrid frequency and period-based for angular speed measurement of DC motor using kalman filter

Novendra Setyawan*[1], Basri Noor Cahyadi[2], Ermanu Azizul Hakim[3], Mas Nurul Achmadiah[4]
Departement of Electrical Engineering, University of Muhammadiyah Malang, Indonesia[1,2,3]
Departement of Electrical Engineering, State Polytechnic of Malang, Indonesia[4]

Article Info
Keywords:
Permanent Magnet DC Motor, Period-Based, Frequency-Based, Rotary Encoder, Kalman Filter

Article history:
Received: March 17, 2022
Accepted: April 18, 2022
Published: May 31, 2022

Cite:
N. Setyawan, B. N. Cahyadi, E. A. Hakim, and M. N. Achmadiah, “Hybrid Frequency and Period Based for Angular Speed Measurement of DC Motor Using Kalman Filter ”, KINETIK, vol. 7, no. 2, May. 2022. https://doi.org/10.22219/kinetik.v7i2.1420

*Corresponding author.
Novendra Setyawan
E-mail address:
novendra@setyawan.ac.id

Abstract
The Incremental Rotary Encoder has been widely used to measure the angular speed of electrical drives such as Permanent Magnet Direct Current Motor (PMDCM). Nevertheless, speed measurement of PMDCM from the encoder signals can be subject to errors in some special conditions, such as in a low-resolution encoder. There are two main methods to measure the angular speed of PMDCM through encoder signal, such as frequency-based and period-based, which has their properties. Hence, this research aimed to improve the angular speed measurement with frequency and period-based measurement hybridization. The Hybrid Method is defined as paralleling the period and frequency and then estimating the angular speed using sensor fusion with Kalman Filter. The experiment is done by comparing all Methods to get the best way to measure. The experiment showed that the Kalman filter parameter was fine-tuned resulting from the sensor fusion or the mixed measurement between the frequency-based and the period-based measure of the angular speed accurately.

1. Introduction

Permanent magnet DC motors (PMDCM) has been used in many application such as automotive, computer zapplication, robotic [1][2][3][[4], and industrial application [5][6][7][8][6][9]. Its advantages over other conventional motors are better speed and torque characteristics, better dynamic response, high efficiency, no need for excitation current, no noise operation, high weight to torque ratio, and relatively low cost [10]. The main problem in PMDCM is to measure and control the speed; here, improvements in speed control are much needed. Hence, most research discusses the PMDCM speed control and measurement.

Incremental encoders are widely used in PMDCM for commercial drive because their cost is meager due to their precise position and speed measurement[11][12]. Speed error measurement results from encoder imperfections or the mistaken use of the calculation from the signal output. The defective encoder is usually caused by manufacturing tolerance and can’t be avoided or caused by imperfect installation. Speed is generally calculated from the encoder output signal as the ratio of angular rotation over time. There are two kinds of quantities keeping constant in speed measuring, period measurement or Fixed Space (FS) and frequency measurement, also called fixed time (FT), which has its own characteristic.

Obtaining speed is a task with many independent variable factors affecting the range of states and can result in significant errors if not appropriately executed [13]. In low price encoder mostly have low pulse per revolution (PPR), such as magnetic encoder, which has five to 7 PPR. According to [13], for an encoder with low PPR, the period measurement method speed error will be increased during the increase of motor speed. In contrast, for the frequency-based measurement, the most significant error will occur at the lowest motor speed. Many different methods are proposed to increase the accuracy and precision of speed measurement. The simple way is to implement a sort of like filter such as the conventional low past filter [12][14]. The drawback of using the traditional filter is the depletion of dynamic response due to the measurement delay caused by the derivative in the filter operation.

Other ways with the state estimation are proposed by using Kalman Filter to estimate the angular speed [15]–[22]. The estimation is used with another state in the PMDCM model, such as the current and the input voltage. Such that results from the sensorless measurement. However, the drawback of state estimation using the mathematical model is the accuracy of the system identification to create the model. A high-speed error can occur if the parameter of the model is not correctly tuned. Hence this paper proposed another approach to enhance the precision and accuracy of the PMDCM speed measurement using the hybridization of frequency and period based on the Kalman Filter sensor fusion method.

2. Research Method

The first step to improve the accuracy of speed measurement is to observe the encoder speed measurement methods where there are two methods to measure the PMDCM using the encoder, such as period measurement or fix space (FS) and frequency measurement or fix time (FT) with its own characteristic. Hence this research proposed two different methods based on both Methods.

