Self-Powered Multi-Parameter Wireless Sensing for Condition Monitoring of Marine Propulsion Shafts

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ABSTRACT

Self-powered multi-parameter wireless sensing enables autonomous condition monitoring of rotating marine machinery, where wired power delivery and frequent maintenance are impractical. This paper presents a self-powered wireless sensor system (SP-WSS) that integrates a compact electromagnetic energy harvester (EH) with sensors for shaft speed, torsional strain/vibration, temperature, and power monitoring. The system was installed on a 300 mm training-ship propulsion shaft and evaluated for 7.2 h under real operating conditions. The harvester delivered an average power of 487.87 mW, exceeding the system demand of 374 mW by 30.4%, and maintained wireless data acquisition during the investigated period. The measured torsional responses captured operational shaft behavior and provided fatigue-relevant loading histories. These results confirm the feasibility of the proposed SP-WSS as a practical sensing platform for prognostics and health management (PHM) applications in marine propulsion systems.

1. INTRODUCTION

PHM aims to improve system safety, reliability, and maintenance efficiency by enabling continuous condition awareness, early fault detection, and predictive maintenance (Vachtsevanos et al., 2006). For rotating marine machinery, PHM requires reliable sensing platforms capable of acquiring operational and mechanical loading data under harsh shipboard conditions. In marine propulsion systems, the propulsion shaft transfers power from the main engine or electric motor to the propeller and is exposed to cyclic torsional loading, vibration, misalignment, fluctuating speed, humidity, temperature variation, and salt exposure. These conditions may lead to bearing wear, mechanical degradation, and torsional fatigue if not monitored effectively (Askari & Hossain, 2022; Jovanović et al., 2024; Vizentin et al., 2020).

Various sensing technologies have been investigated for rotating shaft monitoring, including fiber Bragg grating sensors, electrostatic sensing methods, and magnetostrictive sensors for measuring vibration, strain, and torsional deformation (Reda & Yan, 2019; Lee et al., 2018). However, conventional monitoring systems often rely on wired communication and external power supply, which introduce practical difficulties such as cable routing, slip rings, mechanical wear, and increased maintenance requirements. Wireless sensor systems (WSSs) can reduce these limitations by enabling flexible deployment on rotating components, but battery-powered nodes have limited lifetime and require periodic replacement, which is impractical for long-term propulsion shaft monitoring (Rifan & Pitao, 2021; Wang, 2021).

To address this issue, wireless power transfer (WPT) and energy harvesting (EH) technologies have been studied for battery-free or self-powered sensing systems. WPT methods can transmit power without physical contact, but they generally require external power sources and may involve bulky or mechanically complex structures (Jia & Yan, 2020; Jinliang & Xiaoqiang, 2021; Raminosoa, Wiles, & Wilkins, 2020; Perrin et al., 2020). EH provides an alternative by converting ambient mechanical energy into electrical power. Piezoelectric, triboelectric, and electromagnetic harvesters have been proposed for rotating machinery applications (Fu et al., 2021; Zhang et al., 2023; Grzybek & Micek, 2019; Nezami & Lee, 2019; Zou et al., 2017; Gunn et al., 2021). However, many reported systems have been validated mainly under laboratory conditions, and their output power or system-level integration may be insufficient for continuous multi-parameter wireless monitoring under real ship operating conditions.

