Smart Tribology Training Kit for Real-Time Evaluation of Lubricant Quality based on Temperature and Noise Characteristics under Variable Loading Conditions

Muhammad Nurtanto[1*], *Constantinus Rudy* Prihantoro[1], *Hamid* Abdillah[2] and *Gulzhaina K.* Kassymova[3]

[1]Universitas Negeri Jakarta, Department of Mechanical Engineering Education, 13220 East Jakarta, Indonesia
[2]Universitas Sultan Ageng Tirtayasa, Department of Mechanical Engineering Vocational Education, 42117 Serang City, Indonesia
[3]Abai Kazakh National Pedagogical University, Department of Pedagogy and Psychology, 50010 Almaty, Kazakhstan

Abstract. Degradation of lubricating oil is one major contributor to the increased temperature, noise and wear on mechanical components. Conventional lubricant testing is generally based on expensive laboratory analysis and does not reflect the friction phenomenon in real-time, thus limiting the understanding of the lubricant performance especially for the context of vocational education. This research developed a Smart Tribology Training Kit to assess the quality of lubricants by real-time temperature and noise monitoring under different friction conditions. The research adopts an experimental engineering methodology including requirements analysis, design, element analysis (FEA), fabrication and performance testing. Experiments were conducted with load variations of 2, 6 and 11 kg at rotational speeds of 981 rpm and 1489 rpm under three lubrication conditions viz. oilless, SAE 10W-30 used oil and SAE 10W-30 new oil. The structural analysis was performed and the results were .014 mm of maximum displacement and 1.208 as safety factor, confirming the operational safety in the test range used. The performance tests showed that the lubrication-free conditions had the highest temperatures and noise, while the new oils reduced both parameters consistently. For the oilless condition, the 1489 rpm with 11 kg load generates 35.7°C and 99.9 dBA, whereas the new oil condition generates 32.2°C and 89.2 dBA. Pearson's correlation analysis showed a very strong and statistically significant relationship between temperature and noise across test conditions ($r = 0.934$, $p < 0.001$) confirming the consistency of the dual-sensor measurement approach.

[*] Corresponding author: muhammad.nurtanto@unj.ac.id

1 Introduction

The quality of lubricating oil is an important factor in maintaining the performance, efficiency, and service life of mechanical components that work through contact and friction between surfaces [1]. In automotive, manufacturing, and industrial machinery systems, lubricants function to reduce friction, distribute heat, minimize wear, and reduce vibration and noise during mechanical work processes [2]. So far, oil quality testing has generally been carried out through laboratory tests such as viscosity analysis, flash points, and wear debris using tribometer equipment or oil analysers which have high costs, complex procedures, and require special operators. On the other hand, the test method has not been able to provide direct visualization of the effect of lubricant quality on the increase in temperature and noise due to mechanical friction under certain load conditions. In fact, in real applications, lubricant performance is affected by a combination of engine rotation, friction contact, and the workload that the components receive. This condition shows the need for engineering a lubrication quality testing system that is more applicative, simple, and able to simulate the working principle of frictional elements with load variations in real-time so that the concept of lubricant degradation can be understood empirically.

The problem becomes even more crucial when the deterioration in the quality of lubricants is not detected early. Degraded lubricants cause a decrease in the ability of the oil film layer to separate two frictional surfaces, thereby increasing the working temperature, noise, vibration, and wear of components [3]. The subsequent impact is a decrease in engine efficiency, increased energy consumption, and mechanical failure in moving components. Some industry reports show that about 40% of the damage to rotating machinery bearings and components is related to lubrication system failures and oil contamination. In addition, an increase in temperature due to poor lubrication can accelerate the rate of oil oxidation resulting in a shorter lubricant life [4]. In automotive systems, these conditions not only increase maintenance costs but also have the potential to reduce the operational safety of industrial vehicles and machinery. However, in the process of conceptual understanding, test media that are able to show directly the relationship between lubricant quality, loading, temperature, and noise level are still very limited. As a result, the conceptual understanding of the effect of oil degradation on mechanical performance has not been comprehensively understood through a real experimental approach.