2.1 Rotary Encoder Period and Frequency-based Speed Measurement

The Simplest Method to measure the PMDCM rotor speed is using a frequency base [23]. The frequency-based measurement method measures the frequency or pulse number of the encoder in a fixed period of time. This frequency pulse is proportional to the PMDCM rotor angular speed.

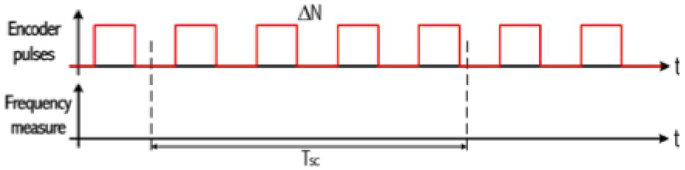

Figure 1. Frequency Base Measurement[13]

The frequency number is measured by counting the number of encoder pulses (ΔN) in a fixed gate time (T_s), which illustrated in Figure 1 with the angular speed (ω) is given in Equation 1.

$$\omega_f = \frac{2\pi\Delta N}{N_p T_s} \tag{1}$$

Where N_p is the number of pulses per rotation (PPR) of the encoder shaft. The measuring error of frequency-based is described in Equation 2 below:

$$e_w = \frac{2\pi}{\omega N_p T_s}[\%] \tag{2}$$

From the error equation, the error measurement will be unacceptable at low speed and decrease inversely with speed.

The period-base measures the period of the encoder pulses using a time-based signal with a period T_{hf}. It is necessary to measure the changing of pulse between low and high signals to count the time-based signal using a digital timer counter [24] which illustrated in Figure 2,

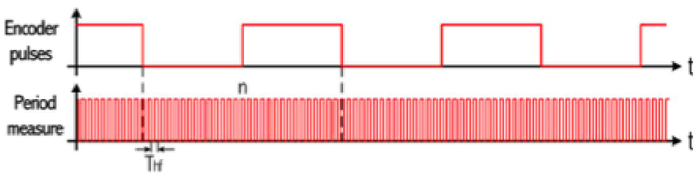

Figure 2. Period-based Measurement[13]

The angular speed of period-based measurement is given in Equation 3.

$$\omega_p = \frac{2\pi}{N_p n T_{hf}} \tag{3}$$

Where n is the number of pulses of the time-based signal. The measuring error of period-based measurement is described in Equation 4 below.

$$e_\omega = \frac{\omega N_p T_{hf}}{2\pi}[\%] \tag{4}$$

Where ω is the angular speed in rad/s, N_p is the amount of pulse per rotation of the encoder, T_s is the sampling period for the frequency base method, and T_{hf} is the max period or the high frequency generated for the period-based measurement; from this equation, the measuring error is proportionally increased due to the speed increasing.

Most electrical drive in an industrial application has a feature with a nominal speed of up to 7000 rpm and an encoder with up to 1024 ppr (pulse per rotation). According to [13], if the period-based and frequency-based are compared, the period-based speed error will be increased along with speed, but the frequency-based is exponentially decreased during the increase of motor speed, as can be seen in Figure 3. Hence this research proposed the hybrid method of measuring the motor speed using period-based and frequency-based.

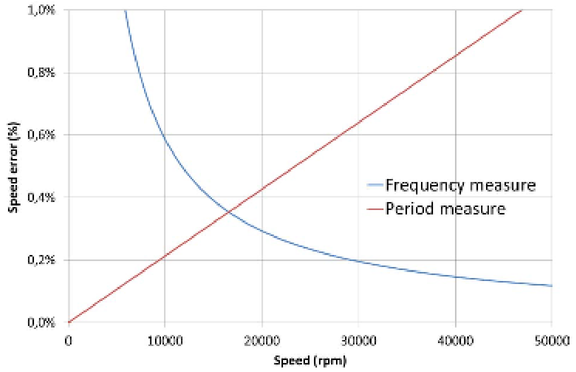

Figure 3. Frequency and Period Base Speed Measurement Comparison

The hybrid method is defined as the switch method between period and frequency-based. Based on the characteristic that showed in Figure 3 the period-based measurement will run first after, in a number speed, the algorithm will be changed to a frequency-based Method. In this research, the speed limit to change between the period base and frequency-based is experimentally chosen.

2.2 Mixed-Method between period and frequency-based

The mixed-method is defined with both method, period, and frequency-based will be running separately and continuously. The measurement value will be approximated using the Kalman filter, which will combine the measurement value between both Methods. The diagram of the mixed method is shown in Figure 4.

