# Integrated Approach for Health Assessment of IC Engine Bearings through Numerical Simulation

M.D. Haneef, R.B. Randall, W.A. Smith, Z. Peng

*School of Mechanical and Manufacturing Engineering, University of New South Wales,*
*UNSW Sydney, NSW 2052, Sydney, Australia*

## Abstract

Wear is known to be the cause of most failures in machine components. A major challenge associated with direct and regular wear monitoring is the need for extensive and recurring inspection. This work presents a simulation based method to predict the wear profile through integrating wear and vibration based data, which can be used to predict remaining useful life (RUL) of machine components. The application is demonstrated on, but not limited to, internal combustion (IC) engine bearings. A new hybrid model was developed to assess the wear behaviour of journal bearings operating in a range of lubrication regimes. In this model, the calculated bearing dynamic forces from increased clearance due to wear have been used for a realistic representation of the bearing lubrication and wear rate prediction. It was found that regions with minimum lubrication were more affected by impacts and thus sustained most wear. The simulated wear profiles and vibration signals resulting from impacts showed strong correspondence. The model is capable of simulating the engine operation, and when vibration and/or wear debris measurements are made, they can be used to estimate the current wear profile and update the wear prediction model. This development allows the study of key performance parameters and can effectively predict wear locations and severity in bearings as well as their RUL.

**Keywords:** Dynamic Simulation, Fault Detection, Wear Analysis, Vibration Analysis, Integrated Approach,

## Introduction

Journal bearings are ideally designed to operate with full film lubrication, however, due to the increasing demands of compactness, together with the need for higher power and speeds, the bearings are often exposed to more severe operating environment [1]. Therefore, effective monitoring of journal bearings used in IC engines is vital as they are highly likely to incur premature failures due to inconsistent operating conditions [2, 3]. This means that it is essential to have an assessment of the remaining useful lifetime to minimize maintenance costs and potential production losses. The most direct method to obtain information about the wear of a particular component is by visual inspection [4]. However, complete dismantling of machines during service is practically unmanageable due to high cost and associated downtime. The other most commonly and widely used technique to identify wear in reciprocating machine components, including bearings, is the ‘wear debris analysis’ method [5]. In this method, the number and nature of particles in oil samples collected from a machine from time to time are used as an indicator of wear progression over time. Another important fault indicator is the resultant vibration response originating from the forces between mechanical elements because of relative motion. A particular combination of contact conditions has a unique vibration response associated with it and any change in engine condition will cause a change in contact forces and hence the consequent vibration signals, which can be used as an indicator of abnormality [6]. All of these techniques have their advantages and disadvantages and independently they can detect only a moderate proportion of faults [7], and so contemporary research is focused on integrating various techniques for more effective condition monitoring programs. These studies suggest that combining these techniques can result in cost benefits to industry due to greater and more reliable information about the health of machine components [8]. The main challenge associated with developing wear indicators for IC engine bearings is the need for an immense amount of data to take account of various operating conditions and bearing geometric imperfections. The amount of experimental work involved in seeding faults and recording the resultant vibration signals and wear debris analysis would be enormous and tedious. Furthermore, running bearings to failure for all combinations of operating conditions on a test engine is infeasible.

Due to this difficulty, much research is centred on developing computer simulation models to generate fault indicators such as vibration signals [9, 10], tribological circumstances and resulting wear behaviour of journal bearings [11]. However, none of the available studies reported integration of the simulated vibration signals with the modelled tribological parameters and corresponding wear. This paper outlines the development of a simulation based technique to integrate wear and vibration based analysis methods for diagnosis and prognosis of engine bearings. The simulated wear profile and vibration signal are ultimately used to predict the remaining useful lifetime of the bearing.

## Simulation Development

The simulation is based on the combined implementation of different mathematical models, which govern the dynamics of each sub-section pertaining to different mechanisms. It is therefore essential that all subsystems are synchronised and work in conjunction with each other. These mainly include the engine dynamics, hydrodynamic lubrication, mixed lubrication model, Hertz contact law, Coulomb’s friction law and wear prediction models. A schematic of the simulation implementation algorithm is shown in Fig. 1.

