JETIR.ORG ISSN: 2349-5162 | ESTD Year : 2014 | Monthly Issue
JOURNAL OF EMERGING TECHNOLOGIES AND INNOVATIVE RESEARCH (JETIR)
An International Scholarly Open Access, Peer-reviewed, Refereed Journal

Investigating Pin Tick Noise and Bushing Wear in Heavy-Duty Applications: A Root Cause Analysis

Author: Vikrant Rayate
Powertrain Design Release Engineer
vikrant.rayate3086@gmail.com

Abstract

This research has been carried out for the validation of the reasons for the pin-tick noise and bushing wear in heavy-duty applications. Interaction among the rod bore roundness, piston pin surface finish, and lubrication best practices was determined through a multifunctional experimental analysis, dyno testing, and root cause analysis trees. Initial hypotheses were the dimensional differences of the rod ends; but further research brought to light that the major role was played by the surface finish of the piston pin and lubrication. It is in this direction where the present work tries to bring out the underlying mechanisms for wear and noise and suggest engineering solutions with systematic evaluation of all potential causes, which include material properties, principles of manufacturing processes to a large extent, and operational parameters.

Word count: 3,688

Keywords: Pin-tick noise, Bushing wear, Heavy-duty applications, Experimental analysis, Dyno testing, Root cause analysis trees, Rod bore roundness, Piston pin surface finish, Lubrication practices, Dimensional discrepancies, Material properties, Manufacturing processes, Operational parameters, Wear and noise mechanisms, Engineering solutions.

1. Introduction

Some of the heavy-duty applications require the performance and reliability of mechanical components for their efficient operation and the dependability of the systems in which they perform the functions. An important problem, which has considerably attracted attention recently, is known as pin-tick noise and bushing wear, which may substantially reduce the lifetime and the operability of machinery. This paper describes the systematic root cause analysis to find out the main factors responsible for the cause. The interaction between component geometries, surface finishes, and lubrication practices becomes therefore very complex. With this motivation for the investigation being to enhance understanding of the root causes of pin tick noise and bushing wear, a foundation should be laid in developing effective strategies to mitigate these into the future of engineering designs and maintenance practices. Overall, this introduction gives much importance to the study at hand and hints that the study could prove to have tremendous contribution to this field.

2. Literature Review

A mixed lubrication model for heavy-duty piston pin joints was further developed by Vladimir Fridman et al. [1], whereby the contact pressure and heat generation have been analyzed that lead to recommendations to reduce asperity contact and wear by surface shape modifications. Chris Hall et al. [2] have identified and reduced the piston pin joint tick noise in engines with the help of a change in the shape of the pin bore, which has enhanced NVH characteristics and eliminated noise during the operation of the engine. Jean-Louis Ligier and Patrick Ragot [3] addressed the severe conditions of piston pin wear in modern engines, proposing design recommendations by numerical simulations that consider mixed lubrication. Sławomir Kowalski et al. [4] studied the wear mechanisms of piston pins, elaborating on the development of lubrication failure and oil contamination as other major factors responsible for causing failures in an engine's running course, thus putting forward the necessity of proper lubrication. Archana Singh et al. [5] researched the effects of lubricant degradation on wear, using steel pin wear tests to reach the conclusion that aging, which naturally accompanies wear, accelerates decomposition of oil by decreasing the effectiveness of antioxidants, hence increasing wear. A test rig was developed by John Truhan et al. [6] to measure friction and wear in heavy-duty diesel engine piston rings and cylinder liners. Their result showed that oil condition and viscosity had immense effects on wear rate under boundary lubrication.

Michael Schuetz and Gary McIntyre [7] developed solid lubricant coatings for automotive pistons that improve wear resistance and reduce friction under very challenging operating conditions, allowing modern internal combustion engines to run with better performance and durability. Roman Morgenstern et al. [8] investigated the utilization of DLC coatings on piston pins, which showed, clearly, reduced frictional losses and wear with improved mileage and fuel economy for automotive diesel engines. Bifeng Yin et al. [9] researched the adaptability of various piston skirt coatings under low-viscosity lubricants for heavy-duty diesel engines and arrived at the conclusion that MoS2 coating has better friction and wear resistance to improve engine performance and durability. K. Selby et al. [10] focused on lubrication problems stemming from low-emission diesel engines by formulating oils with a view toward meeting very stringent emission standards while maintaining sufficient wear protection and cleanliness in an engine. Edney Deschauer Rejowski et al. [11] studied the application of DLC coatings on cylinder liners, which showed a specific fuel consumption reduction of 2.5% and good wear resistance in heavy-duty diesel engines. B.C. T.H.C. Childs and F. Sabbagh [12] studied the boundary lubricated wear of cast irons to estimate automotive piston ring wear.