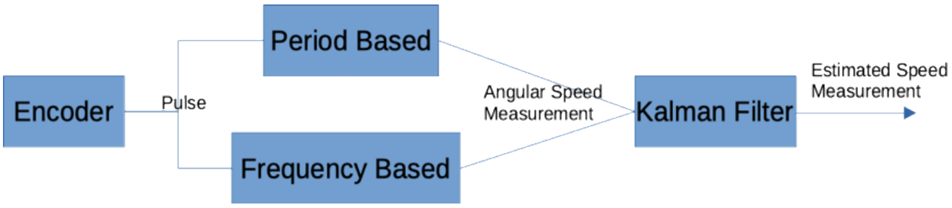

Figure 4. Mixed Method Diagram

The Kalman filter process is defined into three steps, which are predicted, measured, and update. The whole process of the Kalman filter is described in this step:

Predict:

In predict step Equation 5, the physical system that will be measured is defined with ω as the state variable in which the angular speed of PMD that measured using the frequency-based method described in (1).

$$\omega = \frac{2\pi\Delta N}{N_p T_s}$$
$$P = P * T * Q \tag{5}$$

Measurement:

In the measurement step, the new value of the measured variable is obtained with denoted as ω_p. Then, it will be compared with the state estimation, which results from the predicted step that results in error estimation, in Equation 6 which is denoted as Y.

$$Y = \omega_p - H * \omega \quad (6)$$

After estimating the error measurement, the Kalman parameter is updated using the Equation 7 below.

$$K = \frac{P * HT}{(H * P * HT) + R} \quad (7)$$

Update,

Finally, in Equation 8 the speed measurement is obtained by updating the state using error estimation and the Kalman parameter.

$$\begin{aligned} \omega &= \omega + K * Y \\ P &= (I - K * H) * P \end{aligned} \quad (8)$$

Where H is the identity matrix that is given according to the number of state variables and Q is the measurement bias.

3. Results and Discussion

3.1 Frequency-Based vs. Period-Based Measurement

This research is done by experimenting with both methods in a 32-bit microcontroller with a DC motor and a magnetic encoder attached. The PG45 DC motor had a max angular speed of 9600 rpm or 1005 rad/S in 24 Volt. The PG45 DC motor is attached with a seven pulse per rotation (PPR) magnetic encoder. This experiment runs with a maximum of 12 volts with the angular speed reaching 450 rad/s to test the method.

As mentioned in [25], the error measurement estimation of frequency-based and period-based can be calculated by comparing the $\frac{\Delta\omega}{\omega}$ which showed in (2) and (4). The first experiment tested the error measurement between both methods. Using the PG45 properties with seven ppr of the encoder and the maximum voltage is 12 volt, the error measurement comparison between the frequency-based and period-based showed in Figure 5.

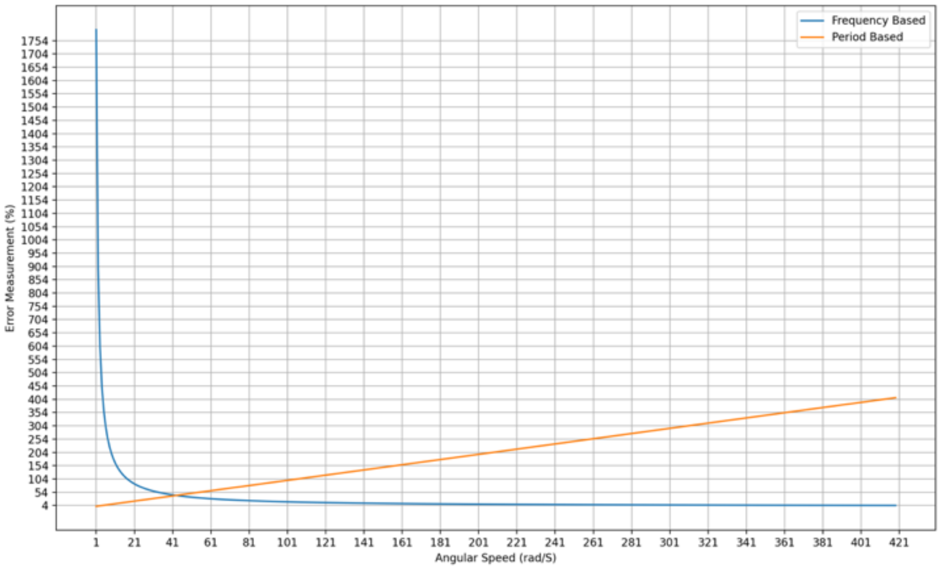

Figure 5. Error Measurement Comparison between Frequency-Based and Period-Based Method

