

Piston Pin Dynamics and Temperature in a C.I. Engine

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ABSTRACT

To investigate free floating piston pin behavior in a heavy duty diesel engine, an unused piston-pin-rod joint was instrumented. Combining telemetry systems with inductively powered transducers, piston pin subsurface temperature and pin rotation with respect to the piston were measured over a 30 minute steady state engine test.

INTRODUCTION

A free floating piston pin joint permits rotation against the piston and the connecting rod. For modern heavy duty diesel engines, a free floating pin joint with a bushed connecting rod is typical, and many have a bushingless steel piston.

Physical observations and manufacturing experience show a range of wear conditions in the short and long term within a single population of production parts. These varied observations appear to be strongly linked to break-in events, and it is generally understood by the authors that piston pin joint break-in is sensitive to dimensional control, surface finish control, lubrication conditions, and temperature.

Under certain break-in conditions, damage to the component surfaces occurs, and the potential for damage motivates the industry to improve the understanding of piston pin behavior. Through a better understanding of piston pin behavior and how that

behavior relates to certain engine parameters, the authors expect to lower damage potential more by explicit design and less by trial and error.

Working cooperatively, Cummins Inc. and IR Telemetrics developed an experimental measurement system to characterize piston pin rotation and surface temperature with engine crank shaft position. This was done on an unused set of components in one cylinder of a Cummins ISX engine. See Figure 1.

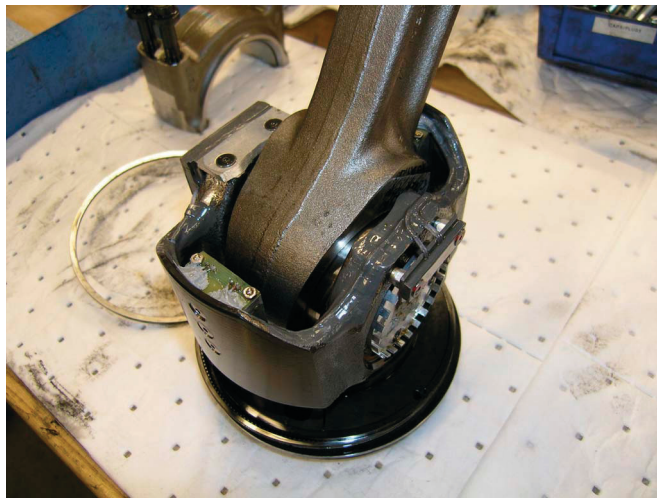


Figure 1. Piston, pin, and connecting rod instrumented for telemetry transmission of pin rotation and pin temperature.

PRESENTED IN THIS PAPER

This paper presents piston pin rotation and temperature measurement data from three perspectives:

- A time domain view of the entire test
- A crank angle domain view over selected time intervals
- A crank cycle domain view that progresses until steady state conditions are reached

VISION OF THE AUTHORS

The authors hope that this paper provokes new thoughts about the piston pin joint design process, helps to refine production engine test cycles, and advances piston pin joint validation methods.

LITERATURE REVIEW

PAPERS - Research done at the Musashi Institute of Technology [1] to instrument an automotive piston pin joint explains two forms of pin joint measurement, one to measure connecting rod torque applied to the piston pin, and the other to measure piston pin rotation with respect to the piston. The fundamentals of the discussion in [1] reinforce several points discussed in the current work, among them that the connecting rod is the driver of pin rotation, the friction at the rod bushing interface determines the applied torque to the pin, and the piston friction supplies the reaction torque to resist the pin rotation.

The authors of [1] go on to study the affects of rod bushing lubrication on applied pin torque, they conveniently plot pin torque and rotation over one complete four-stroke cycle, and they include the rod swing angle as a reference.

The pin rotation transducer in [1] has a continuous resolution of pin rotation, whereas the encoder in the current work does not resolve motion less than 3.6° of rotation, given its discrete nature.

Research done at Renault [2] emphasizes the importance of lubrication in the very early break-in stages of a piston pin joint, which is exacerbated by the high unit loads combined with reduced damage resistance of lead-free bearings found in many modern engines. There is clearly a need to understand and control the risk of damage in a piston pin joint, and the authors acknowledge the scarcity of data on the subject of piston pin behavior.

The analytical results in [2] are presented on a full engine cycle basis, and relationships between total pin load, pin rotation, oil film thickness, and torque variation

are explained analytically with respect to small end temperature.

Analysis results in [3] show that the pin rotational velocity is insignificant which suggests that the EHL performance of the small-end is satisfactory. "Since it is the friction between small-end bush and the pin that drives the pin to move, less pin rotation is an indication of good lubrication in the small-end interface." [3]

SUMMARY - Work done by others is consistent in its attempts to understand piston pin rotation, and the general body of work asserts that the piston pin responds to the net torque onto the pin, the driver being the rod, and the reaction torque being a piston pin bore phenomenon.