3. Approach

3.1 Initial hypothesis

First, we had assumed that the source of the problem might be in the small end-dimensions of the rod. We therefore decided to study the dimensions at the small ends of these rods. Some interesting observations showed from the long-term capability data for both the housing diameter and the roundness of the rods. They seemed to favor one side of the limit.

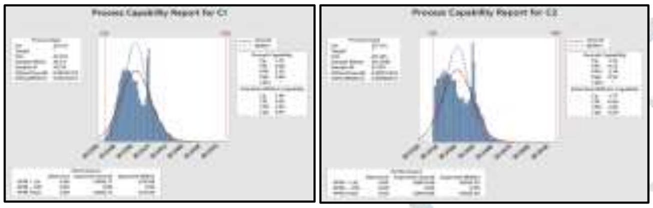

Figure 1: Rod Parent Bore Long Term Capability (Average Diameter)

Measurements of the rod diameter at multiple points, both in the upper and lower sections, were found to approach the minimum & maximum specified limits respectively.

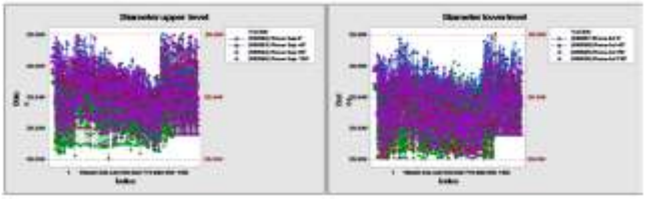

Figure 2: Rod Parent Bore Long Term Data (Both Upper & Lower Level)

The dimensions of the rod-bore housing surpassed the standard limit of 10 µm, which is typically considered to be the upper limit for this type of component.

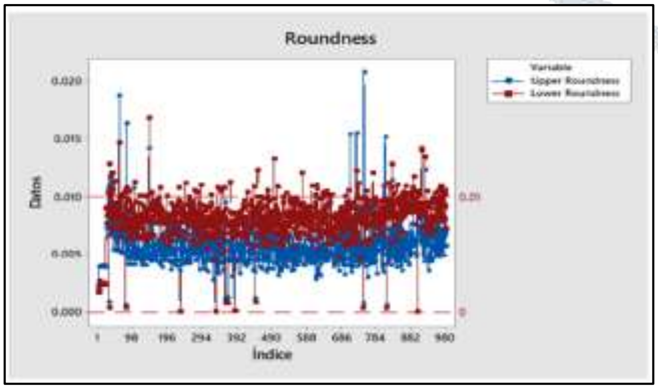

Figure 3: Parent Bore Roundness Long Term Capability

Because of the massive difference in data and the increased allowance for roundness, we tried to evaluate the interaction of the housing bore with the bushing that was latter inserted. In this test, we used four various levels of rod parent bore roundness: 10, 20, 30, and 40 µm. The result of the test indicated that the housing roundness showed an increased contact while that of the rod bore roundness decreased.


Dye Test – 10 microns roundness

- Good contact between bushing and bore

Dye Test – 20 microns roundness

- Non clean up at vertical direction
- Missing some contact

Figure 4: Dye test with 10 microns & 20 microns roundness


Dye Test – 30 microns roundness

- Major non-clean up in vertical direction
- Not enough bushing contact

Dye Test – 40 microns roundness

- No contact between bushing and bore

Figure 5: Dye test with 30 microns & 40 microns roundness

This experiment's results suggested that higher levels of roundness may give rise to inadequate contact. We wanted to determine the effects of this on bushing wear. Has the roundness of the housing correlated with rod bushing wear?

3.2 Dyno Testing

Based on the bench testing performed for rod bore and bushing contact analysis, dyno testing was done with different combinations of housing bore roundness and at different pressures with the bushing.