Various previous studies have developed tribology systems to analyze the characteristics of viscosity, friction coefficients, wear mechanisms, and the effect of temperature on lubricant performance [5], [6]. Another study also developed a sensor-based tribometer for monitoring engine condition and predictive maintenance. In addition to the quality of the lubricant, the loading factor and the construction strength of the mechanical system are also important aspects in the friction element system. Higher loads will increase the surface contact pressure, resulting in greater temperature and noise. Therefore, the construction of the test equipment must have good structural strength to withstand deformation, static stress, and vibration during the testing process. In this study, structural analysis was carried out using the finite element analysis (FEA) approach with a maximum displacement result of 0.014 mm and a safety factor of ≥ 1 so that the construction was declared safe for loading testing. Nonetheless, previous research has generally focused on laboratory testing or analysis of single parameters without integrating loading, temperature changes, and noise characteristics in a single experimental learning medium. In addition, there are still few studies that position tribology training kits as a medium for understanding concepts as well as testing the quality of lubricating oils in real-time based on real operational conditions. The research gap is the basis for the development of a more applicative, educational, and integrated testing system.

This study clarifies the concept of lubricant degradation in the form of tribology training kits based on temperature and noice aspects. The developed system integrates friction discs, variable loading mechanisms, motor rotation settings, as well as temperature sensors and noise sensors to visualize the effect of lubricant quality on the performance of frictional mechanical elements. Tests were conducted on conditions without oil, consumable oil, and new oil with load variations of 2 kg, 6 kg, and 11 kg at 981 rpm and 1489 rpm. This concept is designed as a medium for understanding lubrication principles as well as a platform for testing the quality of lubricating oils based on real-time experiments. Therefore, the purpose of this study is to develop and evaluate a smart tribology training kit that is able to detect changes in temperature and noise characteristics due to lubricant degradation under various loading conditions and engine rotation. This research also aims to produce an understanding media for tribology that is applicable, safe, and supports the strengthening of predictive maintenance competencies and condition monitoring in the vocational field.

2 Method

The design of the Smart Tribology Training Kit was carried out using an experimental engineering approach [7] based on the tribology system to analyze the effect of lubricating oil quality on temperature changes and noise levels in elements that rub against each other. The system is designed to simulate real working conditions on mechanical components through ST60 (S45C) two-disc contacts that provide a variety of load and motor rotation. The aim is to visualize the principle of lubrication, the characteristics of oil degradation, as well as the relationship between frictional force, temperature, and noise empirically. The development process includes system requirements analysis, frame construction design, structural strength simulation using finite element analysis (FEA), fabrication, assembly, sensor integration, and tool performance testing. The design analysis was carried out using Autodesk Inventor 2020 because it has the ability to model three-dimensional, simulate stress, displace, and evaluate safety factors on mechanical structures [8].

The working principle of the training kit is based on the frictional contact between the primary disc and the secondary disc which is affected by the variation in loading and lubricant quality. The system uses a 1 HP AC motor with a rotation variation of 981 rpm and 1489 rpm that is passed through a pulley and V-belt to the main shaft. Loading is given using a loading arm with a mass variation of 2 kg, 6 kg, and 11 kg. The friction between the discs results in changes in temperature and noise levels measured using infrared sensors and sound level meters. Testing was conducted under three lubrication conditions, namely no oil, consumable oil, and SAE 10W-30 new oil. Theoretically, the greater the load and the lower the quality of the lubricant, the friction coefficient increases so that the temperature and noise are higher. In contrast, oils with good viscosity are able to form a film layer that lowers direct contact between surfaces so that heat and noise can be reduced.

The analysis of tribological systems is carried out through the formulation approach of mechanics and friction characteristics. The frictional force that occurs on both discs is calculated using the equation:

Friction Force (Ff),

$$F_f = \mu N \quad (1)$$

where is the frictional force (N), is the friction coefficient, and is the normal force due to loading $F_f \mu N$.