As depicted in Figure 5, the error measurement of the frequency-based measurement method is exponentially decreased as the angular speed is increased. In opposite, the error measurement of the period-based measurement method is linearly increased. The period-based method did the measurement of the angular speed accurately when the angular speed was under 40 rad/s, and the frequency-based was the opposite. It proofed in Figure 6 and Figure 7, the frequency-based method had the error measurement from 5 rad/s to 10 rad/s when the angular speed is under 40 rad/s. The period-based measurement had a two rad/s error difference when the angular speed was under 30 rad/s and increased until five rad/s when the angular speed reached 40 rad/s.

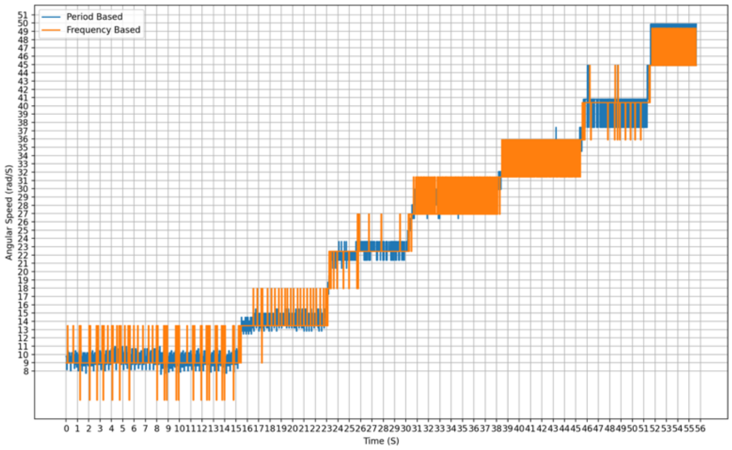

Figure 6. Angular Speed Comparison between Frequency and Period-Based Measurement Method from 9 – 45 rad/s

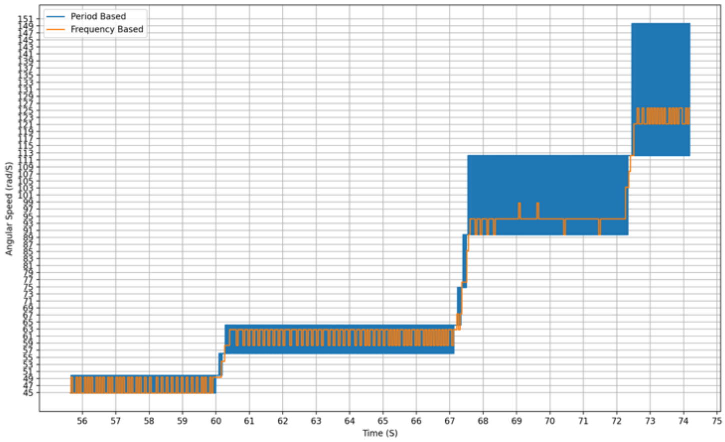

Figure 7. Angular Speed Comparison between Frequency and Period-Based Measurement Method from 45 – 121 rad/s

Figure 7 showed that the period-based measurement oscillated with an amplitude of 20 rad/s when the angular speed was upper than 50 rad/s, and the oscillation was increased until 50 rad/s when the angular speed was over 100 rad/s. The worst is resulting in the angular speed being over 200 rad/s the period-based measurement that the oscillation saturated from 220 rad/s to 440 rad/s so that can not measure and following the increased of the angular speed such as the frequency-based that showed in Figure 8. The frequency-based was accurately measured the angular speed with five rad/s error constantly even though the angular speed is increased until it reaches the maximum.