Conrod Number	Conrod VI ID	Pin Roundness Top	Pin Roundness Bottom	Engine Run #1 Cylider Number	Engine Run # 2 Cylider Number
17	MV	0.0101	0.0109		1
23	DL	0.0102	0.0105		4
24	OK	0.0104	0.0102	8	
18	JF	0.0106	0.0103	6	
20	OJ	0.0106	0.0104	1	
15	ZR	0.0172	0.0189		2
9	ZV	0.0175	0.0168		5
13	AG	0.0180	0.0184		7
16	OJ	0.0196	0.0187	5	
14	AF	0.0197	0.0191	2	
5	AA	0.0268	0.0256		3
4	AC	0.0272	0.0286		6
2	AE	0.0274	0.0256		8
8	ZX	0.0276	0.0265	7	
3	ZQ	0.0292	0.0285	4	
7	ZY	0.0298	0.0294	3	

Figure 6: Engine configuration with housing roundness

A generic durability test of 100 h of operation was conducted for this engine configuration. In all, the two engines ran 16 rods. There is no strong correlation noted between the rod parent bore roundness and the post-test bushing wear along with the resulting clearance.

Figure 7: Engine rod roundness vs. post-test rod wear & clearance

3.3 Root Cause Analysis Tree

Doubtless, our team agreed to re-think the situation with a more structured approach and relevant problem-solving techniques. For this purpose, we developed a root cause analysis tree in which all possible failure causes were incorporated [13]. Every part of the machine, measurement, man, method, mother nature, and material that would have caused that problem under discussion was critically analyzed. For each such parameter, we assessed the data and the information associated with it and transformed the said parameter into green status if enough information is available. Unfortunately, two items remain somewhat unclear, yet the finish of the piston pin and incorrect lubrication cause two bodies to be marked out in red, indicating that they need inquiry.

Figure 8: Root Cause Analysis Tree

3.4 Piston Pin Surface Finish Investigation

Based on the information from the root cause analysis tree, we decided to investigate the piston pin surface finish further. We focused on the faulty engine returns and saw that very little or very minimal graphitization was evident on the piston pins. To get a better idea, we looked at these pins compared to those from good engines that were free of wear. The pins from the good engines clearly showed graphitization, unlike the pins from faulty engines.

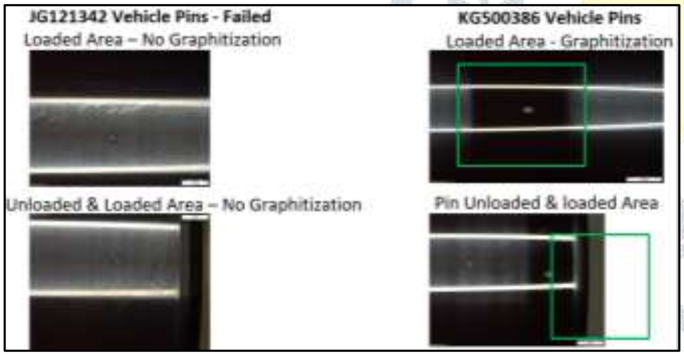

Figure 9: Piston Pin Non Graphitization Vs. Graphitization

I have consulted the supplier on that issue. They told me it was due to the surface peaks of the piston pin. They also had that same problem before with other customers. They gave me a solution, that is, they could add a surface finish specification to control both the peak height and the number of peaks. This is called "RfpH5n", and it is the average of the five highest peaks times the number of peaks per millimeter. A further pin polish operation is necessary to achieve RfpH5n, therefore, the pins treated for "Rfp5Hn" are post polished pins.

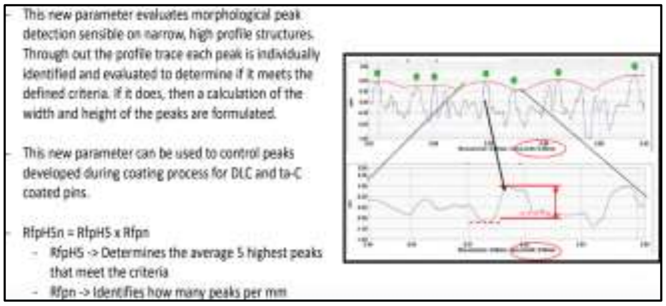
- This new parameter evaluates morphological peak detection sensible on narrow, high profile structures. Through out the profile trace each peak is individually identified and evaluated to determine if it meets the defined criteria. If it does, then a calculation of the width and height of the peaks are formulated.
- This new parameter can be used to control peaks developed during coating process for DLC and ta-C coated pins.
- RfpH5n = RfpH5 x Rfpn
  - RfpH5 -> Determines the average 5 highest peaks that meet the criteria
  - Rfpn -> Identifies how many peaks per mm

