International Journal of Marine Engineering Innovation and Research, Vol. 10(3), Sept. 2025. 766-778
(pISSN: 2541-5972, eISSN: 2548-1479)

System Modeling of Predictive Maintenance for Engine Health Monitoring on Ship Auxiliary Engines Using Vibration Variables

Egas Wahyu Endrianto[1*], Indra Ranu Kusuma [2]

Received: 17 July 2025 / Revised: 26 July 2025 /Accepted: 12 August 2025 / Available Online: 6 September 2025)

***Abstract*— This research presents a dynamic system modelling approach for predictive maintenance of ship auxiliary engines using vibration variables. The model integrates key mechanical components—piston, crankshaft, camshaft, valve train, and timing gear—based on the specifications of a Yanmar TF85 diesel engine. Each subsystem is modelled using a multi-degree-of-freedom (MDOF) state-space framework to represent vibrational and structural dynamics. Simulations are carried out in MATLAB/Simulink under various engine operating conditions, including normal operation at high, medium, and low RPMs, as well as fault scenarios such as damping degradation in the piston and crankshaft. A fuzzy logic system is employed to interpret the vibration data and determine the impact level for each condition. The results indicate that under normal conditions, the engine maintains stable vibration levels, while faults lead to significant increases in velocity RMS values and impact severity. Disturbances in the piston result in dominant amplitude changes, while crankshaft faults affect the frequency propagation throughout the system. These findings confirm that the proposed model can effectively detect early mechanical deviations and support the implementation of predictive maintenance strategies for marine diesel engines**

Keywords— engine model, engine vibration, predictive maintenance.

**Corresponding Author : 6019231007@student.its.ac.id*

I. INTRODUCTION

Marine diesel engines are critical components in ship propulsion systems, responsible for converting combustion energy into mechanical motion. These engines consist of interconnected mechanical subsystems, including pistons, crankshafts, valve trains, and timing gears, all of which operate under continuous cyclic loading and harsh marine environments.[1] Due to the long operating hours and high reliability requirements in maritime operations, it is essential to understand the dynamic behavior and interactions between these subsystems to ensure performance, safety, and longevity.[2]

Vibrations and torsional oscillations in marine diesel engines can lead to structural fatigue, reduced propulsion efficiency, and even catastrophic failure if not properly managed.[3] While prior research has explored the dynamics of individual engine components, such as crankshaft torsional modeling, valve train kinematics, or gear transmission analysis, these approaches often overlook the coupled effects between subsystems.[4] In marine applications, disturbances such as piston imbalance or gear misalignment can propagate throughout the drivetrain, affecting overall engine behavior and vessel performance.

This study proposes a unified dynamic modeling approach for marine diesel engine systems using the state-space method.[5] The model integrates the piston motion, crankshaft torsion, valve train operation, and timing gear interaction into a single multi-degree-of-freedom (MDOF) framework.[6] The simulation covers five engine scenarios, including varying RPM conditions and excessive vibration in selected components, to evaluate how local disturbances affect system-wide dynamics.

The simulation results show that vibration or instability in one component may influence the entire engine structure.[7] The model captures both steady-state and transient behaviors, providing valuable insights into dynamic coupling, critical operating frequencies, and fault propagation paths.[8] This research supports the development of vibration-based condition monitoring and predictive maintenance systems for marine engines, improving reliability and operational efficiency in maritime engineering applications.[9]

The dynamic behavior of diesel engines has long been a subject of interest due to its critical influence on mechanical performance, energy efficiency, and component lifespan.[10] Several studies have focused on the development of mathematical models to simulate piston motion and crankshaft torsional vibration, which are key indicators of internal mechanical health.[4] Multi-DOF crankshaft model using torsional and bending vibration analysis, highlighting the influence of combustion torque and stiffness distribution along the shaft. Their findings laid the foundation for crankshaft-based monitoring systems in engine diagnostics.[11]

Vibration-based condition monitoring for gearboxes, emphasizing the role of stiffness and damping in predicting gear wear and failure patterns.[12] The study underscored the importance of detecting early-stage anomalies in marine propulsion systems, particularly under fluctuating load and speed conditions.[13] Meanwhile, dynamic modeling of valve train systems

Egas Wahyu Endrianto Departement of Marine Engineering, Institut Teknologi Sepuluh Nopember, Surabaya, 60111, Indonesia, 6019231007@student.its.ac.id
Indra Ranu Kusuma, Departement of Marine Engineering, Institut Teknologi Sepuluh Nopember, Surabaya, 60111, Indonesia, ir.kusuma@ne.its.ac.id

has also attracted significant attention, as shown in works that analyze cam-follower mechanisms and valve spring dynamics.[14] These studies reveal that valve bounce, float, and stem oscillation are critical to understanding timing irregularities and mechanical wear.[15]

In the context of integrated engine modeling, recent works have emphasized the need to unify subsystems into a holistic simulation framework.[16] The use of Simulink for modeling multi-body systems allows the coupling of piston, crankshaft, camshaft, gear, and valve dynamics into a single coherent state-space system.[17] This approach enhances the ability to simulate real engine conditions, including internal force transmission and resonance behavior across components.[18]

Complementing physical models, fuzzy logic has gained traction as a soft-computing method for interpreting vibration signals and assigning risk levels.[19] A number of studies have incorporated fuzzy-based FMEA to assess severity, occurrence, and detectability of faults in rotating machinery.[20] In such systems, vibration RMS values are mapped into linguistic terms (e.g., *Low*, *Medium*, *High*) and processed through fuzzy rules to produce diagnostic decisions.[21] This approach is particularly effective when signal patterns are uncertain or noisy, making it suitable for real-time marine engine health monitoring.[22]

In summary, existing literature demonstrates the importance of both deterministic dynamic modeling and fuzzy logic in engine condition analysis.[23] However, few studies integrate these methods into a comprehensive simulation and diagnostic framework specifically tailored for marine diesel engines.[24] This research aims to address that gap by combining multi-DOF modeling with fuzzy-based risk evaluation under various operational scenarios.[13]

II. METHOD

This study employs classical dynamics to model and simulate the behavior of four major mechanical subsystems in a Yanmar TF 85 MH diesel engine: piston, crankshaft, gear timing system, and valve train. Each subsystem is analyzed using force and torque balance equations, incorporating mass, damping, stiffness, and external excitation. The models are implemented in MATLAB/Simulink for simulation under various operating conditions.