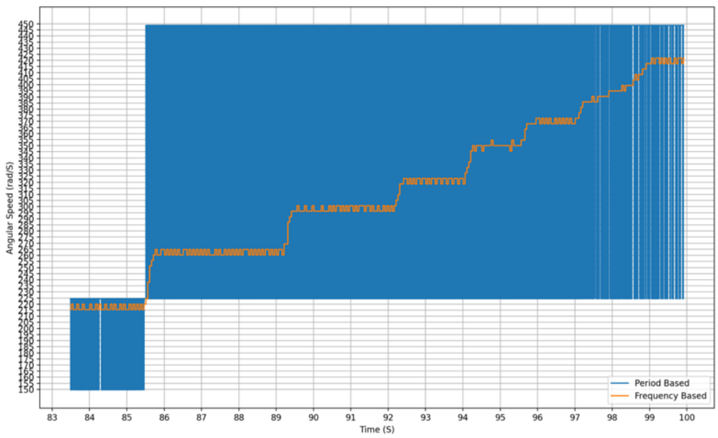

Figure 8. Angular Speed Comparison between Frequency and Period-Based Measurement Method from 215 – 415 rad/s

3.2 Mixed Using Kalman Filter

In Kalman Filter, there was the input of the model to predict the output measurement and compare it using the actual measurement. In this research, the input of the predicting model is using the result of the period-based measurement method and comparing it using the frequency-based method. The first test was compared three methods with angular speeds from 100 rad/s to 200 rad/s. In this test, the parameter of the Kalman Filter was chosen randomly, i.e., $Q = \begin{bmatrix} 0.0001 & 0 \\ 0 & 0.0001 \end{bmatrix}$ and $R = 0.0001$. The reason the R parameter was chosen in small value was to reduce the measurement noise, and the Q parameter was chosen to control the biased from the difference between the period and frequency-based methods. The measurement result is depicted in Figure 9.

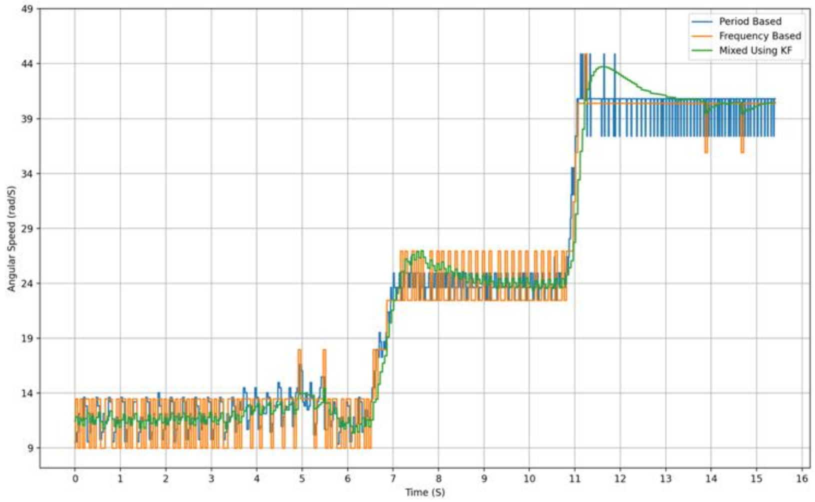

Figure 9. The Comparison between Frequency-Based, Period-Based, and Mixed using Kalman Filter from 10 rad/s to 40 rad/s

Figure 9 shows the comparison between Frequency-based, Period-based, and Mixed using Kalman Filter from 10 rad/s to 40 rad/s. It showed that the mixed method using Kalman Filter could reduce 10% amplitude of the oscillation from the frequency-based method, similarly to the period-based. However, there was a drawback from the mixed-method that resulted in a 10% overshoot. It is still acceptable because it only happens in 2 seconds.

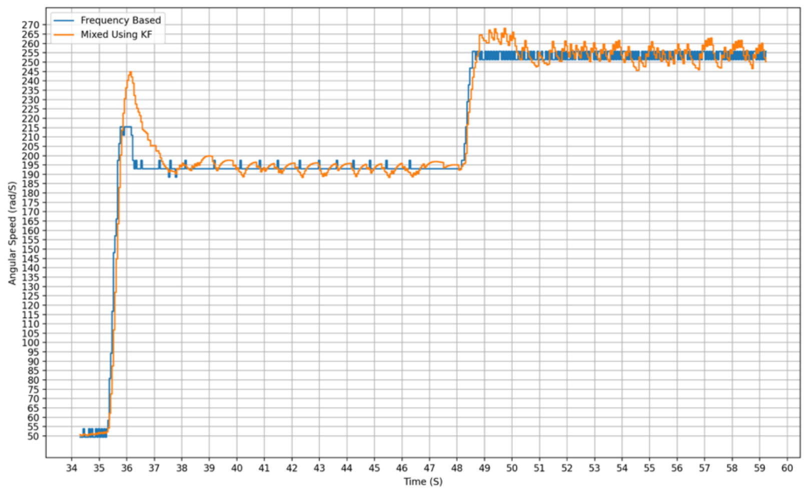

Figure 10. The Comparison between Frequency-Based and Mixed using Kalman Filter from 50 rad/s to 250 rad/s

Figure 10 depicted the comparison between Frequency-based and Mixed using Kalman Filter from 50 rad/s to 250 rad/s. The overshoot of the mixed method using the Kalman filter was increased since the measured angular speed was increased too. The overshoot reached 25%, and the oscillation in the steady-state was increased by 5% to the low angular speed. From that experiment, the parameter of the Kalman Filter was tuned again, and the Q and R parameters were increased ten times which can be shown in Table 1.