Figure 10: RfpH5n explaination

Comparison of this part with post-polishing and without it showed a very significant improvement in the microstructure of the material. In other words, the microstructure of the material improved exactly by 70% in the sample having a new surface finish.

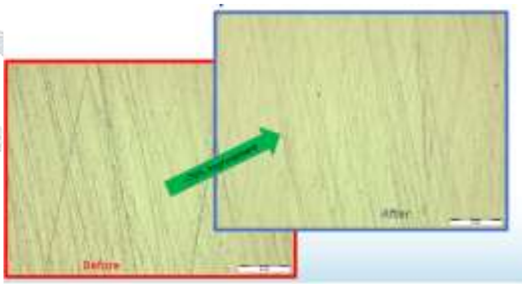

Figure 11: Piston pin microstructure without RfpH5n Vs. With RfpH5n

This was further validated by the dyno testing, which was our next procedure. This we carried out by looking into three sets of pins - the production pin with current surface finish, post-polishing pins, and the warranty pins from the failure engine. The interaction of these pins will let us know that the add-on surface finish is considered effective, and we are capable of replicating the failures with warranty pins.

Figure 12: Root Cause Analysis Tree Updated

Test 1: Current Production Pins

The first test setup utilized the existing production pins with their current surface finish. We also measured the "RfpH5n" characteristics of the pins to establish their condition prior to any post polishing. The result of the tests was that bushing wear was not directly proportional to the surface finish parameters Ra, Rp, or Rpk. Shockingly, the results showed that four pins had high wear while two pins had lower wear although all the pins were about the same in terms of surface finishes.

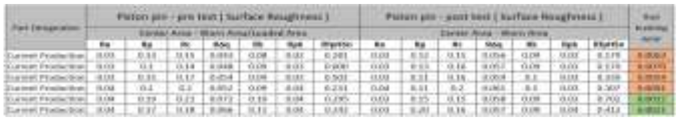
Table 1: Current Production Pins Bushing Wear Results

Test 2: Current Production Pins & Post Polish Pins

The second test configuration used a combination of production and post-polishing pins. The tests indicated that all pins exhibited minimal bushing wear. No notable disparity in bushing wear is observed between the current and post-polished pins.

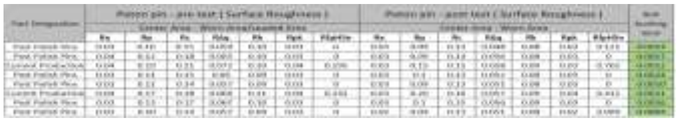

Table 2: Current Production Pins & Post Polish Pins Bushing Wear Results

Test 3: Current Production Pins & Warranty Pins

The third test configuration employed a combination of the current production and warranty pins. The results demonstrated that there was no notable difference in bushing wear between the current production pins and warranty return pins [14]. This finding suggests that the surface finish was not the cause of high bushing wear.

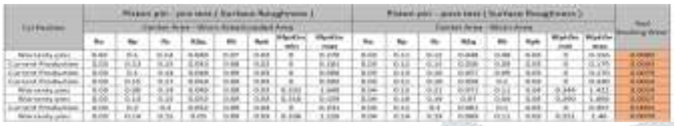

Table 3: Current Production Pins & Warranty Pins Bushing Wear Results

3.5 Interim Corrective Action & Solution

Although the DOE effort with various piston-pin surface combinations was unsuccessful, our team went back to warranty engines and focused on pins from engines that generated customer complaints. As indicated below, the individual piston pins from all returned engines were closely analyzed by measuring the pin surface finish at 16 locations per pin. The results of this detailed analysis were very interesting: the Rpk of the pin surface finish was higher than the acceptable limits in some engines. More precisely, these very pins had connecting rod bushings with significant wear situations, correlating directly with pin-tick noise complaints. It explained that the pin surface finish has a critical influence on bushing wear and correspondingly noise issues, so we can hope to target improvements in pin manufacture and finishing processes to assist in enhancing the general reliability of engines.