A. Engine Modelling

1) The piston is subjected to combustion pressure $P_c(t)$ generating a translational force:

$$F_p(t) = P_c(t).A_p \tag{1}$$

$$m_p\ddot{x}_p + c_p\dot{x}_p + k_px_p = F_p(t) \tag{2}$$

Where, x_p is a piston displacement, m_p is a piston mass c_p, k_p are damping and stiffness coefficients, and A_p is a piston cross-sectional area

2) The piston force is converted into torque on the crankshaft through the crank radius r:

$$T_c(t) = F_p(t).r \tag{3}$$

$$J_c\ddot{\theta}_p + c_c\dot{\theta}_c + k_c\theta_c = T_c(t) \tag{4}$$

Where θ_c is angular displacement of crankshaft, J_c is a crankshaft rotational inertia, and c_c, k_c are torsional damping and stiffness.

3) The timing gear transmits torque from the crankshaft to the camshaft. The system is modeled as a rotational stiffness-damping element between two rotating bodies:

$$T_{mesh}(t) = k_g(\theta_{crank} - \theta_{cam}) + c_g(\dot{\theta}_{crank} - \dot{\theta}_{cam}) \tag{5}$$

To capture dynamic effects, backlash and lubrication losses are introduced as nonlinear stiffness variation in mesh engagement, based on prior tribodynamic studies.

4) The valve train consists of multiple components: camshaft, tappet, pushrod, rocker arm, and valve. Each component is represented by a lumped mass-spring-damper system. The camshaft provides periodic excitation:

B. Fuzzy Logic for Vibration-Based Fault Evaluation

To complement the dynamic modeling of engine components, a fuzzy logic system is developed to assist in evaluating the condition of each mechanical subsystem based on vibration signals. This method provides a structured approach for fault diagnosis by interpreting simulation results into qualitative health indicators.

1) Fuzzy Logic Structure

The fuzzy system is built using a rule-based Mamdani inference model with one input and one output. The input variable is the measured RMS vibration value for each engine component, while the output is a linguistic fault level (e.g., *Safe*, *Caution*, *Warning*, *Critical*). Each major component—piston, crankshaft, valve train, and gear—has its own fuzzy system block in Simulink, allowing for localized evaluation of dynamic health status. This study utilizes two fuzzy logic systems, the first is fuzzy standard vibrations and the second is fuzzy risk matrix. Both systems are interconnected; the first is used to determine the impact value, while the second evaluates the risk level.

2) Membership Function and Ranges

a) Fuzzy Standard Vibration

The first fuzzy logic system is designed to evaluate the vibration-based impact level of engine components. The input variable is categorized into four linguistic terms: *Good*, *Satisfactory*, *Unsatisfactory*, and *Unacceptable*, in accordance with ISO vibration severity standards. The corresponding RMS vibration ranges for each category are defined as follows:

- *Good*: 0.0 – 2.3 mm/s
- *Satisfactory*: 2.3 – 4.5 mm/s
- *Unsatisfactory*: 4.5 – 7.1 mm/s
- *Unacceptable*: >7.1 mm/s

These ranges reflect the general vibration limits for small and medium-sized rotating machinery as outlined in ISO 10816-3 for operating conditions. Triangular or trapezoidal membership functions are used to represent the transition between categories.

b) Fuzzy Risk Matrix

The second fuzzy logic system adopts a structure based on the risk assessment matrix shown in Figure 1. It receives two inputs—impact severity and failure probability—and produces a single output representing the overall risk level.

Almost Certain	5	7	12	17	22	25
Likely	4	4	9	14	19	24
Possible	3	3	8	13	18	23
Unlikely	2	2	6	11	16	21
Rare	1	1	5	10	15	20
		1	2	3	4	5
		Very Low	Low	Moderate	High	Very High

Figure. 1. Fuzzy Risk Matri

Failure Mode and Effects Analysis

The Failure Mode and Effects Analysis (FMEA) process is conducted to analyze potential failures in the main engine components, namely the piston, crankshaft, camshaft, gear, and valve train. Each component is systematically examined to identify possible failure modes, their causes, and their impacts on the overall engine system. Failure modes such as wear, material fatigue, misalignment, and lubrication failure are the primary focus. The objective of the FMEA design is to link the identified vibration-based risk levels with appropriate predictive maintenance actions, ensuring that maintenance strategies are aligned with the severity of each risk level.

TABLE 1.
FAILURE MODE AND EFFECTS ANALYSIS

Components	Failure Mode	End Effects	Recommendations
Piston	Slap	Increase Vibrations	Implement proper assembly procedures and torque specifications during maintenance
Crankshaft	Loosened	Increase Vibrations	Implement proper assembly procedures and torque specifications during maintenance. Regularly inspect crankshaft end play and bearing condition

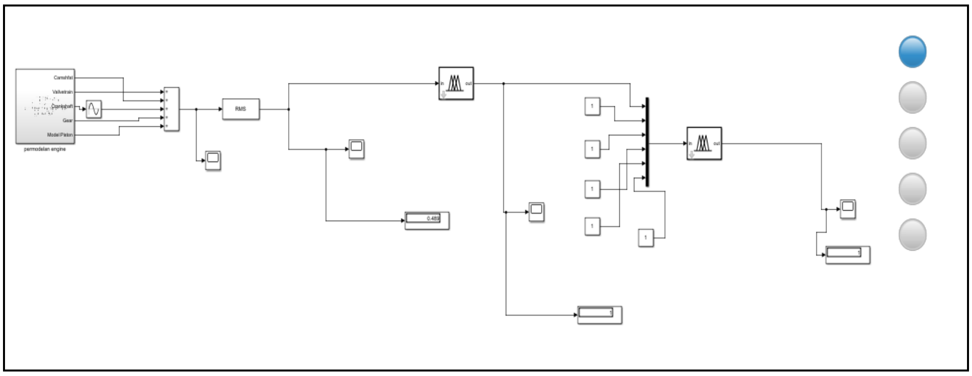

Figure. 2. Block Diagram System in Simulink/MATLAB

III. RESULTS & DISCUSSION

In this subsection, simulation is carried out using the previously developed model in Simulink. The results include vibration response plots, RMS vibration values for each component, and decision outputs indicating whether corrective action is required for specific components. Several simulation scenarios are defined to evaluate engine behavior under various conditions:

A. Simulation Scenario

- Scenario 1: Engine operating at high RPM (normal condition)
- Scenario 2: Engine operating at medium RPM (normal condition)
- Scenario 3: Engine operating at low RPM (normal condition)
- Scenario 4: Excessive vibration on the piston
- Scenario 5: Excessive vibration on the crankshaft

1) **Scenario 1**

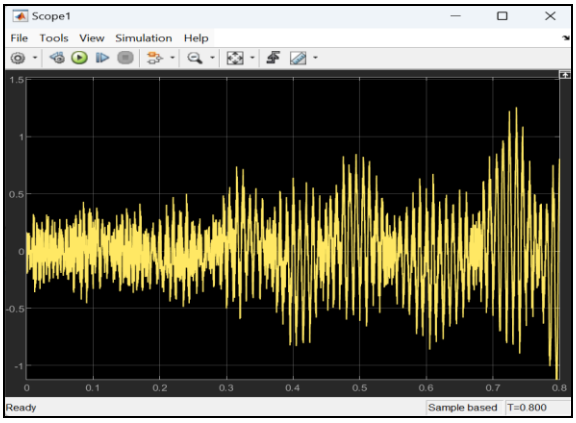

Figure. 3. Output Vibration of Scenario 1 with High RPM

The figure above illustrates the output of the engine model under ideal conditions without any disturbances. Each sample from 0.1 to 0.8 corresponds sequentially to crankshaft angles of 45°, 90°, 135°, 180°, 225°, 270°, 315°, and 360°, respectively. The resulting vibrations are converted into Root Mean Square (RMS) velocity values (VRMS), and the corresponding graph is presented below.

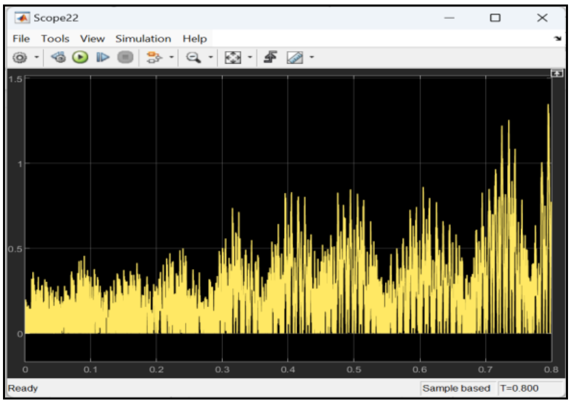

Figure. 3. Output VRMS of Scenario 1 with High RPM

The figure above shows the RMS velocity (VRMS) values obtained from the vibration simulation at low engine RPM. It can be observed that the vibration intensity increases progressively across each sample point (0.0, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8), where each sample represents a sequential crankshaft angle input of 0°, 45°, 90°, 135°, 180°, 225°, 270°, 315°, and 360°, respectively. The full range from 0° to 360° represents one complete combustion cycle. Within this cycle, the intake valve opens between 0° and 45°, while from 315° to 360° the piston approaches the Top Dead Center (TDC) position.

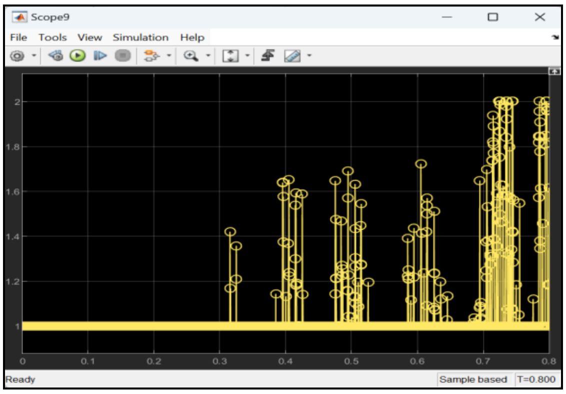

Figure. 4.Output Impact Value Of Scenario 1

As shown in Figure 4, the simulated vibration results were classified according to standard categories, falling within the "Good" and "Satisfactory" ranges. This indicates that the system accurately detects vibrations from the engine operating under normal or acceptable conditions. From 0° to 135°, the vibration remains stable, while from 135° to 360°, fluctuations are observed—representing the engine dynamics as it exerts effort to reach a certain RPM. In this case, the engine exhibits increased vibration levels as it attempts to achieve higher RPM. Once the vibration impact values are obtained, they are processed through a fuzzy risk matrix to determine the corresponding vibration risk level. This evaluation uses the failure likelihood data of each component as input parameters. The resulting risk level assessment derived from the fuzzy risk matrix is shown as follows.

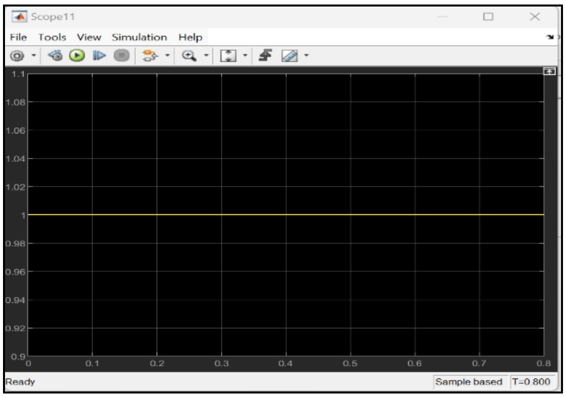

Figure. 5. Output Risk Level of Simulation Scenario 1

The graph above demonstrates that the system successfully interprets the impact values derived from the previous fuzzy output, taking into account the failure probabilities of each component. The resulting risk level is categorized as Level 1 or Low. Based on this assessment, the recommended predictive maintenance action is to monitor performance.

2) **Scenario 2**

In Scenario 2, a simulation was conducted using the designed system in Simulink with a medium RPM input and without any disturbances. The simulation produced four key results: vibration output, conversion to VRMS, standard or impact value, and risk level. These four results are discussed in detail in the following sections.