Table 1. Paraemeter Setting of Kalman Filter

Parameter	Value 1	Value 2
Q	$\begin{bmatrix} 0.0001 & 0 \\ 0 & 0.0001 \end{bmatrix}$	$\begin{bmatrix} 0.001 & 0 \\ 0 & 0.001 \end{bmatrix}$
R	0.00001	0.0001

Figure 11 and Figure 12 showed the comparison between Frequency-based and Mixed using Kalman Filter from 10 rad/s to 110 rad/s and 210 rad/s to 350 rad/s. It showed that the steady-state still oscillated but reduced by 1%, and the overshoot in low angular speed was reduced to 8.9%. At high angular speed, the overshoot is maintained from 8% to 9%, and the steady-state was still oscillated but not over than the frequency-based method, which has high accuracy when the angular speed is high. It can be shown in Figure 12. It shows that if the Kalman filter parameter was fine-tuned, the sensor fusion or the mixed measurement between the frequency-based and the period-based could measure the angular speed accurately compared to the single frequency-based method.

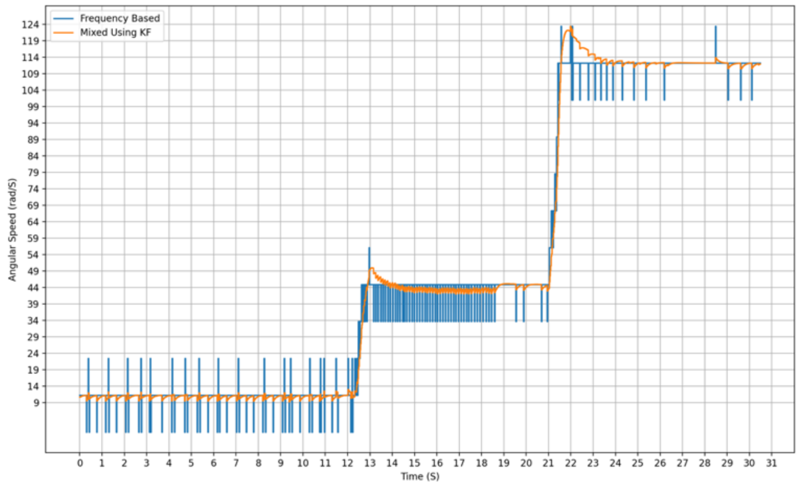

Figure 11. The comparison between Frequency-Based and Mixed using Kalman Filter from 10 rad/s to 110 rad/s with Parameter Setting 2

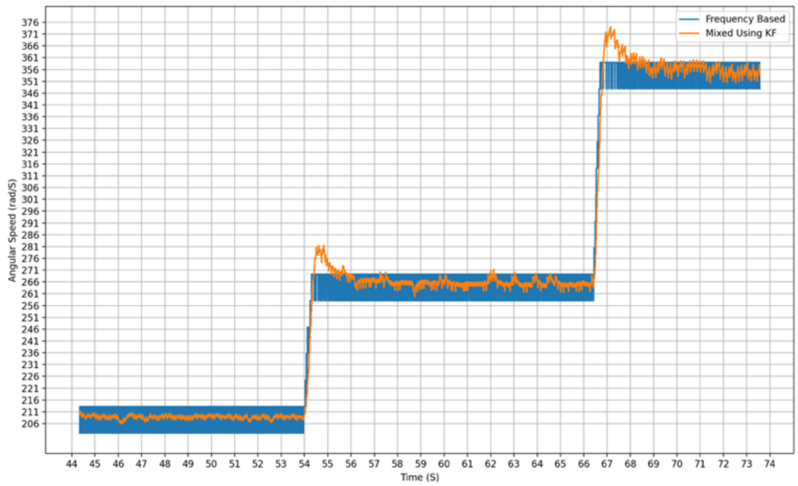

Figure 12. The Comparison between Frequency-Based and Mixed using Kalman Filter from 210 rad/s to 350 rad/s with Parameter Setting 2

4. Conclusion

This research implemented the sensor fusion method between frequency-based and period-based measurement successfully. The proposed method can increase the measurement accuracy by reducing the error measurement and steady-state oscillation. Even though there was an overshoot in two seconds but still acceptable since the overshoot is under 10%.