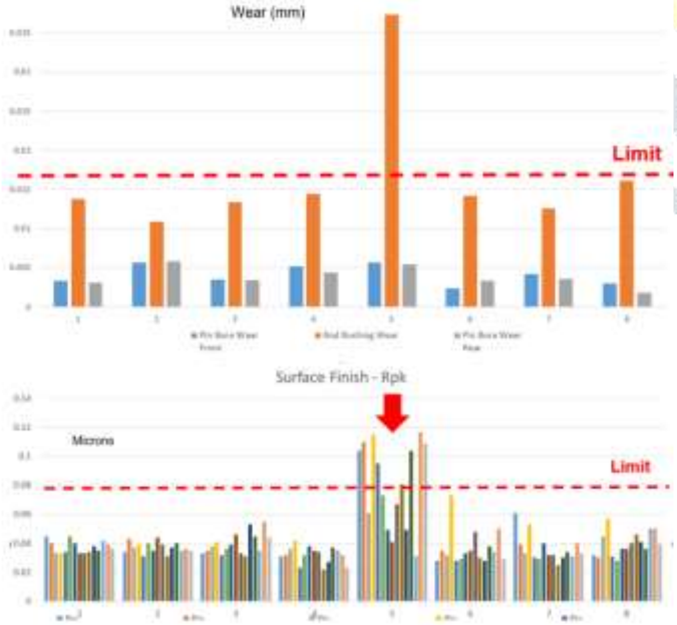

Figure 13: Rod Bushing Wear Vs. Piston Pin Surface Finish (Rpk)

This has brought us to visiting the premises of the supplier, where it was found that, in actuality, the cleanliness of the cleaning phase after the application of the DLC coating for the process of producing the piston pins was poor and that the cleaning condition of that area and the brushing equipment was not good. It is an essential process to ensure that the nodules created with the DLC coating process grind and the surface is smooth. If proper control of cleanliness is not ensured, the chances are high that the nodules may not be fully grounded, hence < précising > a surface that is not smooth as expected. To address this issue, an audit of the process was conducted, and later 5S procedure was undertaken. Changes implemented as part of the 5S process: Floor cleaning was done once every 2 days. Cleaning of equipment, workstations - every day All tools must be in their designated place The carts and dummy bins should be maintained, organized, and cleaned.

3.6 Root Cause Analysis Tree: Updated

The manufacturing process of piston pins was improved for better cleanliness, which helped the problem to some extent; however, it could not be completely resolved as the wrong lubrication continued as a major problem that needed further improvement.

Figure 14: Root Cause Analysis Tree Updated

To correct problems with inadequate or improper lubrication, a baseline of the noise level must be established and the level existing in defective engines returned to warranty. Subjective and objective tests furnished us with this information: the subjective test is one which attempts to simulate conditions the customer would experience and perceive who genuinely describes the noise level; an objective test, on the other hand, records these noise signals using an NVH data acquisition system.

3.7 Subjective Test: Current State

Warranty engine was tested and results established that it has high intensity and time interval of tick noise compared to the subjective evaluation. NVH measurement showed the warranty engines having high signal amplitude for cylinders 2 and 8, with low amplitude noticed for other cylinders. Rods belonging to these cylinders also had higher wear and clearance compared to other rods [15].

3.8 Objective NVH Test: Current State

The subjective test followed by the objective test to verify the prediction if the noise and the signal can be captured by the accelerometers and the NVH Data Acquisition system. The sequential procedure to be followed during the NVH test is as follows:

Problem: The customer complained of a start-up and load knocking and ticking noise. Model indicated additional piston-to-rod clearance than normal; the leading offenders being the piston-rod #8 assembly, then the piston-rod #2, and #6, respectively.

Instrumentation: Eight accelerometers were mounted on the outer walls of the left and right cylinder banks to measure the ticking noise between a complaint engine supplied by CQI and uncompliant engine. There are also microphones inside the engine bay at left and right locations, a vehicle exterior microphone, and interior microphones.

The instrumentation also provides for assurances for CAM position and CAN channels.