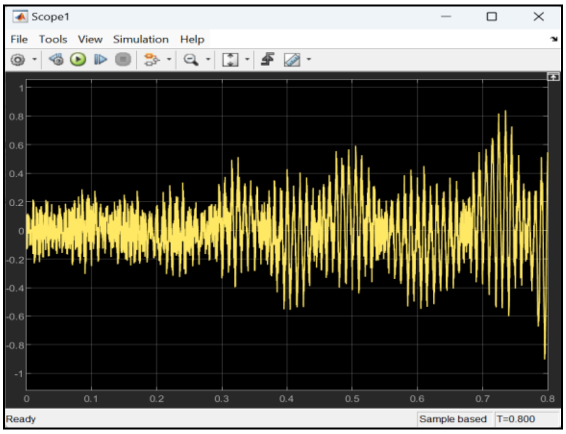

Figure. 6. Output of Vibration Scenario 2 with Medium RPM

The figure above illustrates the output of the engine model operating at medium RPM under ideal conditions without any disturbances. Each sample from 0.1 to 0.8 corresponds sequentially to crankshaft angles of 45°, 90°, 135°, 180°, 225°, 270°, 315°, and 360°, respectively. It can be observed that the harmonic vibration output at medium RPM is similar to that at high RPM. However, a key difference lies in the amplitude spike, which does not reach a value of one. This indicates that the input RPM significantly affects the resulting engine vibration, even in the absence of any component disturbances.

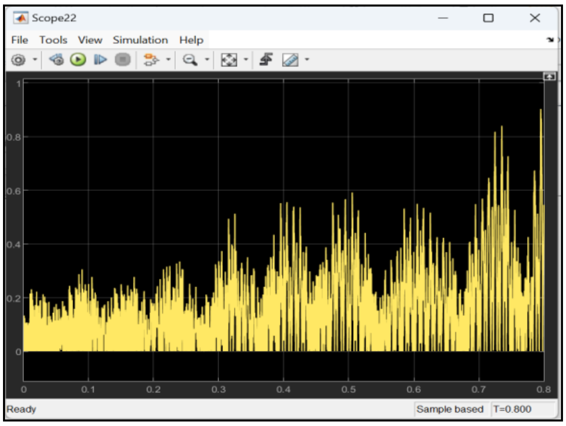

Figure. 7. Output of VRMS Scenario 2 with Medium RPM

In Figure 7, the resulting VRMS values are approximately like those obtained from the vibration simulation at medium RPM. Compared to the high RPM simulation, the amplitude remains below a value of one, and there are no significant vibration spikes across the crankshaft angles. The VRMS graph appears more stable, and this stability has a notable influence on the resulting impact values, which are explained in more detail in the following figure.

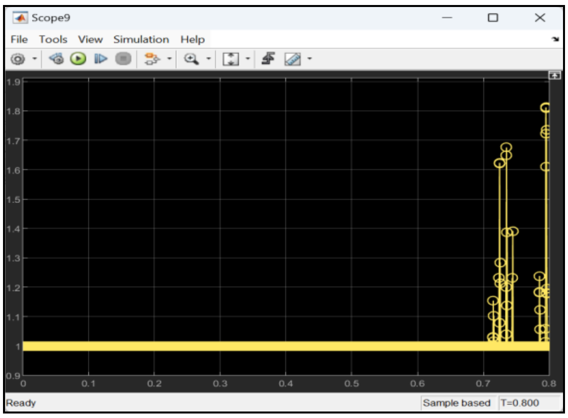

Figure. 8. Output of Impact Value Scenario 2 with Medium RPM

The graph above presents the simulation results of impact values at medium RPM. It can be observed that from crankshaft angles 0° to 315°, the impact values remain relatively stable, with no significant spikes and a consistent value of 1. However, between 315° and 360°, several spikes occur, with the highest value reaching 1.8. This indicates that under medium RPM conditions, vibration stability is improved, as evidenced by the limited number of spikes confined to a specific angular range. The spike at 360° is considered normal, as it corresponds to the piston approaching the Top Dead Center (TDC) position. After analyzing the impact values under medium RPM simulation, these values are then input into the fuzzy risk matrix, with the resulting fuzzy risk levels illustrated in the following figure.

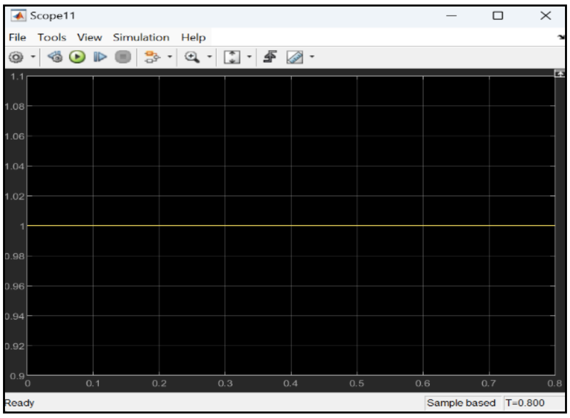

Figure. 9. Output of Risk Level Scenario 2 with Medium RPM

The graph above confirms that the system successfully interprets the impact values obtained from the previous fuzzy output, taking into account the failure probability of each component. The resulting risk level is categorized as Level 1, or Low. Based on this assessment, the recommended predictive maintenance action is to monitor performance.

3) **Scenario 3**

In Scenario 3, a simulation was conducted using the designed system in Simulink with a low RPM input and without any disturbances.

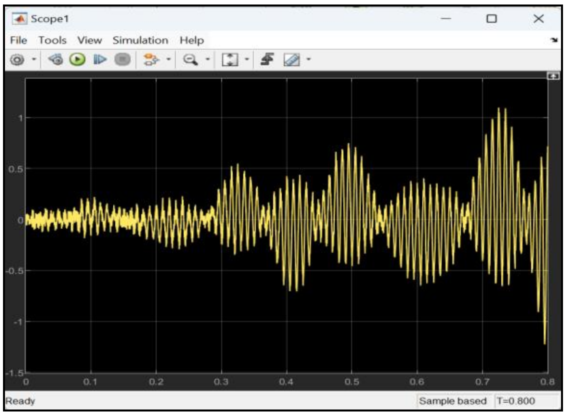

Figure. 10. Output of Vibration Scenario 3 with Low RPM

The figure above shows the output of the engine model operating at medium RPM under ideal conditions, without any disturbances. Each sample from 0.1 to 0.8 corresponds sequentially to crankshaft angles of 45°, 90°, 135°, 180°, 225°, 270°, 315°, and 360°, respectively.