The engine used in the current work uses a bushingless piston pin, relying on coatings and precise bore profiling to accommodate the piston pin bore friction. The Variation in pin behavior is of interest to the authors of the current paper, and this provides the motivation to study actual pin rotation and temperature. Experimental results given in this paper compliment the assertions given by others, and they add to the knowledge by relating measured pin temperatures to measured pin rotation.

BACKGROUND

Observed variation in connecting rod bushing and piston pin bore surface conditions on run parts suggests variation in piston pin joint interface behavior. While the angular displacement and velocity of the connecting rod relative to the piston is a kinematical certainty, the relative displacements and velocities at the piston/pin and pin/rod interfaces can vary in a free floating joint design.

Instantaneous friction conditions determine how the rod angular displacement and velocity is shared between the piston and the rod. In a durable pin joint, the total relative motion between the rod and the piston is shared by the pin so as not to exceed any thresholds of damage.

Figure 2 shows a typical small end rod bushing early life wear pattern. The outer edges of the bore show the greatest polishing, which is a function of the components' combined stiffness.

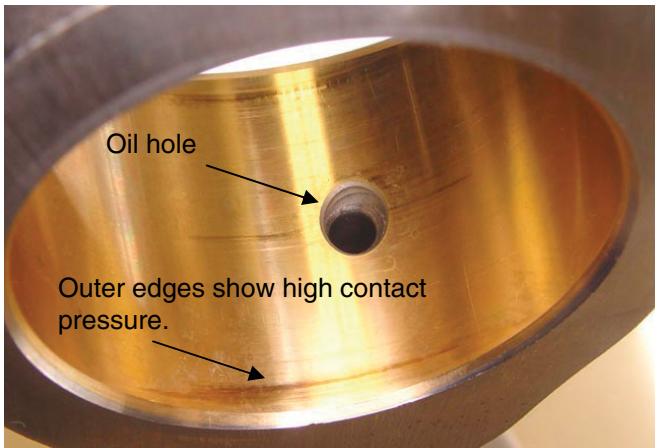


Figure 2. Typical small end connecting rod bushing early life wear pattern. The darkened bands are the polished regions.

Finite element modeling of bushing dry contact pressure shown in Figure 3 was predicted for a piston, pin, and connecting rod under maximum cylinder pressure and steady state piston temperature conditions, and the analytical solution corresponds well with the polishing bands in Figure 2.

Figures 4 and 5 show typical early life pin bore indications in a piston and a corresponding finite element model results for dry contact pressure. Dry contact pressure analyses of piston and rod bores correspond well with the location of polishing marks, but these analyses do not account for variations in pin joint conditions observed by the authors.

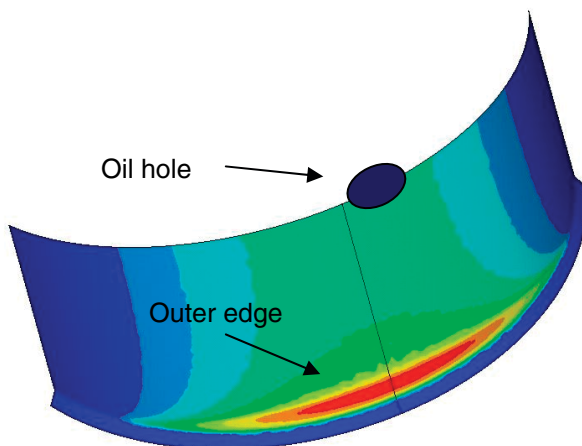


Figure 3. Finite element analysis prediction of bushing contact pressure. Note that the narrow high pressure zone at the outer edge corresponds with the dark bands in Figure 2, but this plot shows only one half of the loaded portion of the bushing with the oil hole visible for orientation purposes.

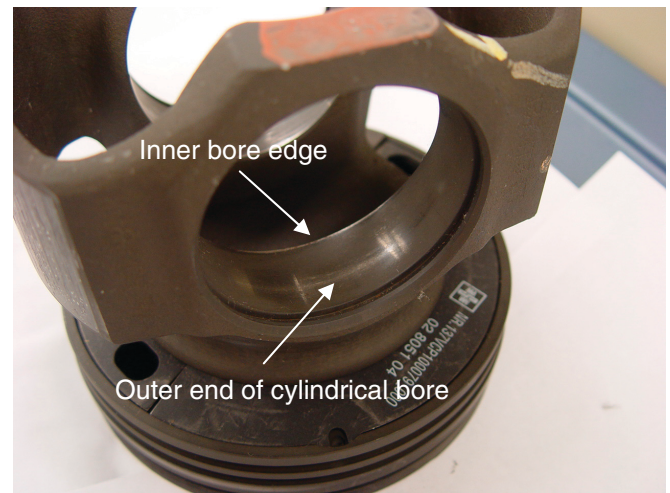


Figure 4. Piston pin bore with typical polishing of the inboard and outboard edges. The polished areas show up as bright, steel colored zones revealed through the manganese phosphate coating.