Figure 15: Left & Right Engine Bay Mic

Figure 16: Engine Block Accelerometers & Vehicle Exterior Mic

Figure 17: Vehicle Interior Aachen Head & Microphone

Test Condition: The test was conducted under an ambient soak cold start, including cranking, high idle (CAT warm-up), warm idle under no load, and warm idle with a loaded engine.

Observations—Data were compared between the complaint engine (provided by the CQI) and a non-complaint engine during high idle, warm idle no load, and warm idle loaded conditions. Characterization of the ticking noise was clearly audible at the vehicle interior microphone from the complaint engine during the initial, high idle period. Correlation of this characteristic of the ticking noise also points to cylinder #8. Yes, the ticking noise of the complaint did fade away once the engine was warmed. As appropriately captured in the slides, Part analysis, similar to that performed during the engine teardown, revealed cylinder #8 as the one with the most tick noise content.

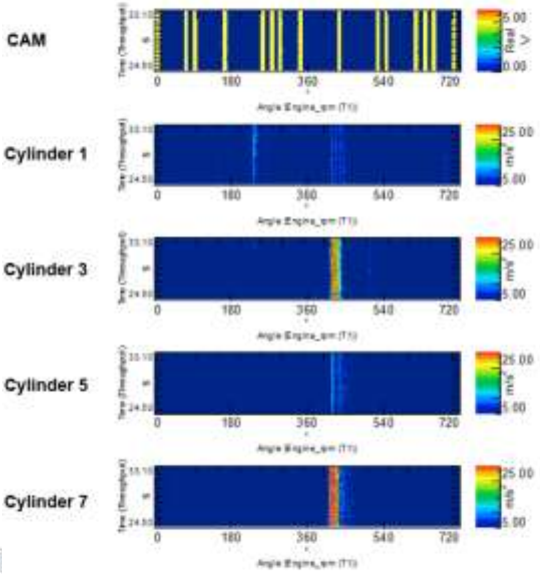

Figure 18: Engine Noise Signal Left Bank (Odd Cylinders)

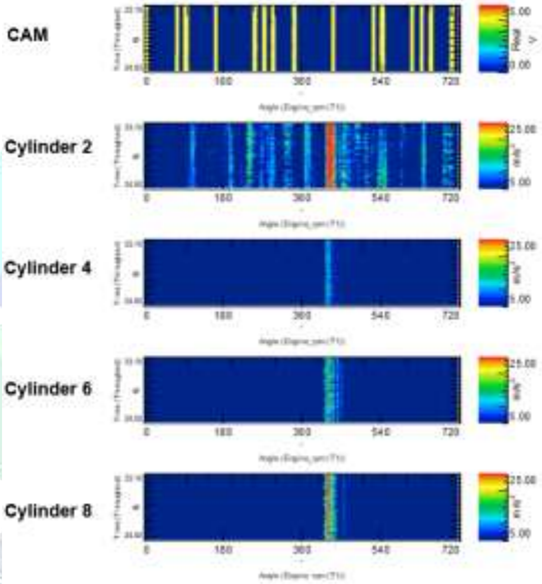

Figure 19: Engine Noise Signal Right Bank (Even Cylinders)

Determination of whether lubrication could reduce or eliminate the engine noise would have required a method to increase the lubrication to the connecting rod. This formed the basis for the suggestion to add lubrication slots into the bushing of the connecting rod. The design chosen allowed existing rods to be machined without having to-be replaced. Once the rods had been machined with this design, they were reassembled in the same engine and vehicle.

3.9 Subjective Test: Lube Slot

The objective assessment yielded a reduction in the level of noise intensity and duration across three consecutive days of testing. The ticking noise was no longer detectable, leading to the hypothesis that the engine noise originated from the belt, valvetrain, or pump systems rather than form the cylinder or piston-connecting rod movement.

3.10 Objective NVH Test: Lube Slot

Subjective evaluation was followed by an objective NVH evaluation. The solution to add the lubrication slot worked well and none of the cylinders exhibited any noise signal.