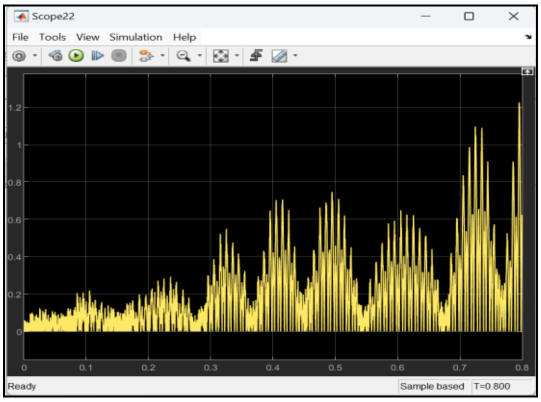

Figure. 11. Output of VRMS Scenario 3 with Low RPM

In Figure 11, the resulting VRMS values are approximately similar to those obtained from the vibration simulation at low RPM. Compared to the simulations at medium and high RPM, the amplitude remains below a value of one, and no significant vibration spikes occur across the crankshaft angles.

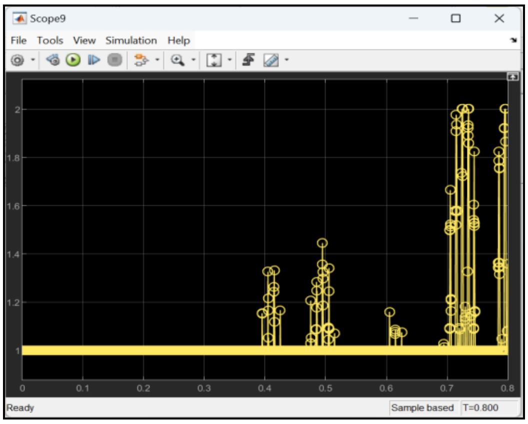

Figure. 12. Output of Impact Value Scenario 3 with Low RPM

Figure 12 presents the vibration simulation results, which have been classified according to standard criteria and fall into the "Good" and "Satisfactory" categories. This indicates that the system accurately detects engine vibrations under normal conditions, within acceptable standard limits. From 0° to 135°, the vibration remains stable, while from 135° to 360°, several fluctuations occur, reflecting the dynamic behavior of the engine.

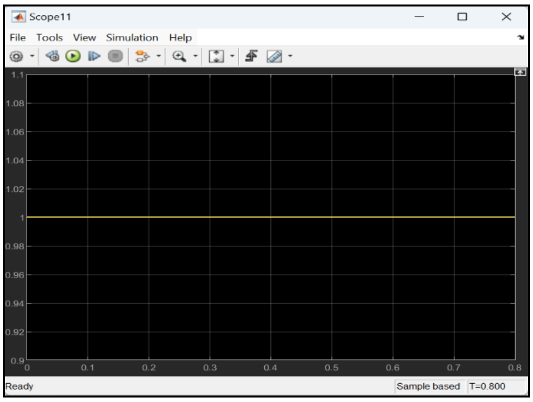

Figure. 13. Output of Risk Level Scenario 3 with Low RPM

The graph above demonstrates that the system effectively interprets the impact values generated from the previous fuzzy logic output, while also considering the probability of failure for each component. The analysis indicates that the resulting risk level is categorized as Level 1, or Low. Accordingly, the recommended predictive maintenance strategy is performance monitoring.

4) Scenario 4

In Scenario 4, a simulation was conducted by introducing a disturbance in one of the components, specifically the piston. The simulation was performed at medium RPM, which, in previous scenarios without disturbances, demonstrated relatively stable behavior compared to other RPM variations.

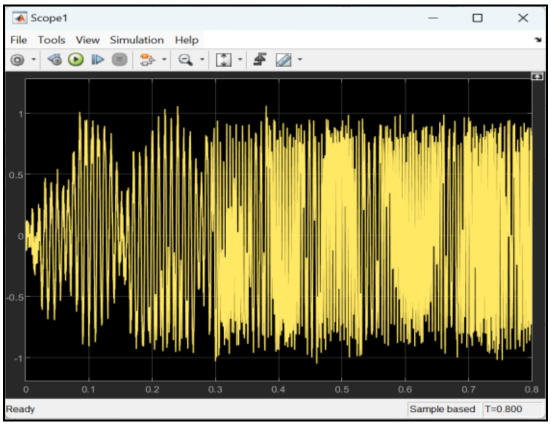

Figure. 14. Output of Vibration Simulation with Piston Disturbance

The vibration results from the simulation with an added disturbance on the piston can be seen in Figure 14. It is evident that the waveform becomes thicker across all crankshaft angles. From 0° to 135°, the waveform remains harmonic and consistent with the undisturbed simulation, although it appears denser. However, from 135° to 360°, a significant amount of noise is observed, while the waveform amplitude remains relatively constant. This phenomenon occurs as the piston moves from the Bottom Dead Center (BDC) at 135° toward the Top Dead Center (TDC) at 360°, where rough contact between the piston and the cylinder liner may take place. This contact generates high levels of waveform noise, although the vibration level still remains within the acceptable standard

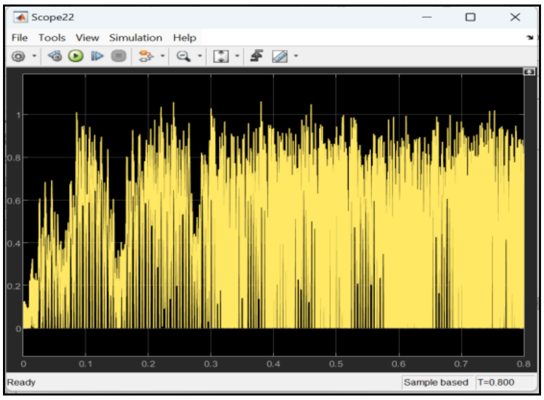

Figure. 15. Output of VRMS with Piston Disturbance

The results shown in the figure above present the VRMS graph obtained from the simulation with a disturbance on the piston. The interpretation of this graph aligns with the vibration waveform results, where significant noise is observed in the range of 135° to 360° crankshaft angles. To provide a clearer understanding, the impact values will be presented next, as they further highlight the effects observed in the vibration and VRMS graphs.