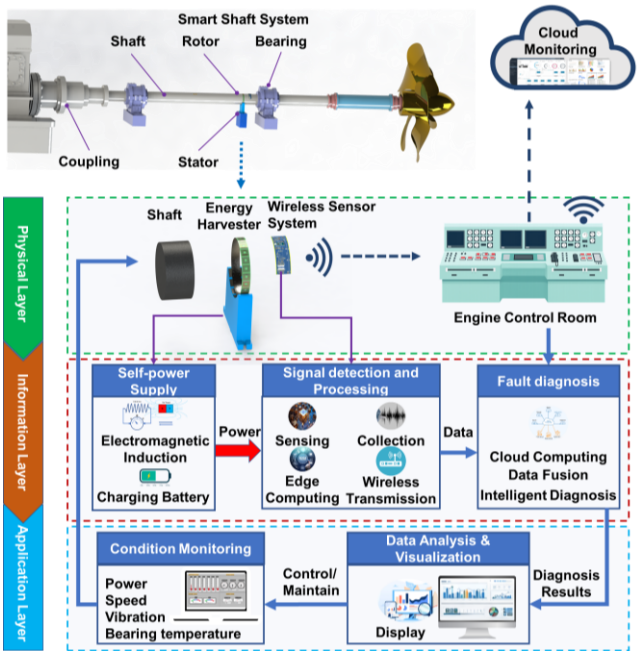
Practical PHM-oriented shaft monitoring also requires simultaneous measurement of multiple parameters. Shaft speed, strain/vibration, temperature, and power-related variables provide complementary information for operating-state identification, mechanical loading assessment, thermal condition monitoring, and self-diagnosis of the sensing platform. In contrast, many existing systems rely mainly on single-parameter measurements, which may not provide sufficient information for condition assessment and future

prognostic analysis. Therefore, an integrated self-powered sensing platform capable of multi-parameter monitoring under real ship operating conditions remains an important research need.

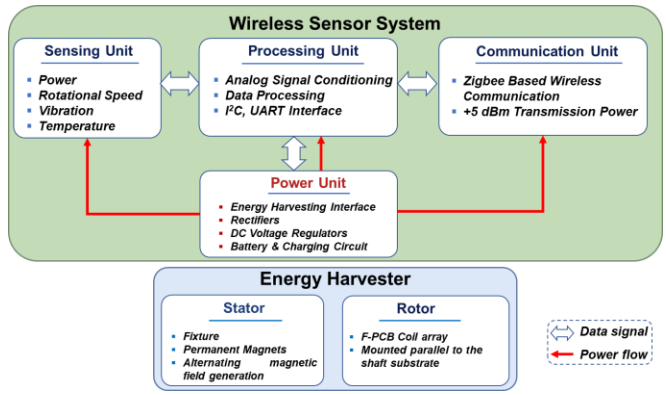
This paper presents a self-powered multi-parameter WSS for PHM-oriented condition monitoring of marine propulsion shafts. Compared with previous wireless sensing and EH studies for rotating shafts, the developed platform integrates energy harvesting, sensing, embedded processing, and wireless communication into a compact on-shaft module. It employs a thin stacked flexible printed circuit board (F-PCB) coil rotor suitable for installation on a 300 mm rotating shaft and is validated under actual shipboard operating conditions. The main contributions are: (i) development of a compact electromagnetic EH using stacked F-PCB coils for low-speed propulsion shafts; (ii) implementation of a self-powered multi-parameter WSS for rotational speed, temperature, strain/vibration, and power monitoring; and (iii) real-ship validation through a 7.2-hour deployment, including energy-balance evaluation, operating-regime separation, and fatigue-oriented cyclic-loading analysis. The results demonstrate the feasibility of the proposed platform as a practical basis for future fatigue-oriented PHM applications.

2. SYSTEM ARCHITECTURE

Figure 1 shows the PHM-oriented architecture of the proposed SP-WSS. The system integrates energy harvesting, multi-parameter sensing, embedded processing, and wireless communication in a compact on-shaft module for propulsion shaft health monitoring.



a)



b)

Figure 1. System architecture of the proposed SP-WSS: a) PHM-oriented layered architecture; b) block diagram of the SP-WSS installed on a ship propulsion shaft.

2.1. PHM-Oriented Layered Architecture

As shown in Figure 1(a), the architecture consists of physical, information, and application layers. The physical layer includes the propulsion shaft, EM EH, and sensors for shaft speed, strain/vibration, temperature, and power consumption. The information layer performs signal conditioning, data acquisition, embedded processing, power regulation, and wireless packet preparation.