The friction coefficient is calculated using the relationship of the friction force to the normal force as follows:

friction coefficient (μ),

$$\mu = \frac{F_f}{N} \quad (2)$$

The magnitude of the contact stress on the surface of the disc is calculated using the equation:
contact stress (σ),

$$\sigma = \frac{F}{A} \quad (3)$$

where is the contact voltage (Pa), is the loading force (N), and is the contact area of the disc surface σFA(m²)

Friction temperature analysis using the frictional energy approach:

Friction Energy (Q),

$$Q = \mu N v t \quad (4)$$

where is the frictional heat energy (J), is the frictional linear velocity (m/s), and is the test time(s). The equation shows that an increase in friction and loading coefficients causes the heat energy generated to be greater.Qvt

System rotation analysis is performed using angular velocity relationships:

Angular velocity (ω),

$$\omega = \frac{2\pi n}{60} \quad (5)$$

where is the angular velocity (rad/s) and is the rotation of the motor (rpm).ωn

The construction of the training kit frame was analyzed using FEA-based static simulations to ensure that the structure was able to withstand operational loads without experiencing excessive deformation. The frame material uses mild steel with a yield strength value of 207 MPa. Displacement, stress, and safety factor analysis was carried out using a maximum load of 40 kg. Structural stress is calculated using equations:

Stress Structure,

$$\sigma = \frac{F}{A} \quad (6)$$

While the displacement of the system was analyzed using the elastic deformation approach:

Displacement,

$$u(t) = A \sin \omega t \quad (7)$$

The structural safety factor is calculated using the equation:

Safety Factor (SF),

$$SF = \frac{\sigma_y}{\sigma_{max}} \quad (8)$$

where is SFthe safety factor, is $\sigma_y$the yield strength of the material, and is the maximum voltage of the simulation result. The structure is declared secure when the value ofσ_{max} SF ≥ 1.

Once the design meets the criteria of structural strength and operational safety, the next stage is the fabrication and performance testing of the training kit. Tests were performed to evaluate the sensitivity of temperature sensors and noise sensors to changes in lubricant quality under various loading and rev conditions. Each test was conducted for 10 minutes using 220 ml of lubricant with three test conditions, namely no oil, consumable oil, and new SAE 10W-30 oil. The observed parameters included changes in temperature and noise levels at each rotation and load variation. The test results data were then analyzed to evaluate the training kit's ability to visualize the effect of lubricant quality on the thermal and acoustic characteristics of the tribology system in real-time. Use 170 x 250 mm paper size (W x H mm) and adjust the margins to those shown in the Table 1. The final printed area will be 130 x 210 mm. Do not add any page numbers.

The performance test results data were analyzed by Pearson correlation analysis to quantify the relationships of experimental variables. The correlation coefficient (r) is calculated for four pairs of variables; load to temperature, load to noise, rotational velocity to temperature and rotational velocity to noise. Additional temperature and noise correlations are performed to assess the consistency of the dual-sensor measurement approach. Statistical significance was defined at a threshold of $p< 0.05$. All statistical analyses were conducted on the combined data set (18 observations: 6 load-rotation speed combinations × 3 lubrication conditions) and on each lubrication condition separately.

3 Result and Discussion

3.1 Smart Tribology Training Kit Construction and Fabrication Design

The initial stage of research is focused on the development of the construction of the Smart Tribology Training Kit as a medium for testing the quality of lubricating oils based on actual tribology phenomena. The system is designed using two ST60 (S45C) discs that rub against each other through a variety of loading and motor rotation to produce temperature and noise changes. This principle was developed to directly visualize the relationship between lubricant degradation, friction force, and mechanical performance. So far, lubricant quality testing has been mostly carried out through a laboratory approach using a viscometer or oil analyzer, making it difficult to represent the actual friction conditions of the engine elements. Therefore, this study positions the training kit as a medium for understanding tribology concepts as well as simulating the operational conditions of the lubrication system in real-time.

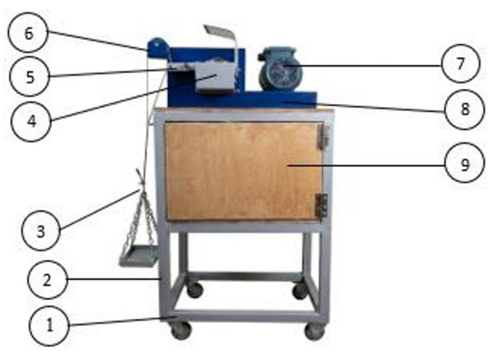

Fig. 1: The construction design and assembly *of the Smart Tribology Training Kit* consists of: (1) a drive wheel; (2) Frame trainer kits; (3) weights; (4) oil reservoir; (5) load shedding; (6) pulley; (7) AC motor; (8) Body kits; and (9) storage space (drawers).