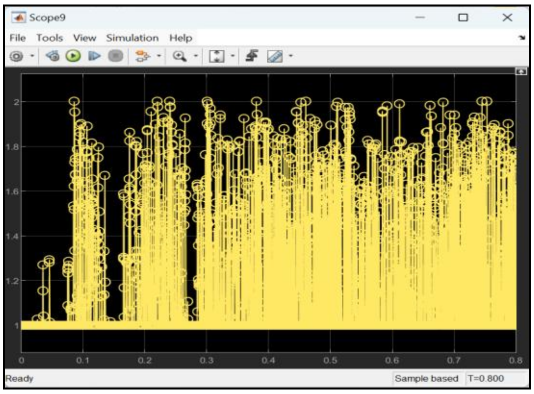

Figure. 16. Output of VRMS with Piston Disturbance

As explained in the previous figures, significant noise was observed between crankshaft angles 135° and 360°. However, the current graph clearly reveals that noise also occurs between 0° and 45°. This may indicate that an anomaly has been present since the initial piston movement from 0°. Possible causes include wear, improper installation not in accordance with the guidebook, or potential slap

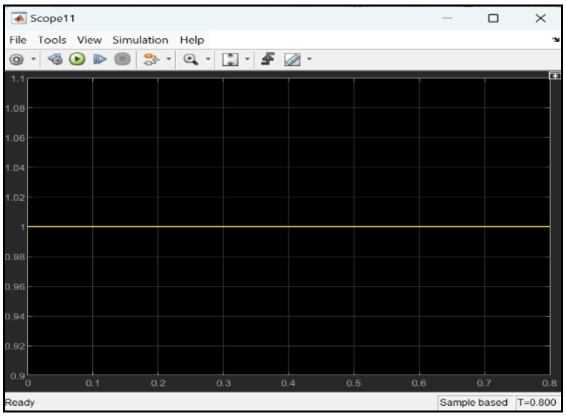

Figure. 17. Output of Risk Level with Piston Disturbance

The graph above shows that the resulting risk level remains constant at Level 1. Based on the analysis of the previous three graphs, waveform noise indicates an anomaly in the piston. However, the risk level output remains at 1. This result is derived from the fuzzy risk matrix, which takes the impact value and the probability of failure as inputs. The probability of failure is obtained from historical data; therefore, it is possible for anomalies to occur in the piston while the engine vibrations still fall within acceptable standards. This case demonstrates the applicability of predictive maintenance. As a result, the recommended action is to inspect and recalibrate the piston installation.

5) Scenario 5

In Scenario 5, a simulation of the engine model was performed by introducing a disturbance in the crankshaft. Such disturbances may result from misalignment or issues with the crankshaft bearing. After running the simulation, the resulting vibration graph is shown below.

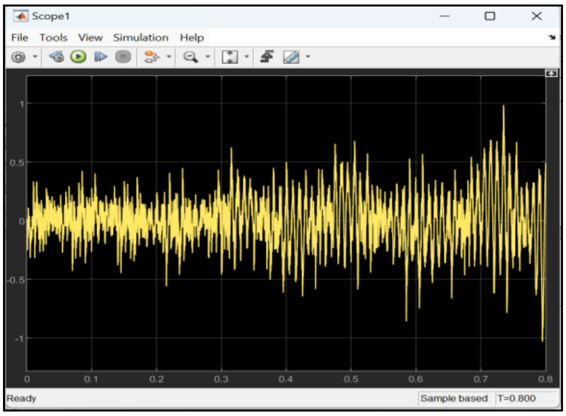

Figure. 18. Output of Risk Level with Crankshaft Disturbance

The vibration simulation results with a disturbance on the crankshaft show a noticeable difference compared to the undisturbed condition. Across the full crankshaft rotation from 0° to 360°, an overall increase in vibration is observed, which still appears relatively harmonic. However, several sharp amplitude spikes occur at specific crank angles, indicating the presence of minor disturbances in the crankshaft. These disturbances cause slight irregularities in the vibration pattern, but overall, the engine is still considered to be operating normally, without any visible performance issues.

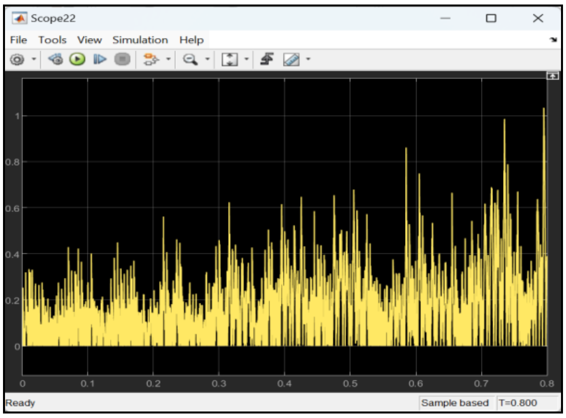

Figure. 19. Output of VRMS with Crankshaft Disturbance

In the VRMS graph above, the output increases steadily from 0° to 360°, similar to the undisturbed condition. However, the key difference lies in several noticeable VRMS spikes at specific crankshaft angles. These spikes may indicate minor disturbances, such as insufficient lubrication or a reduction in stiffness coefficient, which could suggest wear on the crankshaft. For a clearer understanding, the impact value graph shown below provides further insight.