At the application layer, wirelessly transmitted data are visualized, stored, and analyzed for PHM-oriented tasks. Shaft speed provides operating context; strain/vibration represents mechanical loading and fatigue-relevant response; temperature supports thermal and bearing-condition monitoring; and power-related variables enable self-diagnosis of the sensing platform. Together, these parameters support anomaly detection, baseline assessment, fatigue-cycle counting, cumulative damage tracking, and future remaining useful life prediction.

2.2. Physical Implementation of the SP-WSS

Figure 1(b) shows the physical implementation concept of the SP-WSS. The EM EH consists of stacked F-PCB coils mounted on the rotating shaft and permanent magnets fixed to the bearing housing. Relative motion between the coils and magnetic field induces electrical power through electromagnetic induction.

The WSS includes a power unit, sensing unit, processing unit, and communication unit. The power unit rectifies and regulates harvested energy, manages battery charging, and distributes power to the sensors, microcontroller, and wireless module. The battery serves as an energy buffer during low-speed or transient conditions.

For reproducibility, the shaft node measures strain, torque-related response, power, RPM, and the energy balance between the EH and WSS. Wireless communication is

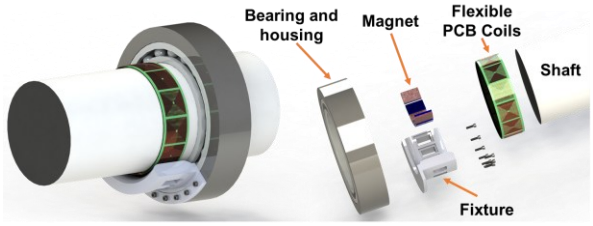
implemented using XBee modules for real-time data transmission from the rotating shaft to a stationary monitoring computer, where synchronized data are continuously recorded for post-processing.

2.3. System Operation Principle

During propulsion shaft rotation, the EM EH converts rotational mechanical energy into electrical power through electromagnetic induction. The generated energy is rectified and regulated by the power management unit to supply the sensing, processing, and wireless communication modules. The integrated sensors measure rotational speed, temperature, torsional strain/vibration, and system power consumption. These signals are conditioned, digitized, and organized by a low-power microcontroller before being wirelessly transmitted to an external monitoring system. The received data can then be visualized and analyzed to assess shaft operating conditions. By correlating multiple parameters, the proposed SP-WSS can support anomaly detection, fatigue-oriented loading analysis, cumulative damage tracking, and future remaining useful life prediction. Therefore, the system provides a self-powered sensing infrastructure for PHM-oriented propulsion shaft monitoring.

3. SELF-POWERED EH DESIGN

The EM EH employs stacked F-PCB coils integrated into a thin rotor structure for compact integration on low-speed marine propulsion shafts. The rotor, with a total thickness of 3 mm, is wrapped around the propulsion shaft. Permanent magnets mounted on a stator fixture integrated into the bearing housing generate alternating magnetic fields as the shaft rotates.



a) b)

Figure 2. Structural configuration of the proposed EM EH: (a) integrated configuration mounted on the propulsion shaft; and (b) exploded view of the rotor–stator assembly.

Each F-PCB sheet contains four laminated planar coil layers interconnected through vias. For the real-ship implementation, 18 coil bundles provide 1104 turns connected in parallel to increase induced voltage at low speed while reducing internal resistance. Compared with wire-wound coils, the F-PCB structure offers compactness, high turn density, manufacturability, and scalability for different shaft diameters.