The system construction consists of a 1 HP AC motor, a pulley and V-belt system, a main shaft, primary and secondary discs, a loading arm, an oil body, and a temperature and noise sensor (see Figure 1). Load variations are given of 2 kg, 6 kg, and 11 kg at 981 rpm and 1489 rpm. Theoretically, the increased load causes the normal force between surfaces to increase so that the friction force and working temperature are higher. In tribology systems, these conditions are directly related to the ability of lubricants to form a layer of film (lubricating film) to reduce direct contact between surface asperities. Previous studies have explained that the viscosity quality of lubricants greatly determines the friction reduction and heat distribution ability of mechanical systems. However, some other studies have shown that increased viscosity does not always result in optimal performance because over-thick lubricants can increase mechanical resistance and energy consumption. This condition suggests that lubrication performance is affected by the complex interactions between viscosity, loading, and rotational speed.

The development of this training kit shows a different approach compared to previous studies that used more laboratory-scale tribometers without the integration of conceptual understanding media [9]. Some studies support the use of sensor-based monitoring systems for predictive maintenance because they are able to provide real-time information on engine conditions [10]. However, there is criticism that industrial monitoring systems tend to be complex, expensive, and difficult to apply in understanding and skills in vocational. This study tries to bridge the gap through a simple training kit approach but is still able to show the actual tribological phenomenon. In the context of modern conceptual understanding, this approach is relevant to strengthening the competence of condition monitoring and smart maintenance in the Industry 4.0 era because it not only understands theoretical concepts, but also conducts empirical observations on changes in lubrication characteristics.

3.2 Static Analysis of Construction and Load Stability

Static analysis was carried out to ensure that the construction of the training kit was able to accept operational loads without deformation or structural failure. The simulation was carried out using Autodesk Inventor 2020 based on finite element analysis (FEA) with mild steel material which has a yield strength of 207 MPa and an elastic modulus of 220 GPa. The analysis showed a maximum displacement of 0.014 mm with a maximum voltage of 2.706 MPa at a load of 40 kg. A safety factor value of 1.208 indicates that the structure is still in the safe category for use in load-based tribology testing (see Fig. 2).

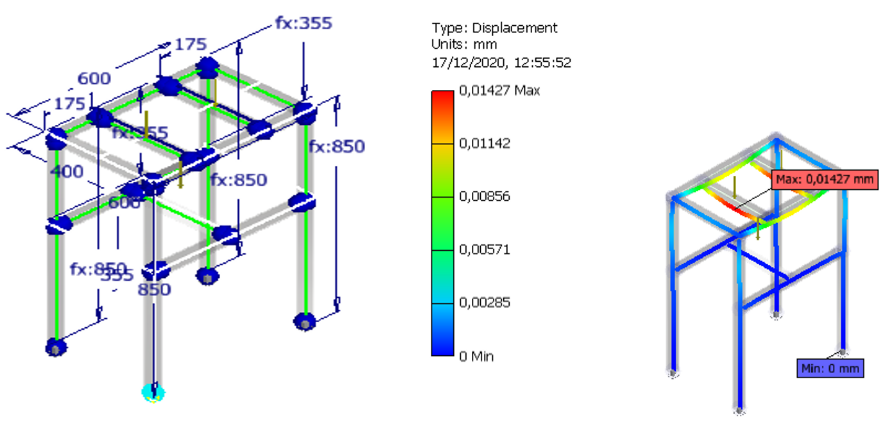

Fig. 2: Results of static simulation of training kit construction: (a) stress *distribution*, (b) frame displacement.

These findings suggest that structural stability has an important influence on the accuracy of tribological testing. In the loading system, too large a deformation can cause a change in the normal force distribution so that temperature and noise readings become unstable. Some studies support the use of FEA in mechanical system design because it is able to effectively predict stress distribution and critical points of structural failure [11]. Other studies show that numerical simulations often differ from actual conditions due to the influence of vibration, welding joints, and dynamic contacts during operations [12]. Therefore, this study does not only rely on structural simulations but also performs performance validation directly through experimental testing.