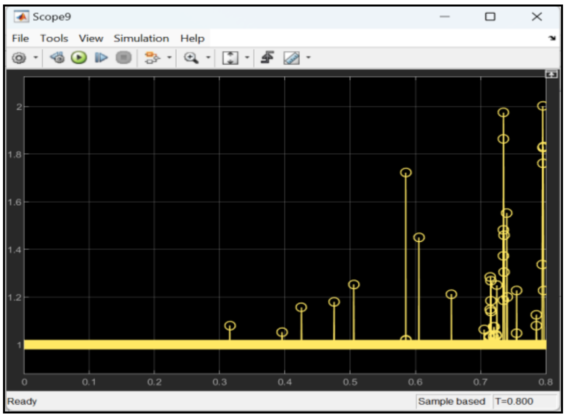

Figure. 20. Output of Impact Value with Crankshaft Disturbance

The graph above shows that between crankshaft angles 135° and 360°, there are more noticeable spikes compared to the impact values under undisturbed conditions. This indicates that the crankshaft experiences small-scale vibration surges within this angular range. By analyzing the impact values, it is possible to identify the type of disturbance affecting the crankshaft. Consequently, appropriate predictive maintenance actions can be planned based on the resulting risk level. A more detailed explanation of the risk level is provided in the graph below

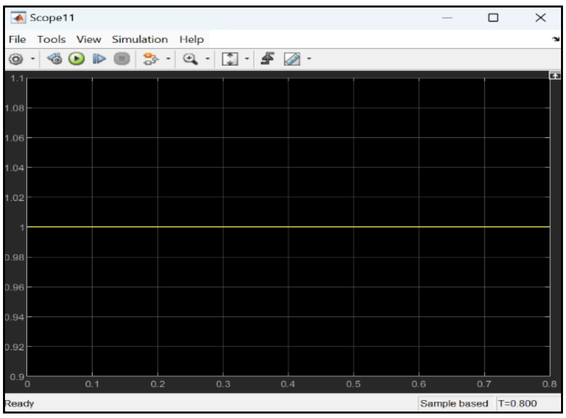

Figure. 21. Output of Risk Level with Crankshaft Disturbance

The risk level graph above shows a value of 1, indicating that despite the presence of vibration spikes, the overall risk remains low. This result supports the implementation of predictive maintenance, as the system can recommend appropriate future maintenance actions. Based on the analysis of the previous three graphs, there are indications of minor crankshaft wear, likely due to a slight reduction in stiffness coefficient, which may be caused by inadequate lubrication. The recommended maintenance action is to select a lubricant that matches the engine's characteristics, in order to minimize potential wear on the crankshaft.

IV. CONCLUSIONS

Following the research and the various processes involved in designing a predictive maintenance system for engine health monitoring, the following conclusions can be drawn:

a) A vibration-based engine health monitoring system using fuzzy logic has been successfully developed. The model includes key components of a ship's auxiliary engines such as the piston, crankshaft, valve train, camshaft, and timing gear—structured in a state-space multi-degree-of-freedom form and simulated using MATLAB/Simulink. The system is capable of processing vibration data into impact severity levels through fuzzy inference, thereby supporting real-time condition monitoring of the engine.
   - Under normal conditions, whether at high, medium, or low RPM, the system exhibits stable vibration levels within standard thresholds. This demonstrates the model's capability to represent engine performance under healthy operating conditions.
   - In the disturbance scenario applied to the piston—such as reduced damping—a significant increase in vibration amplitude was observed. This indicates that the piston is highly sensitive to damping changes and has a major influence on overall system stability.
   - The disturbance scenario on the crankshaft affected the propagation pattern of vibration frequencies throughout the system. Although the amplitude was not as high as that caused by piston disturbances, it caused fluctuations in energy distribution, which may serve as early indicators of torque imbalance.
   - The implemented fuzzy system successfully classified engine conditions based on vibration impact levels. Increased severity levels were recorded when disturbances were introduced, confirming the system's ability to distinguish between healthy and abnormal states.

b) The fuzzy logic approach has proven to be effective in detecting anomalies and changes in engine conditions when compared to conventional monitoring methods. Through various simulation scenarios under different RPMs and disturbances, the system demonstrated the ability to accurately distinguish between normal and abnormal conditions and provided early warning indications of potential failures—particularly in critical components such as the piston and crankshaft.

Several aspects should be considered for future research to improve and expand the current study:

a) Real Vibration Data Acquisition, the system's accuracy and reliability can be enhanced by incorporating real vibration data from actual engine operations. This would allow for a more detailed and realistic assessment of engine performance.
b) Integration of Vibration Sensors, future developments may involve integrating vibration sensors to capture real-time data directly from the engine. This real-time monitoring will enable more precise diagnostics and timely maintenance actions.
c) Experimental Validation, it is essential to conduct experimental validation of the simulation results to verify the accuracy and reliability of the developed model against the actual dynamic behavior of the engine in operational settings.
d) Environmental Considerations, the influence of operational conditions on ships, such as external vibrations and noise from other onboard systems, should be taken into account. This will ensure that the predictive maintenance system maintains its accuracy and robustness under real-world maritime conditions.

ACKNOWLEDGEMENT

First and foremost, I would like to express my sincere gratitude to Allah SWT for granting me the strength, health, and perseverance to complete this thesis. Without His guidance and blessings, none of this would have been possible.

I am deeply grateful to my academic advisor, Dr. Indra Ranu Kusuma, S.T., M.Sc., for his continuous guidance, encouragement, and valuable insights throughout the course of this research. His expertise and support have been essential in shaping the direction of this study and ensuring the quality of the outcomes.

My heartfelt thanks also go to all lecturers and staff members of the Department of Marine Engineering, Institut Teknologi Sepuluh Nopember (ITS), for providing an excellent academic environment and the necessary resources that enabled me to carry out this research. Special appreciation is extended to the laboratory staff and administrative personnel for their assistance during the simulation and data processing stages.

I am also thankful to my fellow students and research colleagues for the constructive discussions, collaboration, and mutual support throughout this academic journey. Their encouragement has been a great source of motivation, especially during challenging periods.

To the authors and researchers whose previous work in engine dynamics, vibration analysis, and predictive maintenance served as the foundation of this thesis, I express my respect and appreciation. Their contributions have greatly inspired the development of this research.

Most importantly, I would like to express my deepest appreciation to my beloved family. To my parents, who have supported me unconditionally with love, prayers, and encouragement—you have been my greatest source of strength. To my siblings and all family members, thank you for your continuous moral support and belief in my capabilities.

Lastly, I extend my sincere thanks to everyone who, in any way, contributed to the completion of this work. Your presence and support, no matter how big or small, have meant a great deal to me.