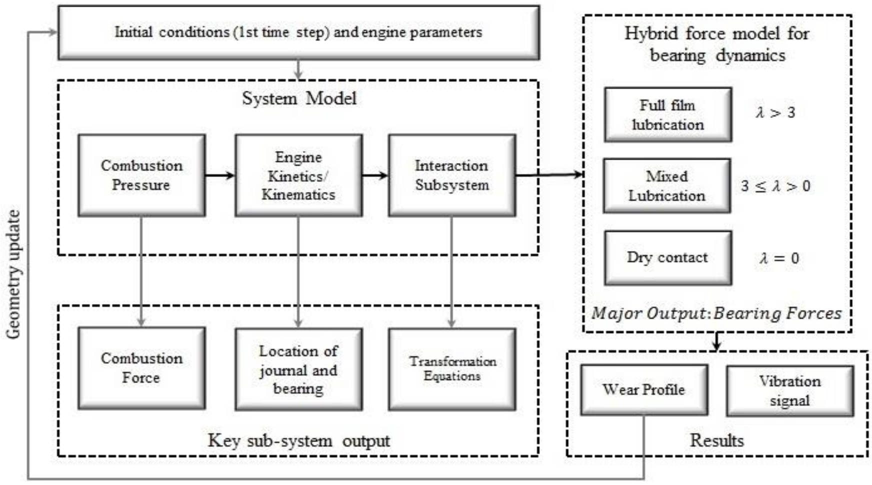

*Fig. 1: Schematic of simulation implementation algorithm*

The key initial conditions are the displacements and velocities of the piston, crankshaft and the connecting rod, that are established based on the operating condition and the developed engine kinematics. The major input to the simulation is the combustion force, which is carefully simulated for each case to achieve a steady state running speed of the engine. With increasing engine speed and growing bearing clearance (due to wear), the magnitude of the engines’ inertial forces increases. This initiates the diminishing of the oil film, causing high impact forces in the bearing which are evaluated by the hybrid force model (top right in Fig. 1). The bearing forces are the key output of the simulation, which depend on the state of lubrication at each instant, as determined by the oil film parameter $\lambda$ [12], and are used for wear and vibration simulation. Details about the mathematical formulation of each subsystem, the initial conditions and the engine parameters used in the simulation can be found in [13]. The following sections discuss the results and methods pertaining to wear and vibration analysis for fault detection and then the use of vibration based data for wear and RUL prediction.

## Simulation of Wear Profiles and Vibration Signals

As a consequence of oil film depletion and direct contact the wear exposure and severity increases. A detailed investigation of the wear situation for various combinations of speed, clearance and external loads, through developed simulation, is presented in [13]. In that recent work by the authors, the simulated bearing forces were used to estimate the wear profiles under a range of operating conditions. However, that work was aimed at demonstrating the use of the developed model for wear profile prediction by using the simulated bearing forces. The current work expands the use of the developed simulation to obtain the vibration signals resulting from wear and study their compliance with the simulated wear profiles and ultimately for predicting RUL. At first, to demonstrate the capability of the model to closely predict the wear profiles a comparison of the experimental [14] and model predicted wear profiles for a case of 7000 rpm and with 80 N.m external toque, operated for 100 hours is presented in Fig. 2. It is observed that a similar profile is obtained for both the cases, and the results show a good agreement with major wear occurring at 0°/360°. This implies that the presented method is successful in predicting the wear profile and calculating the wear depths at each instant.

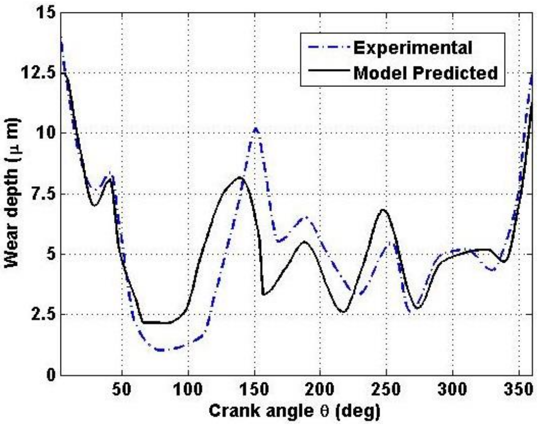

*Fig. 2: Wear depth experimental [14] and model predicted*

The vibration signals were simulated using the obtained bearing forces from the model, the method being validated by experimental data collected from a Toyota 3S-FE 2.0 L engine available in the UNSW engine test laboratory [10]. The experimental vibration signals were obtained for 27 combinations of three speeds (1500/2000/3000 rpm), three external torques (50/80/110 N.m) and three clearances (0.1/0.2/0.4 mm). The information of interest about the fault is contained in the repetition frequency and pattern of impulses rather than the raw frequency content, so envelope analysis is the most suitable technique to process the vibration signals for fault detection [14, 15].