The experiment showed that if the Kalman filter parameter was fine-tuned, the sensor fusion or the mixed measurement between the frequency-based and the period-based measure the angular speed accurately. However, it was done by processing both methods, which can increase the processing computation that can be investigated further. It also can be developed using a model-based Kalman filter, which only uses a single measurement method.

Acknowledgment

This research is supported by Direktorat Penelitian dan Pengabdian Masyarakat (DPPM) of Universitas Muhammadiyah Malang through Engineering Faculty Internal Research Grant. The authors are grateful for supporting the present work.

References

[1] E. Engineering, I. Teknologi, and S. Nopember, "Adaptive Gaussian Parameter Particle Swarm Optimization And Its Implementation in Mobile Robot Path Planning," pp. 238–243, 2017. https://doi.org/10.1109/ISITIA.2017.8124087

[2] N. A. Mardhiyah and N. Setyawan, "Pengenalan Posisi Multi Objek Menggunakan Neural Network dan Scan Lines Pada Robot Sepak Bola," in *Prosiding SENTRA (Seminar Teknologi dan Rekayasa)*, 2019, no. 5, pp. 58–64. https://doi.org/10.22219/sentra.v0i4.2311

[3] N. Setyawan, N. A. Mardiyah, and K. Hidayat, "Deteksi Dan Prediksi Trajektori Objek Bergerak Dengan Omni-Vision Menggunakan PSO-NN dan Interpolasi Polynomial," *Multitek Indones.*, vol. 13, no. 1, pp. 66–80, 2019. http://dx.doi.org/10.24269/mtkind.v13i1.1691

[4] N. Setyawan, N. Mardiyah, K. Hidayat, and Z. Has, "Object detection of omnidirectional vision using PSO-neural network for soccer robot," in *2018 5th International Conference on Electrical Engineering, Computer Science and Informatics (EECSI)*, 2018, pp. 117–121. https://doi.org/10.1109/EECSI.2018.8752833

[5] D. Somwanshi, M. Bundele, G. Kumar, and G. Parashar, "Comparison of fuzzy-PID and PID controller for speed control of DC motor using LabVIEW," *Procedia Comput. Sci.*, vol. 152, pp. 252–260, 2019. https://doi.org/10.1016/j.procs.2019.05.019

[6] E. H. Putra, Z. Has, and M. Effendy, "Robust Adaptive Sliding Mode Control Design with Genetic Algorithm for Brushless DC Motor," *Proceeding Electr. Eng. Comput. Sci. Informatics*, vol. 5, no. 5, pp. 330–335, 2018. https://doi.org/10.1109/EECSI.2018.8752768

[7] N. Setyawan, N. A. Mardiyah, M. N. Achmadiah, R. Effendi, and A. Jazidie, "Active fault tolerant control for missing measurement problem in a Quarter car model with linear matrix inequality approach," *2017 Int. Electron. Symp. Eng. Technol. Appl.*, no. 1, pp. 207–211, 2017. https://doi.org/10.1109/ELECSYM.2017.8240404

[8] Z. Zulfatman and M. F. Rahmat, "Application of self-tuning fuzzy PID controller on industrial hydraulic actuator using system identification approach," *Int. J. Smart Sens. Intell. Syst.*, vol. 2, no. 2, pp. 246–261, 2009. https://doi.org/10.21307/ijssis-2017-349

[9] G. W. Kurniawan, N. Setyawan, and E. A. Hakim, "PID Trajectory Tracking Control 4 Omni-Wheel Robot," SinarFe7, vol. 2, no. 1, pp. 345–350, 2019.