REFERENCES

[1] X. Zheng, X. Luo, Y. Qiu, and Z. Hao, "Modeling and NVH analysis of a full engine dynamic model with valve train system," *Appl. Sci.*, vol. 10, no. 15, p. 5145, 2020, doi: 10.3390/app10155145.

[2] I. S. Haq, A. Y. Darma, and R. A. Batubara, "Penggunaan metode failure mode and effect analysis (FMEA) dalam identifikasi kegagalan mesin untuk dasar penentuan tindakan perawatan di pabrik kelapa sawit Libo," *J. Vokasi Teknol. Ind.*, vol. 3, no. 1, 2021, doi: 10.36870/jvti.v3i1.209.

[3] A. S. Mendes, P. S. Meirelles, and D. E. Zampieri, "Analysis of torsional vibration in internal combustion engines: Modelling and experimental validation," *Proc. Inst. Mech. Eng., Part K: J. Multi-Body Dyn.*, vol. 222, no. 2, pp. 155–178, 2008, doi: 10.1243/14644193jmbd126.

[4] P. Horváth and J. Égert, "Dynamic analysis of a one-cylinder engine crankshaft," *Acta Tech. Jaurinensis*, vol. 8, no. 4, p. 280, 2015, doi: 10.14513/actatechjaur.v8.n4.379.

[5] E. Armentani, F. Caputo, L. Esposito, V. Giannella, and R. Citarella, "Multibody simulation for the vibration analysis of a turbocharged diesel engine," *Appl. Sci.*, vol. 8, no. 7, p. 1192, 2018, doi: 10.3390/app8071192.

[6] M. Babagiray, H. Solmaz, D. İpci, and F. Aksoy, "Modeling and validation of crankshaft speed fluctuations of a single-cylinder four-stroke diesel engine," *Proc. Inst. Mech. Eng., Part D: J. Automob. Eng.*, vol. 236, no. 4, pp. 553–568, 2022, doi: 10.1177/09544070211026290.

[7] A. Sumtsov and K. Szurman, "UNIS, a.s., Division Aerospace and Advanced Control, Brno, Czech Republic," *n.d.*

[8] Y. H. Zweiri, J. F. Whidborne, and L. D. Seneviratne, "Dynamic simulation of a single-cylinder diesel engine including dynamometer modelling and friction," *Proc. Inst. Mech. Eng., Part D: J. Automob. Eng.*, vol. 213, no. 4, pp. 391–402, 1999, doi: 10.1243/0954407991526955.

[9] S. Demirci, C. Hajiyev, and A. Schwenke, "Fuzzy logic-based automated engine health monitoring for commercial aircraft," *Aircraft Eng. Aerosp. Technol.*, vol. 80, no. 5, pp. 516–525, 2008, doi: 10.1108/00022660810899883.

[10] Z. Geng and J. Chen, "Investigation into piston-slap-induced vibration for engine condition simulation and monitoring," *J. Sound Vib.*, vol. 282, no. 3–5, pp. 735–751, 2005, doi: 10.1016/j.jsv.2004.03.057.

[11] S. Kaliki, N. L. T. Thenu, M. F. Noya, and A. Hadi, "Analisis getaran torsional poros baling-baling pada KN Ular Laut 405," *ALE Proceeding*, vol. 5, pp. 37–45, 2022, doi: 10.30598/ale.5.2022.37-45.

[12] W. Bartelmus, "Mathematical modelling and computer simulations as an aid to gearbox diagnostics," *Mech. Syst. Signal Process.*, vol. 15, no. 5, pp. 855–871, 2001, doi: 10.1006/mssp.2001.1411.

[13] S. Paul, R. Turnbull, D. Khodadad, and M. Löfstrand, "A vibration based automatic fault detection scheme for drilling process using type-2 fuzzy logic," 2022.

[14] N. Bohara, R. Jegadeeshwaran, and S. G., "Carbide coated insert health monitoring using machine learning approach through vibration analysis," *Int. J. Prognostics Health Manag.*, vol. 8, no. 2, 2020, doi: 10.36001/ijphm.2017.v8i2.2635.

[15] C. Zhou, Z. Xiao, S. Chen, and X. Han, "Normal and tangential oil film stiffness of modified spur gear with non-Newtonian elastohydrodynamic lubrication," *Tribol. Int.*, vol. 109, pp. 319–327, 2017, doi: 10.1016/j.triboint.2016.12.045.

[16] I. Komorska, "Modeling of vibration signal for reciprocating engine diagnostics," *n.d.*

[17] M. Pająk, M. Kluczyk, Ł. Muślewski, D. Lisjak, and D. Kolar, "Ship diesel engine fault diagnosis using data science and machine learning," *Electronics*, vol. 12, no. 18, p. 3860, 2023, doi: 10.3390/electronics12183860.

[18] K. Xu, L. C. Tang, M. Xie, S. L. Ho, and M. L. Zhu, "Fuzzy assessment of FMEA for engine systems," 2002.

[19] S. Demirci, C. Hajiyev, and A. Schwenke, "Fuzzy logic-based automated engine health monitoring for commercial aircraft," *Aircraft Eng. Aerosp. Technol.*, vol. 80, no. 5, pp. 516–525, 2008, doi: 10.1108/00022660810899883.

[20] O. V. Afanaseva, O. K. Bezyukov, and A. A. Ignatenko, "Method for assessing the relationship between the characteristics of vibroactivity and the design parameters of a marine diesel," no. 05, 2023

[21] M. S. G. Barnabas, N. Sarathkumar, N. Aswinkumar, and M. Venkatesh, "Failure Rate Analysis of IC Engine Components," vol. 2, no. 5, 2012.

[22] J. Chen, "Internal combustion engine diagnostics using vibration simulation," Ph.D. dissertation, UNSW Sydney, 2013, doi: 10.26190/UNSWORKS/16365.

[23] X. Bi et al., "VMD-KFCM algorithm for the fault diagnosis of diesel engine vibration signals," 2020.

[24] C. Wang, Z. Peng, R. Liu, and C. Chen, "Research on multi-fault diagnosis method based on time domain features of vibration signals," *Sensors*, vol. 22, no. 21, p. 8164, 2022, doi: 10.3390/s22218164.

[25] M. Tiboni, C. Remino, R. Bussola, and C. Amici, "A review on vibration-based condition monitoring of rotating machinery," 2022.