Fig. *3* (a) – (b) show the experimental and simulated squared envelopes, respectively, for the case of 3000 rpm/80N.m torque and operation at 4 times the normal clearance (0.4 mm). The impact locations corresponding to crank angular rotation were correctly revealed from both the experimental and simulated vibration signals. However, the amplitude of the simulated envelope is lower than that of the experimental one, due to the fact that the frequency response functions used for the simulation of vibration signals cut off at 6400 Hz, whereas the experimental vibration signals were recorded with a frequency range of 25600 Hz. Note that the 540° mark in Fig. 3 (a) and (b), corresponds to the 0° mark in the wear analysis results presented in Fig. 2. For all the 27 cases considered, the simulated vibration signals matched well with the experimentally obtained signals and also confirmed the critical wear locations identified during the wear analysis.

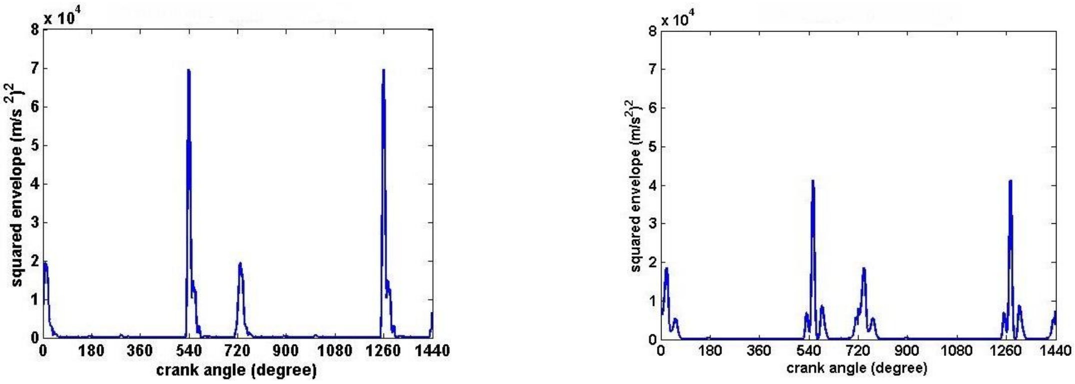

*Fig. 3: Squared envelope at 3000 rpm/80 N.m torque (a) experimental [10], and (b) model predicted*

To establish a direct quantitative correlation between the wear and vibration based analysis, appropriate indicators were selected from both types of data and were combined. Three vibration based indicators were selected from the simulated vibration signals, namely, the amplitude of Fourier coefficients (V1), the area under the curve of the squared envelopes (V2) and the I-Kaz Coefficient (V3) [17]. Two wear based indicators were also selected: the bearing clearance (W1), which is an indicator of wear depth, and the instantaneous wear rate (W2). A correlation analysis in pairs was performed between W1 and V1, V2 and V3. The I-Kaz coefficient (V3) of the vibration signals was found to be the most strongly correlated with the bearing clearance (W1) with a correlation coefficient of 0.9567. This implies that the changes in bearing geometry were picked up by the vibration signals promptly and the I-Kaz coefficient of the vibration signal was found to be a reliable indicator of the wear situation.

## Wear Estimation and Prediction Using Developed Simulation

In the previous section it was stated that the bearing clearance (W1) is strongly correlated with the I-Kaz coefficient (V3) of the simulated vibration signals. In this section the method of using a known vibration signal for estimation of worn bearing clearance is discussed first. Fig. 4 shows the polynomial (3rd order) best-fit curve for bearing clearance (W1) vs I-Kaz coefficient (V3) for the case of 7000 rpm operated for 100 hours, giving the relationship:

$$W1 = (3.528 \times 10^7 \times V3^3 - 2.522 \times 10^4 \times V3^2 - 19.62 \times V3 + 0.09961)\, mm \qquad (1)$$

The developed relation in Eq. (1) allows determination of the bearing clearance (and wear depth) at any instant of engine operation at a given speed, provided the vibration signal is known. Similar curves can be generated through simulation for any given set of operating conditions (constant and variable) to have a reliable estimate of the wear situation in the bearing at any instant, without physically inspecting it.

Moreover, the other wear based indicator mentioned in the previous section which is the instantaneous wear rate (W2) is also an important outcome of the simulation as it provides a direct estimate of how fast the bearing wears for a given set of operating conditions. A plot of wear rate (mm/s) variation verses time (T) for the same case of 7000 rpm/80 N.m torque is shown in Fig. 5. The information about the wear depth at any instant can be conveniently obtained by integrating the wear rate curve fitted Eq. (2) over the intended time interval.

$$W2 = [(2.635 \times 10^{-19}) \times T^2 + (2.043 \times 10^{-13}) \times T - (1.174 \times 10^{-9})]\ mm/s \qquad (2)$$

Similar curves can be generated for a range of different speed and clearance conditions. A plot of the wear rate verses time for a duration of 500 hours operated at variable speeds is shown in Fig. 6. The respective wear depths ($\Delta_i\ , i = A - E$) at the end of each session (A-E) of 100 hours was calculated by integrating the corresponding wear rate curve over the running time, and are also shown in Fig. 6. The total wear depth at the end of 500 hours is obtained by adding the wear depths obtained in each interval which is found to be 23.82 µm. Thus the prediction of the remaining lifetime of the bearings operated at any given service condition can be performed.