4. TRAINING SHIP DEPLOYMENT AND TEST SETUP

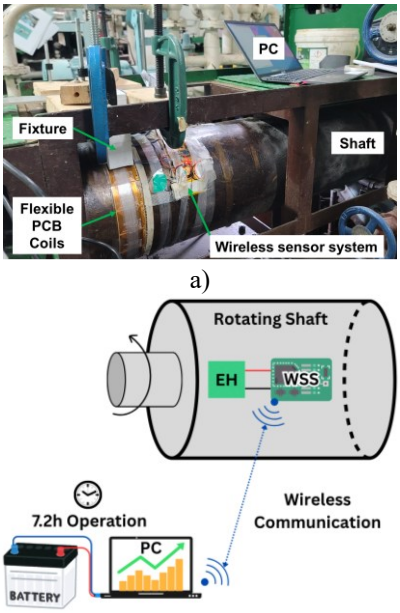


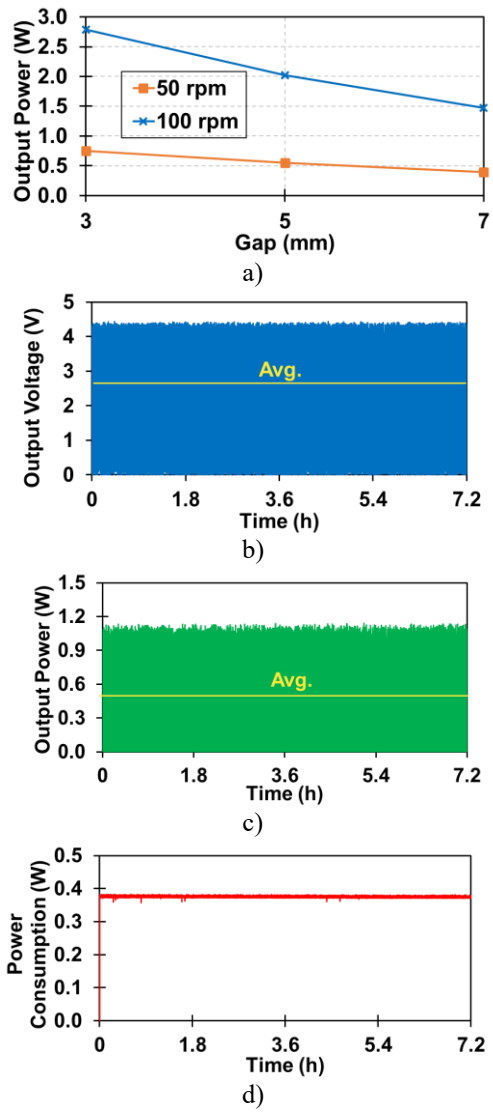
Figure 3. Real-ship deployment and experimental setup of the proposed SP-WSS: (a) installation of the EH and WSS on the propulsion shaft; and (b) wireless monitoring configuration.

Figure 3 shows the real-ship installation and measurement configuration. The EH rotor and wireless sensing module were mounted on a 300 mm diameter propulsion shaft of a training ship, while the magnet stator was integrated near the bearing housing with an approximate air gap of 5 mm to accommodate shaft runout. The sensor and energy data were transmitted from the rotating shaft module to a stationary computer using 2.4 GHz XBee modules. The wireless link had a nominal RF data rate of 250 kbps, and stable transmission was maintained at an approximate receiver distance of 5 m. The torsional strain/vibration signal was sampled at 1024 samples/s, while lower-bandwidth parameters were sampled at lower update rates. The experiment was conducted during normal ship operation for 7.2 h, with shaft speed varying from 0 to 120 rpm depending on operating mode. The test duration was mainly limited by the external battery powering the stationary receiver, not by the SP-WSS energy availability; therefore, the experiment is interpreted as a real-ship feasibility demonstration rather than full long-term PHM validation.

5. EXPERIMENTAL RESULTS

Figure 4 summarizes the 7.2-hour shipboard test. The EH output voltage ranged from 0 to 4.42 V, and the peak output power reached 1137.71 mW. In addition, the laboratory EH power test in Figure 4(a) shows that the harvested power increased with rotational speed and decreased with air-gap distance. At 50 rpm, the output power was 753.7, 547.3, and

397.4 mW for 3, 5, and 7 mm gaps, respectively. At 100 rpm, it increased to 2788.5, 2024.9, and 1470.4 mW, respectively. For the 5 mm gap used in the shipboard test, the EH generated 547.3 mW at 50 rpm and 2024.9 mW at 100 rpm, both exceeding the average SP-WSS power consumption of 374 mW. The average harvested voltage and power during the shipboard test were 2.69 V and 487.87 mW, respectively. Since the average SP-WSS power consumption was 374 mW, the system achieved a positive energy margin of 113.87 mW, corresponding to 30.4%. This confirms that harvested energy was sufficient to support sensing, embedded processing, and wireless communication during the investigated period. The shaft speed varied from 0 to 163 rpm, and the temperature remained stable at approximately 43 °C, indicating stable thermal behavior during the test.