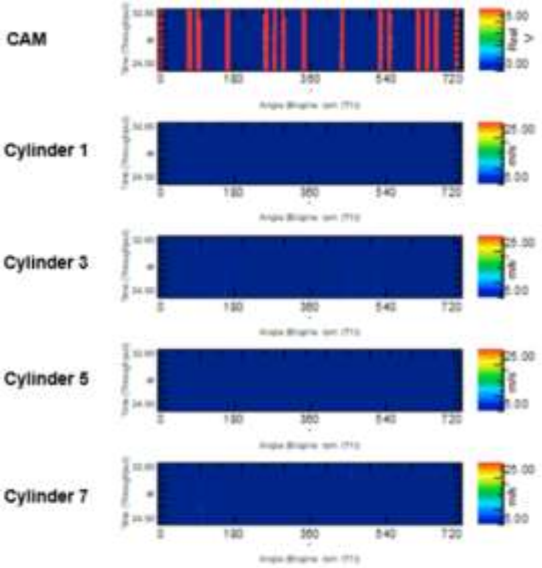

Figure 20: Engine Noise Signal Left Bank (Odd Cylinders)

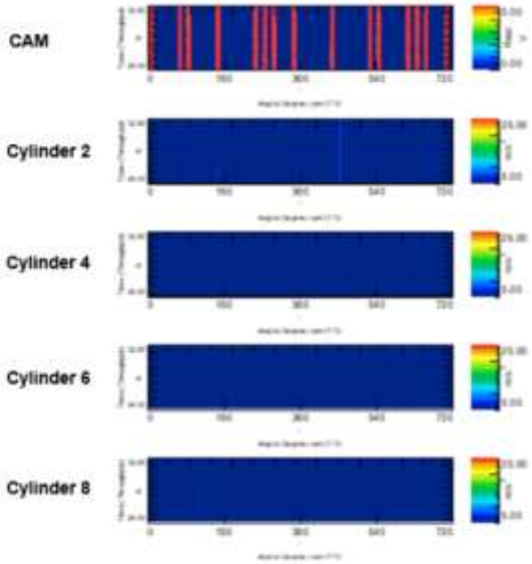

Figure 21: Engine Noise Signal Right Bank (Even Cylinders)

4. Conclusions

Research findings clearly identify the surface condition of piston pins and insufficient lubrication as the root causes of pin-tick noise and bushing wear in heavy-duty applications. This paper presents the verification process for improved surface finishing and lubrication methods to contain these problems, through a test program comparing current production pins to post-polished and warranty return pins. This work therefore points out the fact that solution-giving in engineering calls for a multilevel approach that combines theoretical knowledge with practical experimentation. Future research will investigate the use of an optimized design for the lubrication slot to the rod, in which different groove designs and combinations, along with different rod bushing materials, and mating component combinations, can be explored to ensure a robust solution that removes this problem from the root cause.

5. Future Work

No doubt, future research should delve into the benefits that would be attained from the incursion of lubrication slots within the connecting rods. The research work done in the current study was oriented towards the performance developed by different groove designs and its own capability to work in unison with other components. The research will be extended to the evaluation of different materials for rod bushes and pursuit of optimal configurations that ensure maximum efficiency. This was to be an incorporation of all holistic engineering requirements to provide an effective solution to the problems of pin-tick noise and bushing wear. This paper attempts to blend these factors through a detailed analysis and thereafter establish best practice that can hugely increase the durability as well as the reliability of mechanical systems for future frontier jumping over friction and wear problems of heavy machinery.

References

[1] Vladimir Fridman, Ilya Piraner, and Kent Clark. 2006. Modeling of Mixed Lubrication Conditions in a Heavy Duty Piston Pin Joint. *ASME 2006 Internal Combustion Engine Division Spring Technical Conference (ICES2006)* 42061, (January 2006), 741–748. DOI:https://doi.org/10.1115/ices2006-1412

[2] Chris Hall, Yu Chen, and Omar Mian. 2013. Analysis and Resolution of Piston Pin Joint Tick Noise. *Internal Combustion Engine Division Fall Technical Conference* 56109, (October 2013). DOI:https://doi.org/10.1115/icef2013-19085

[3] Jean-Louis Ligier and Patrick Ragot. 2005. Piston Pin: Wear and Rotating Motion. *SAE technical paper series* 115, (April 2005), 760–768. DOI:https://doi.org/10.4271/2005-01-1651