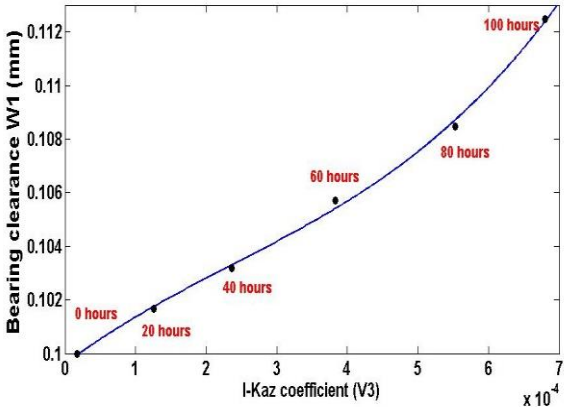

*Fig. 4: Relation between V3 and W1 - 7000 rpm (100 hours)*

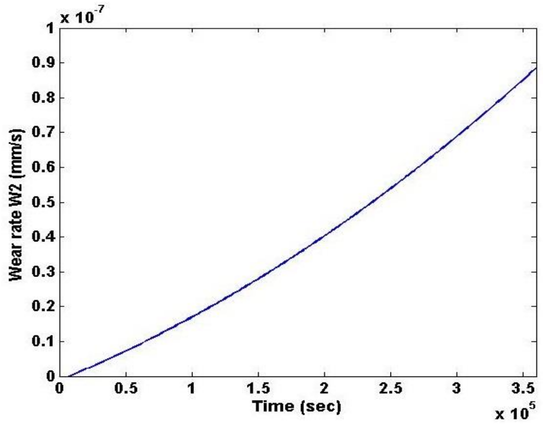

*Fig. 5: Instantaneous wear rate vs time (7000 rpm)*

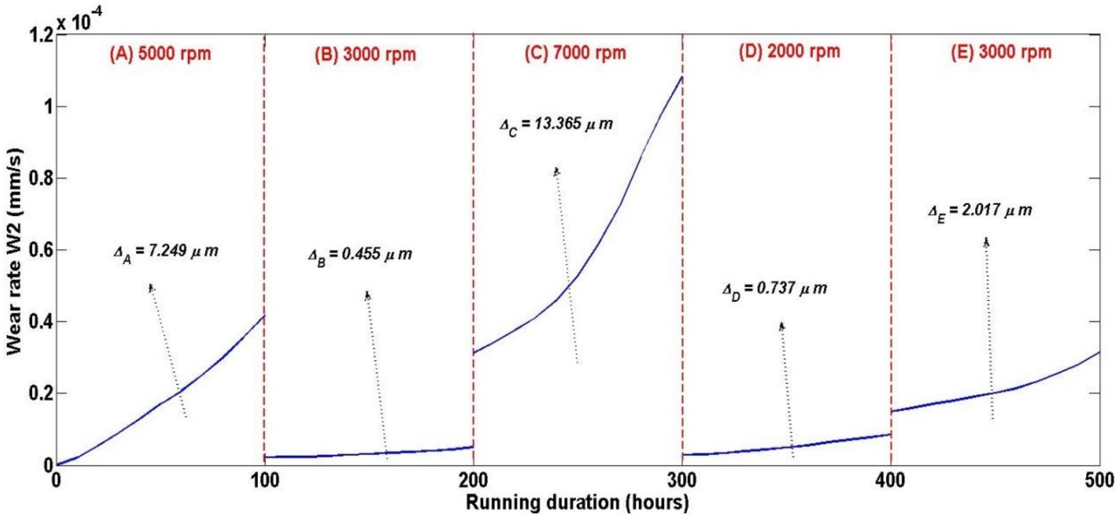

*Fig. 6: Wear Rate variation at variable speed conditions (500 hours of operation)*

It is seen that the goal of integrating the wear and vibration based techniques for effective wear estimation and RUL prediction was achieved through the simulation. The accuracy of the results can be further improved by updating the physics-based simulation with more experimental data, especially at higher speed conditions, for better correlation. Though in this work the research was conducted with reference to a particular engine (Toyota 3SFE 2.0 litre), the simulation is not limited to this. The methodology is universal in that it can be adjusted to study wear in the bearings of any engine, provided the engine parameters are updated accordingly.