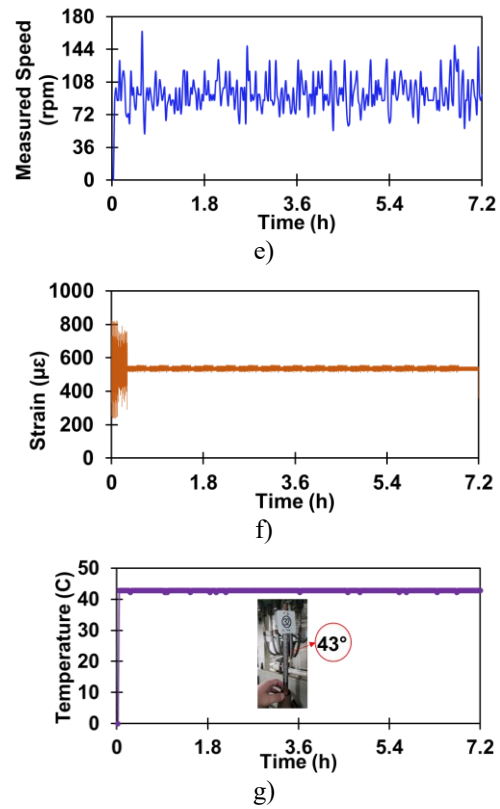


Figure 4. Experimental results obtained during the 7.2-hour real-ship deployment of the proposed SP-WSS: (a) EH output power from laboratory testing; (b) EH output voltage; (c) harvested output power; (d) SP-WSS power consumption; (e) propulsion shaft rotational speed; (f) measured torsional strain response; (g) propulsion shaft temperature.

The strain response was analyzed separately for startup/transient and steady-state windows to avoid mixing different operating regimes. During startup/transient operation, the shaft speed rapidly increased and the strain response ranged from 250.91 to +816.90 με at approximately 95.93 rpm, indicating a pronounced acceleration response. During steady-state operation, the strain ranged from 519.65 to +543.92 με at approximately 88.89 rpm, showing a much narrower range. This separation is important for PHM because transient data highlight event-related loading, whereas steady-state data are more suitable for baseline and trend analysis. Compared with previous systems, many reported studies focused mainly on laboratory validation, EH-only performance, WPT-based power supply, or single-parameter sensing. In contrast, the proposed SP-WSS integrates stacked F-PCB coil-based energy harvesting, multi-parameter sensing, embedded processing, and wireless transmission into a single on-shaft module. In addition, it was evaluated on a 300 mm propulsion shaft under real ship operating conditions and explicitly reports the wireless communication distance, energy balance, operating-regime separation, and fatigue-oriented cyclic-loading analysis.

Table 1. Comparison of reported EH/WSS systems for rotating shaft monitoring.

References	Power source / Max output power	Test speed range	Monitored parameters	Wireless link / receiver distance	Test bed
Lee et al. (2018)	Battery-less magnetostrictive sensing	N/R	Torsional vibration	Passive/non-powered sensing; distance N/R	Lab shaft and LPG carrier propulsion shaft
Zhang et al. (2022)	Variable-reluctance EM EH; 726 mW at 200 rpm	Low-speed rotation; 200 rpm reported	Vibration spectrum of rotating motor/stator	Wireless sensing demonstrated; distance N/R	Lab rotating machinery test bed
Zhang et al. (2023)	Variable-reluctance EM EH; 336.7–851.8 mW at 200–328 rpm	200–328 rpm	Acceleration / condition monitoring	Wi-Fi-based WSN; distance N/R	Lab rotating machinery test bed
Cao et al. (2017)	Triboelectric–electromagnetic hybrid generator; 13 mW at 250 rpm	250 rpm reported	Energy harvesting demonstration	N/A	Lab rotating energy harvesting test
This work	Stacked F-PCB EM EH; 2.79 W at 100 rpm in lab and 1.14 W peak / 487.87 mW average on ship	Lab: 25–100 rpm; ship: 0–163 rpm	Shaft speed, strain/vibration, temperature, EH power, WSS power consumption	XBee 2.4 GHz, 250 kbps, approximately 5 m	300 mm training-ship propulsion shaft

Therefore, the proposed platform provides a more practical basis for PHM-oriented propulsion shaft monitoring.