THE MYSTERY

Variations in piston pin joint observations range from indications as shown in Figures 2 and 4 to indications of material transfer. The circumstances that make the difference between a piston pin that polishes and a piston pin that accumulates damage are not clearly understood. It is thought that as heat builds in the components from combustion, oil film conditions deteriorate between the load bearing surfaces, and contact pressure patterns shift with thermal distortion.

Prior to the test, the authors pretest speculated that the pin rotation relative to the piston stopped for large portions of the time within one complete cycle, forcing the rod bushing pin interface to accommodate the majority of rod rotation, and during this event, the oil film at the rod bushing interface broke down, increasing torque transmission from the rod to the pin. Given this condition, the authors also speculated that if the bushing/pin oil film depleted to a threshold where surface asperity contact became critical, the piston relieved the condition by permitting pin rotation, which limited the rod interface damage potential.

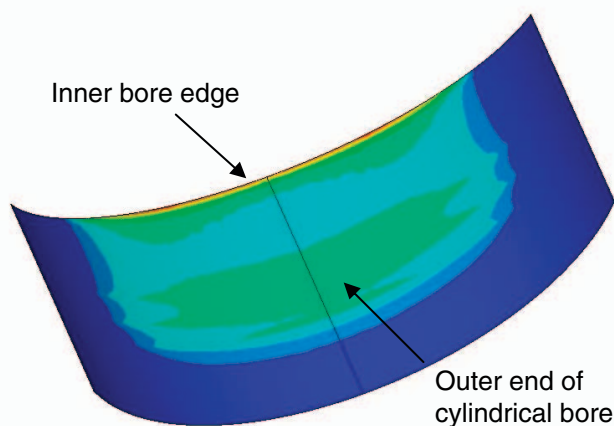


Figure 5. Finite element analysis prediction of piston pin bore contact pressure with thermal distortion of the piston applied. The orientation of this figure corresponds to the photograph in Figure 4.

The authors speculated that in certain cases, if the piston bore interface reaction torque threshold was too high, the joint began a material exchange at both interfaces, but the mystery remains as to what subtleties moved the damage threshold to critical levels in some cases, but not in others.

Leading into the pin dynamic measurements described in this paper, the authors anticipated that clues would come from a few engine cycles in the early moments of the test.

Piston pin dynamics and temperature measurement

MOTIVATION - The motivation for the work described earlier drove the authors to measure piston pin rotation relative to the piston and to track this measurement as a function of crank angle, cycle by cycle, starting with components in the as new condition. Since pin joint damage on the tested engine platform under aggressive testing conditions sometimes occurs within 15 minutes of start up, a 30 minute test was established to capture piston pin rotation events which could help explain various damage scenarios.

EXTENSION OF THE WORK – Since the authors believed that particular pin motion events heat the piston pin mid section enough to affect the load path through the pin, thermocouples were added to the pin and tracked with pin rotation.

TEST SETUP – A single cylinder kit, consisting of a piston, piston pin, connecting rod, and cylinder liner for an ISX 15 liter diesel engine was instrumented to provide wireless measurements of pin surface temperature and pin rotation relative to the piston. The

cylinder kit parts were randomly taken from production part inventory, instrumented, and then installed into cylinder #1 of the test engine. Figure 1 shows the kit assembled as received from IR Telemetrics, and Figure 6 shows the placement of seven thermocouples in the piston pin. These thermocouples were approximately 0.5 mm below the pin OD, and they were placed at seven different depths from one end of the pin inside equally circumferentially spaced pockets.

Pin rotation instrumentation - The Pin rotation transmitter was designed to measure piston pin rotation in a running engine. The transducer employs a two channel optical interrupter to track the position of a wrist pin with respect to the piston. This permitted monitoring the angular position verses time, including the direction of rotation. The Pin Rotation transmitter consists of a telemetry transmitter combined with a dual optical photo interrupter, signal conditioning, two to one channel analog encoder, and a microwave telemetry transmitter. Figure 7 shows the schematic of the telemetry instrumentation.