3.3 Temperature and Noise Performance Testing

Performance testing is performed to evaluate the sensitivity of the training kit in detecting changes in temperature and noise levels due to variations in lubricant quality. The test was conducted under three conditions, namely no oil, SAE 10W-30 consumable oil, and SAE 10W-30 new oil for 10 minutes of testing. The results showed that increased loading and motor revs caused the temperature and noise to increase significantly, especially in conditions without lubricants. At 1489 rpm and 11 kg load, the oilless temperature reaches 35.7°C with a noise level of 99.9 dBa. Meanwhile, the use of new oil produces a lower temperature of 32.2°C with a noise of 89.2 dBa (see Table 1).

Tabel 1: Performance test results of training kits based on temperature changes and noise levels

Speed	Load	Temperature Δ*T*			Noise		
(Rpm/Hz)	(Kg)	No Oil	Used Oil	New Oil	No Oil	Used Oil	New Oil
981/30	2	32.4	31.0	30.0	89.9	84.5	81.8
	6	31.8	31.2	30.6	94.3	85.0	82.8
	11	34.1	31.9	31.5	97.5	88.0	85.0
1489/50	2	33.6	31.5	31.0	92.0	86.3	83.5
	6	35.0	31.7	30.8	98.0	88.8	86.4
	11	35.7	32.7	32.2	99.9	91.6	89.2

These results show that the quality of the lubricant has a direct effect on the ability to reduce heat and noise due to friction. In the tribology concept, lubricants that still have good viscosity are able to form a film layer that reduces direct contact with metals so that the friction coefficient becomes lower. In contrast, consumable oils undergo viscosity degradation due to oxidation and contamination so that friction reduction ability decreases. These findings support previous studies that have shown that lubricant degradation is correlated with increased temperature, vibration, and acoustic emissions in rotating machinery systems [13]. However, several other studies have stated that temperature and noise are not only affected by lubricant quality but also by material surface conditions, disc roughness, shaft alignment, and loading stability [14]. This shows that tribological phenomena are multidimensional and cannot be explained through a single parameter. Therefore, the integration of temperature and noise sensors in this study is an important approach to produce a more comprehensive understanding of the behavior of lubrication systems.

Table 2 shows that the new oil is able to reduce average temperatures by 8.1% and average noise by 10.9% against no oil conditions across the combination of speed and load. The consumable oil achieves an intermediate reduction (an average of 6.1% temperature and 8.2% noise), confirming that the degradation of lubricants measurably decreases the capacity of the protective film to form. The magnitude of the noise reduction (10.9%) that slightly exceeds the temperature reduction (8.1%) is consistent with the multi-mechanism nature of triboacoustic emissions, the lubricant simultaneously suppresses the dissipation of macrothermal energy and the high-frequency asperity interaction event that produces acoustic emissions.

Tabel 2: Temperature and noise reduction percentage matrix across test conditions

Speed	Load	Temperature Reduction (%)			Noise Reduction (%)		
(Rpm/Hz)	(Kg)	Used Oil vs No Oil	New Oil vs No Oil	New Oil vs Used Oil	Used Oil vs No Oil	New Oil vs No Oil	New Oil vs Used Oil
981/30	2	4.3	7.4	3.2	6.0	9.0	3.2
	6	1.9	3.8	1.9	9.9	12.2	2.6
	11	6.5	7.6	1.3	9.7	12.8	3.4
1489/50	2	6.3	7.7	1.6	6.2	9.2	3.2
	6	9.4	12.0	2.8	9.4	11.8	2.7
	11	8.4	9.8	1.5	8.3	10.7	2.6
Average		**6.1**	**8.1**	**2.1**	**8.2**	**10.9**	**3.0**