From a PHM perspective, the measured speed, strain/vibration, temperature, and power data provide complementary information for condition assessment, anomaly detection, and prognostic modeling. In addition, a low-speed segment near 45 rpm was selected for fatigue-oriented cyclic-loading analysis. The measured torsional strain was converted into stress using the calibrated strain–stress conversion coefficient, and the stress history was analyzed using mean-stress separation, rainflow cycle counting, Goodman correction, and Miner's linear damage rule, following Choi and Lee (2024).

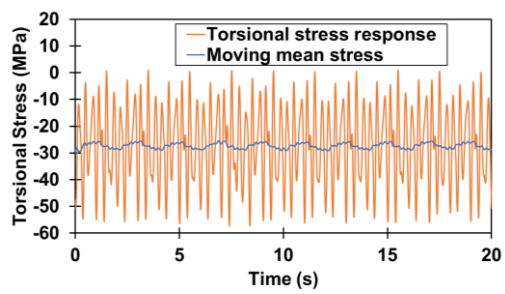
For the 45 rpm segment, the stress signal was separated into moving mean and alternating components. Cycle amplitudes and mean stresses were obtained from rainflow-counted extrema, corrected using the Goodman relation, and combined with the S–N curve to estimate the number of cycles to failure.

$$\tau_{AC}(t) = \tau(t) - \tau_{mean}(t) \quad (1)$$

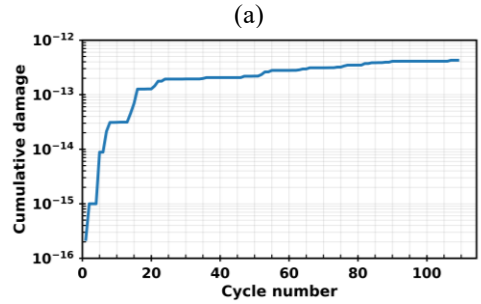
$$S_a = \frac{\tau_{max} - \tau_{min}}{2} \quad (2)$$

$$S_m = \frac{\tau_{max} + \tau_{min}}{2} \quad (3)$$

where: $\tau(t)$, $\tau_{mean}(t)$, $\tau_{AC}(t)$ denote the measured torsional stress, moving mean stress, and alternating torsional stress component, respectively. S_a is the alternating stress amplitude, τ_{max} and τ_{min} are the maximum and minimum stresses of each cycle.



(a)



(b)

Figure 5. Cyclic-loading analysis near 45 rpm: (a) estimated stress and moving mean stress; (b) cumulative damage evolution.

The rainflow results showed that most counted cycles were concentrated in the low-to-moderate stress-amplitude range. The mean alternating stress amplitude was approximately 11.58 MPa, while the maximum value reached 28.26 MPa, indicating that the measured torsional response was dominated by relatively low-amplitude cyclic loading with a limited number of higher-amplitude events.

$$S_{Nf} = \frac{S_a}{1 - \frac{S_m}{S_u}} \quad (4)$$

$$D = \sum_i \frac{n_i}{N_i} \quad (5)$$

where: S_u, S_{Nf}, n_i, N_i denote the ultimate tensile strength, equivalent fully reversed stress amplitude, number of counted cycles, and cycles to failure obtained from the S–N curve, respectively.

As shown in Figure 5(b), Miner's rule produced a stepwise cumulative damage trend, with a total estimated damage of 4.276706×10^{-13}. Although this value is extremely small under the assumed S–N curve, Goodman correction, and stress calibration conditions, the result demonstrates that the platform can provide stress histories suitable for fatigue-oriented PHM, cumulative damage tracking, and future remaining useful life prediction.