## Conclusion

The developed method proved to be useful in providing close estimates of the wear depth and prediction of the remaining useful lifetime of the bearings, under given operating conditions. Overall, the hybrid simulation was found to be an effective tool to estimate engine bearing wear and to establish correlation between the changing operating conditions and corresponding variations in wear depth and resulting vibration signals at any given instant of time. The methodology can be used to develop the wear maps of the bearing for any range of intended operating conditions of the engine, to keep track of wear and have an estimate of the deterioration in its performance over time. The objectives of acquiring both the diagnostic and prognostic measures through the combined wear and vibration based approach are thus accomplished, through the developed simulation based method.

## References

1. Wang, Q., F. Shi & S.C. Lee, A Mixed-Lubrication Study of Journal Bearing Conformal Contacts. Journal of Tribology, 1997. 119(3): p. 456-461.
2. Dufrane, K.F., T.H. McCloskey & J.W. Kannel, Wear of Steam Turbine Journal Bearings at Low Operating Speeds. Journal of Lubrication Technology, 1983. 105(3): p. 313-317.
3. Taylor, C.M., Automobile engine tribology—design considerations for efficiency and durability. Wear, 1998. 221(1): p. 1-8.
4. Tsang, A.H.C., Condition based maintenance: tools and decision making. Journal of Quality in Maintenance Engineering, 1995. 1(3): p. 3-17.
5. Macián, V., Tormos, B., Olmeda, P. & Montoro, L., Analytical approach to wear rate determination for internal combustion engine condition monitoring based on oil analysis. Tribology International, 2003.36(10): p.771-776
6. Dalpiaz, G., A. Rivola, & R. Rubini, Effectiveness and sensitivity of vibration processing techniques for local fault detection in gears. Mechanical Systems and Signal Processing, 2000. 14(3): p. 387-412.
7. Peng, Z., N.J. Kessissoglou & M. Cox, A study of the effect of contaminant particles in lubricants using wear debris and vibration condition monitoring techniques. Wear, 2005. 258(11–12): p. 1651-1662.
8. Loutas, T.H., Roulias, D., Pauly & E., Kostopoulos, V., The combined use of vibration, acoustic emission and oil debris on-line monitoring towards a more effective condition monitoring of rotating machinery. Mechanical Systems and Signal Processing, 2011. 25(4): p. 1339-1352.
9. Chi, J.N., Non-invasive Diagnostics of Excessive Bearing Clearance in Reciprocating Machinery. 1995: PhD Thesis, Massachusetts Institute of Technology, Department of Mechanical Engineering.
10. Chen, J., Randall, R., Feng, N. & Peeters, B., Modelling and diagnosis of big-end bearing knock fault in internal combustion engines. Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science, 2014.
11. Bai, Z.F., H.B. Zhang & Y. Sun, Wear prediction for dry revolute joint with clearance in multibody system by integrating dynamics model and wear model. Latin American Journal of Solids and Structures, 2014. 11: p. 2624-2647.
12. Shahmohamadi, H., Rahmani, R., Rahnejat, H., Garner, C. P., & Dowson, D., Big End Bearing Losses with Thermal Cavitation Flow Under Cylinder Deactivation. Tribology Letters, 2015. 57(1): p. 1-17.
13. Haneef, M.D., R.B. Randall & Z. Peng, Wear profile prediction of IC engine bearings by dynamic simulation. Wear, 2016. 364–365: p. 84-102.
14. Ushijima, K., Aoyama, S., Kitahara, K., Okamoto, Y., Jones, G., & Xu, H., A Study on Engine Bearing Wear and Fatigue Using EHL Analysis and Experimental Analysis. 1999, SAE International.
15. Randall, R.B., J. Antoni & S. Chobsaard, The relationship between spectral correlation and envelope analysis in the diagnostics of bearing faults and other cyclostationary machine signals. Mechanical Systems and Signal Processing, 2001. 15(5): p. 945-962.
16. Randall, R.B., Vibration-based Condition Monitoring: Industrial, Aerospace and Automotive Applications. 2011: Wiley.
17. Nuawi, M. Z., Nor, M. J. M., Jamaludin, N., Abdullah, S., Lamin, F. & Nizwan, C. K. E., Development of integrated kurtosis-based algorithm for z-filter technique. Journal of applied sciences, 2008. 8(8): p. 1541-1547.