[4] Sławomir Kowalski, Bogusław Cieślikowski, Dalibor Barta, Ján Dižo, and Aleš Dittrich. 2023. Analysis of the Operational Wear of the Combustion Engine Piston Pin. *Lubricants* 11, 3 (March 2023), 100. DOI:https://doi.org/10.3390/lubricants11030100

[5] Archana Singh, Ravi T. Gandra, Eric W. Schneider, and Sanjay K. Biswas. 2011. Lubricant Degradation and Related Wear of a Steel Pin in Lubricated Sliding Against a Steel Disc. *ACS Applied Materials & Interfaces* 3, 7 (July 2011), 2512–2521. DOI:https://doi.org/10.1021/am200375a

[6] John J. Truhan, Jun Qu, and Peter J. Blau. 2005. A rig test to measure friction and wear of heavy duty diesel engine piston rings and cylinder liners using realistic lubricants. *Tribology International* 38, 3 (March 2005), 211–218. DOI:https://doi.org/10.1016/j.triboint.2004.08.003

[7] Michael Schuetz and Gary McIntyre. 2005. Solid Lubricant Coatings for Automotive Engine Pistons. *World Tribology Congress III*, Volume 2, (January 2005), 541–545. DOI:https://doi.org/10.1115/wtc2005-63086

[8] Roman Morgenstern, Wolfgang Kießling, and Simon Reichstein. 2008. Reduced Friction Losses and Wear by DLC Coating of Piston Pins. *ASME 2008 Internal Combustion Engine Division Spring Technical Conference* (January 2008), 289–297. DOI:https://doi.org/10.1115/ices2008-1650

[9] Bifeng Yin, Xuefeng Wang, Bo Xu, Gongyin Huang, and Xin Kuang. 2021. Adaptability of piston skirt coatings on the tribological performance of heavy-duty diesel engine under low viscosity

lubricant. *Industrial Lubrication and Tribology* 73, 6 (August 2021), 986–992. DOI:https://doi.org/10.1108/ilt-02-2021-0047

[10] K. Selby, M. Urbanak, D. Colbourne, H. Leonhardt, P. Burnett, F. Machatschek, and S. Beviere. 2005. Meeting the Lubrication Challenges of Heavy Duty Low Emission Diesel Engines. *World Tribology Congress III*, Volume 1, (January 2005), 547–548. DOI:https://doi.org/10.1115/wtc2005-63983

[11] Edney Deschauer Rejowski, Paulo Mordente Sr, Marina Fuser Pillis, and Tom Casserly. 2012. Application of DLC Coating in Cylinder Liners for Friction Reduction. *SAE Technical Paper Series* (April 2012). DOI:https://doi.org/10.4271/2012-01-1329

[12] T.H.C. Childs and F. Sabbagh. 1989. Boundary-lubricated wear of cast irons to simulate automotive piston ring wear rates. *Wear* 134, 1 (November 1989), 81–97. DOI:https://doi.org/10.1016/0043-1648(89)90063-x

[13] Yi Wang, Limin Wu, Shuo Liu, Mei Li, Xianghui Meng, and Yi Cui. 2019. Numerical Study on Fretting Wear of Mating Surface Between Piston Crown and Skirt in Heavy Duty Diesel Engine. *Journal of Engineering for Gas Turbines and Power* 141, 8 (April 2019). DOI:https://doi.org/10.1115/1.4043274

[14] Stephen H. Hill, Susan E. Hartfield-Wünsch, and Simon C. Tung. 1996. Bench Wear Testing of Common Gasoline Engine Cylinder Bore Surface/Piston Ring Combinations. *Tribology Transactions* 39, 4 (January 1996), 929–935. DOI:https://doi.org/10.1080/10402009608983614

[15] Austin H. Shaw, Jun Qu, Chinpei Wang, and Roger D. England. 2017. Tribological study of diesel piston skirt coatings in CJ-4 and PC-11 engine oils. *Wear* 376-377, (April 2017), 1673–1681. DOI:https://doi.org/10.1016/j.wear.2017.01.082

Definitions/Abbreviations

Dyno testing

Root cause analysis trees

Rod bore roundness

Piston pin surface finish

RfpH5n (Surface Finish Parameter)

DOE: Design of Experiments

DLC: Diamond Like Carbon

NVH: Noise, Vibration, and Harshness

CAM: Camshaft

CAN: Controller Area Network

CQI: Complaint Quality Inspection