6. CONCLUSION

This paper presented a self-powered multi-parameter wireless sensor system (SP-WSS) for condition monitoring of marine propulsion shafts. The developed system integrates a stacked F-PCB coil-based electromagnetic energy harvester with an on-shaft wireless sensing module capable of measuring rotational speed, torsional strain/vibration, temperature, and power-related variables under real ship operating conditions. A 7.2-hour deployment on a 300 mm training-ship propulsion shaft demonstrated stable operation with a positive energy balance, where the average harvested power of 487.87 mW exceeded the average system power consumption of 374 mW. The measured data enabled the separation of startup/transient and steady-state operating regimes and captured fatigue-relevant torsional loading responses. In addition, a low-speed cyclic-loading analysis near 45 rpm yielded a mean alternating stress amplitude of 11.58 MPa, a maximum alternating stress amplitude of 28.26 MPa, and an estimated cumulative damage of 4.276706×10^{-13} under the assumed analysis conditions. The results demonstrate the feasibility of the proposed SP-WSS as a practical self-powered sensing platform for real-ship propulsion shaft monitoring and provide a foundation for future PHM-oriented studies. Future work will focus on longer-duration deployments under broader speed, load, and abnormal operating conditions, together with the development and validation of PHM algorithms for operating-state classification, anomaly detection, health indicator construction, fatigue assessment, and remaining useful life estimation.

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BIOGRAPHIES

Van Ai Hoang received a Bachelor's degree in Marine Electrical Engineering from Vietnam Maritime University in 2016, and both Master's and Ph.D. degrees in Marine Electronic, Communication, and Computer Engineering from Mokpo National Maritime University (MMU), Korea, in 2020 and 2024, respectively. In 2025, he has been working as a postdoctoral researcher affiliated with Korea Maritime & Ocean University (KMOU), contributing to projects in marine systems and motion control technologies. Currently, he is a postdoctoral researcher in the Division of Marine Mechatronics at MMU. His research interests include wireless power transfer, wireless sensor systems, energy harvesting, autonomous robots, low-cost sensors, algorithm development, mathematical modeling, filtering, power electronics, automatic control, optimization, and power system control.

Yang Gon Kim received his Ph.D. degree in mechanical engineering from Korea Maritime & Ocean University in 2016. He is particularly interested in vibration analysis & shaft alignment of the propulsion shafting system and now working as professor at Mokpo National Maritime University in Korea.

Young Chul Lee received the B.S. and M.S. degrees in electronic engineering from Yeungnam University, Gyeongsan, Republic of Korea, in 1995 and 1997, respectively, and the Ph.D. degree in electronic engineering from Information and Communications University (ICU; merged with the Korea Advanced Institute of Science and Technology (KAIST) in 2009), Daejeon, Republic of Korea, in 2005. From 1997 to 2000, he was with the R&D Division of SK hynix, Cheongju, Republic of Korea, where he was involved in the development of MOSFET devices for DRAM applications. Since 2005, he has been with Mokpo National Maritime University, Mokpo, Republic of Korea, where he is currently a Full Professor with the Division of Marine Mechatronics. From 2008 to 2013, he participated in 60 GHz and E-band wireless system research as a Technical Consultant with Telecom Malaysia Research & Development (TMRND), Malaysia. Since 2016, he has been actively involved in the International Telecommunication Union Radiocommunication Sector (ITU-R) Study Group 3 (SG3) activities in the field of radio-wave propagation. He has contributed to and supported the adoption of multiple ITU-R contributions related to Building Entry Loss (BEL) and propagation modeling. His current research interests include millimeter-wave and satellite communication systems, radio-wave propagation modeling, wireless power transfer (WPT), electromagnetic energy harvesting (EH), self-powered wireless sensor systems, propulsion shaft condition monitoring, prognostics and health management (PHM) for marine machinery, and wireless sensing technologies for ship engine-room and maritime applications.