Pearson correlation analysis was used to quantify relationships between variables across all 18 observations. The analysis demonstrated that both parameters responded consistently to the same tribological phenomenon, exhibiting a very strong and statistically significant positive correlation between temperature and noise ($r = 0.934$, $p < 0.001$). Under new oil conditions, there was a significant positive correlation between load and temperature based on lubrication condition ($r = 0.813$, $p = 0.049$) and under no oil conditions, there was a significant positive correlation between load and noise based on lubrication condition ($r = 0.886$, $p = 0.019$). On the other hand, the global correlation between load and temperature ($r = 0.398$, $p = 0.102$), load and noise ($r = 0.425$, $p = 0.079$), rotational speed and temperature ($r = 0.359$, $p = 0.144$) and rotational speed and noise ($r = 0.282$, $p = 0.256$) were not statistically significant on the combined dataset. The pattern shows that lubricant quality is the most important explanatory variable in the test range used, masking the individual statistical effects of load and rotational speed when all lubrication conditions are combined.

4 Conclusion

This study successfully developed Smart Tribology Training Kit as an integrated experimental platform that can visualize lubricant degradation by real-time temperature and acoustic monitoring. Results showed that the quality of the lubricant has a direct impact on the stability of the mechanical system. The use of new lubricant resulted in consistently lower temperatures and noise than when the system was used with used or no lubricant. Structural analysis showed that the system has adequate rigidity to allow for reliable testing. The results show the potential of integrating temperature, noise and load monitoring into predictive maintenance and IoT-based smart lubrication systems for Industry 4.0 applications. However, there are still several limitations such as the lack of sensor calibration, uncontrolled environmental conditions, absence of experimental replication and a relatively low structural safety factor that might influence the accuracy of the measurements and the generalizability of the results. Future studies should use calibrated instruments, controlled testing environments, replicated experiments and improved structural designs for the system to improve its reliability and practical applicability.

This publication was funded by the Indonesia Endowment Fund for Education (LPDP) on behalf of the Indonesian Ministry of Higher Education, Science and Technology, and managed under the EQUITY Program (Contract Number 4308/B3/DT.03.08/2025 and B/284/UN39/HK.07.00/2025).

References

1. W. Chokelarb, P. Sriprom, Heliyon 10, e37486 (2024). https://doi.org/10.1016/j.heliyon.2024.e37486
2. I. Minami, Appl. Sci. 7, 445 (2017). https://doi.org/10.3390/app7050445
3. J. Li, Z. Zhou, X. Jiao, et al., Surf. Interfaces 53, 105037 (2024). https://doi.org/10.1016/j.surfin.2024.105037
4. R. Su, et al., Lubricants 12, 116 (2024). https://doi.org/10.3390/lubricants12040116
5. J.A. Heredia-Cancino, M. Ramezani, M.E. Álvarez-Ramos, Tribol. Int. 124, 230 (2018). https://doi.org/10.1016/j.triboint.2018.04.015
6. F. Cyriac, T.X. Yi, S.K. Poornachary, et al., Tribol. Int. 157, 106896 (2021). https://doi.org/10.1016/j.triboint.2021.106896
7. D.M. Buede, W.D. Miller, The Engineering Design of Systems: Models and Methods, 4th edn. (John Wiley & Sons, Canada, 2024)
8. S. Ruiz de Galarreta, J.R.T. Jeffers, S. Ghouse, Mater. Des. 189, 108546 (2020). https://doi.org/10.1016/j.matdes.2020.108546
9. M. Marian, S. Tremmel, Lubricants 9, 86 (2021). https://doi.org/10.3390/lubricants9090086
10. M. Pech, J. Vrchota, J. Bednář, Sensors 21, 1470 (2021). https://doi.org/10.3390/s21041470
11. A.A. Chojaczyk, A.P. Teixeira, L.C. Neves, et al., Struct. Saf. 52, 78 (2015). https://doi.org/10.1016/j.strusafe.2014.09.002
12. M. Abbasi, B. Bagheri, F. Sharifi, Trans. Nonferrous Met. Soc. China 31, 2626 (2021). https://doi.org/10.1016/S1003-6326(21)65681-9
13. P. Feng, P. Borghesani, W.A. Smith, et al., Appl. Mech. Rev. 72, 020801 (2019). https://doi.org/10.1115/1.4044799
14. X. Guo, et al., Lubricants 14, 107 (2026). https://doi.org/10.3390/lubricants14030107