[10] Z. Tir, O. Malik, M. A. Hamida, H. Cherif, Y. Bekakra, and A. Kadrine, "Implementation of a fuzzy logic speed controller for a permanent magnet dc motor using a low-cost Arduino platform," *2017 5th Int. Conf. Electr. Eng. - Boumerdes, ICEE-B 2017*, vol. 2017-Janua, pp. 1–4, 2017. https://doi.org/10.1109/ICEE-B.2017.8192218

[11] M. Zhao and J. Lin, "Health assessment of rotating machinery using a rotary encoder," *IEEE Trans. Ind. Electron.*, vol. 65, no. 3, pp. 2548–2556, 2017. https://doi.org/10.1109/TIE.2017.2739689

[12] A. F. Ilmiawan, D. Wijanarko, A. H. Arofat, H. Hindersyah, and A. Purwadi, "An easy speed measurement for incremental rotary encoder using multi stage moving average method," in *2014 International Conference on Electrical Engineering and Computer Science (ICEECS)*, 2014, pp. 363–368. https://doi.org/10.1109/ICEECS.2014.7045279

[13] F. Brugnano, C. Concari, E. Imamovic, F. Savi, A. Toscani, and R. Zanichelli, "A simple and accurate algorithm for speed measurement in electric drives using incremental encoder," *Proc. IECON 2017 - 43rd Annu. Conf. IEEE Ind. Electron. Soc.*, vol. 2017-Janua, pp. 8551–8556, 2017. https://doi.org/10.1109/IECON.2017.8217502

[14] A. C. Negrea, M. Imecs, I. Iov Incze, A. Pop, and C. Szabo, "Error compensation methods in speed identification using incremental encoder," in *2012 international conference and exposition on electrical and power engineering*, 2012, pp. 441–445. https://doi.org/10.1109/ICEPE.2012.6463857

[15] G. G. Rigatos, "Particle and Kalman filtering for state estimation and control of DC motors," *ISA Trans.*, vol. 48, no. 1, pp. 62–72, 2009. https://doi.org/10.1016/j.isatra.2008.10.005

[16] S. Praesomboon, S. Athaphaisal, S. Yimman, R. Boontawan, and K. Dejhan, "Sensorless speed control of DC servo motor using Kalman filter," in *2009 7th International Conference on Information, Communications and Signal Processing (ICICS)*, 2009, pp. 1–5. https://doi.org/10.1109/ICICS.2009.5397682

[17] V. Aishwarya and B. Jayanand, "Estimation and control of sensorless brushless dc motor drive using extended kalman filter," in *2016 International Conference on Circuit, Power and Computing Technologies (ICCPCT)*, 2016, pp. 1–7. https://doi.org/10.1109/ICCPCT.2016.7530343

[18] K. S. Gaeid, "Optimal gain Kalman filter design with Dc motor speed controlled parameters," J. Asian Sci. Res., vol. 3, no. 12, pp. 1157–1172, 2013.

[19] D. Lenine, B. R. Reddy, and S. V. Kumar, "Estimation of speed and rotor position of BLDC motor using extended Kalman filter," 2007.

[20] A. Khalid and A. Nawaz, "Sensor less control of DC motor using Kalman filter for low cost CNC machine," in *2014 International Conference on Robotics and Emerging Allied Technologies in Engineering (iCREATE)*, 2014, pp. 180–185. https://doi.org/10.1109/iCREATE.2014.6828362

[21] Z. Aydogmus and O. Aydogmus, "A comparison of artificial neural network and extended Kalman filter based sensorless speed estimation," *Measurement*, vol. 63, pp. 152–158, 2015. https://doi.org/10.1016/j.measurement.2014.12.010

[22] P. Deshpande and A. Deshpande, "Inferential control of DC motor using Kalman Filter," in *2012 2nd International Conference on Power, Control and Embedded Systems*, 2012, pp. 1–5. https://doi.org/10.1109/ICPCES.2012.6508056

[23] N. Hagiwara, Y. Suzuki, and H. Murase, "A method of improving the resolution and accuracy of rotary encoders using a code compensation technique," *IEEE Trans. Instrum. Meas.*, vol. 41, no. 1, pp. 98–101, 1992. https://doi.org/10.1109/19.126640

[24] D. Zheng, S. Zhang, S. Wang, C. Hu, and X. Zhao, "A capacitive rotary encoder based on quadrature modulation and demodulation," *IEEE Trans. Instrum. Meas.*, vol. 64, no. 1, pp. 143–153, 2014. https://doi.org/10.1109/TIM.2014.2328456

[25] R. Petrella, M. Tursini, L. Peretti, and M. Zigliotto, "Speed measurement algorithms for low-resolution incremental encoder equipped drives: A comparative analysis," *Int. Aegean Conf. Electr. Mach. Power Electron. Electromotion ACEMP'07 Electromotion'07 Jt. Conf.*, pp. 780–787, 2007. https://doi.org/10.1109/ACEMP.2007.4510607