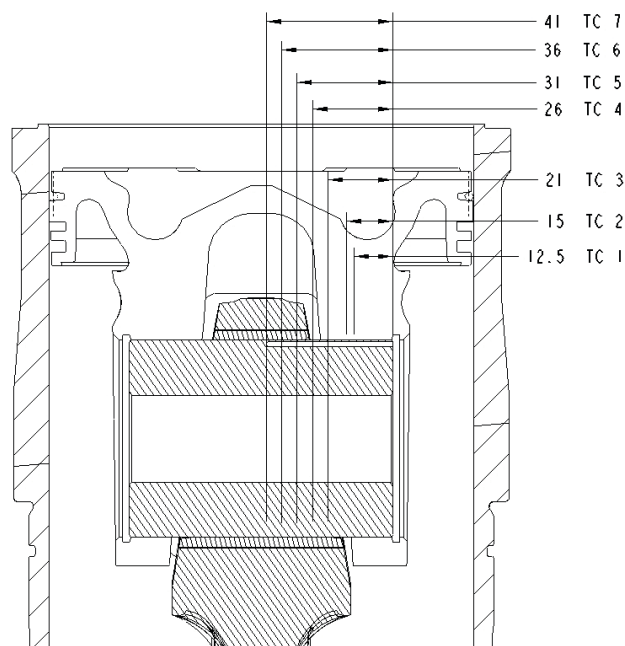


Figure 6. Placement of seven thermocouples in the piston pin. Dimensions shown are in mm.

The optical interrupter spacing and size was optimized for engine measurements and provided a resolution of 3.6 degrees. The grating geometry was designed to be immune to oil film, oil spray, or liquid oil. The signals from the optical sensor were conditioned to maintain a stable measurement over a range of the optical pickup temperature from room temperature to 150 degrees Celsius.

The rotation data from each channel of the optical encoders was buffered and combined into a single analog waveform through a novel two to one channel optical encoder. This encoder allowed two channels of data to be transmitted as a single continuous signal by a telemetry transmitter. By combining the two channels of data via encoding, the number of telemetry transmitters needed was reduced to one transmitter. This reduced the power requirements and increased reliability by reducing the number of components required for a rotation measurement.

The output of the 2 to 1 channel analog encoder signal was adjusted to meet the requirements of the analog telemetry transmitter. The telemetry transmitter used a technique of double FM encoding to transmit the data via a frequency modulated microwave radio signal. Upon reception of the signal the encoded data was recovered, allowing the data acquisition (DAQ) to both record and time stamp every 3.6 degree incremental transition of the encoder.

In addition to encoder transitions, this DAQ system was also configured to receive and record a 1/rev synch pulse coming from a commercial encoder attached to the crankshaft. A proprietary software package was required to read and post-process the raw data file before conversion to a user readable format.

Pin temperature instrumentation – The piston pin was modified with 2 mm diameter holes bored by an EDM electrode into one end of the pin at seven locations equally spaced circumferentially but at different depths to roughly capture axial temperature gradients. These holes were placed to result in a 0.5 mm wall thickness from the outside surface of the pin, and the depths were chosen so as to resolve temperature from the mid length of the pin to the mid section of the piston pin leg bore. To minimize mechanical stress concentrations, the bottoms of the holes were spherical. Finally, it was assumed that temperature over the pin length would be roughly symmetrical about a transverse plane passing through the mid length of the pin, so only one half of the pin length was instrumented.

The pin temperature measurements were transferred using a standard telemetry transmitter. The transmitter was built into a custom housing that fit inside of the hollow piston pin. In this case the transmitter used thermocouples that were inserted into the seven holes previously described. The transmitter was powered by an inductive pickup coil built into one end of the transmitter packaging, and the opposite end of the transmitter housed the microwave transmitter and thermocouple connections.

The thermocouple signals were passed to the amplifiers and ice point compensation circuits through a sequentially switched multiplexer. The multiplexed signals were each transmitted for a period of ½ second. The amplified and multiplexed transducer signals were encoded into a square wave frequency, and a signal to square wave conversion was done by a very stable voltage to frequency converter. This first frequency modulation (FM) was followed by a second frequency modulation of the microwave signal before the signal was transmitted.

The double FM encoding is a proprietary technique. It allows for large variations in the microwave signal without affecting the square wave data frequency from the first frequency modulation. The received microwave signal was then amplified and decoded to recover the square wave frequency signal without affecting the encoded transducer data.

The microwave signal was transmitted to a receiver, and the demodulated signal returned the original square wave encoded data. This data was then recorded by a second independent DAQ system. This system also required proprietary software to demultiplex and post-process the data to provide an ASCII CSV formatted file with temperatures verses time.

Engine instrumentation — Two additional DAQ units were used to collect various engine operating parameters. The first was a high speed, large capacity

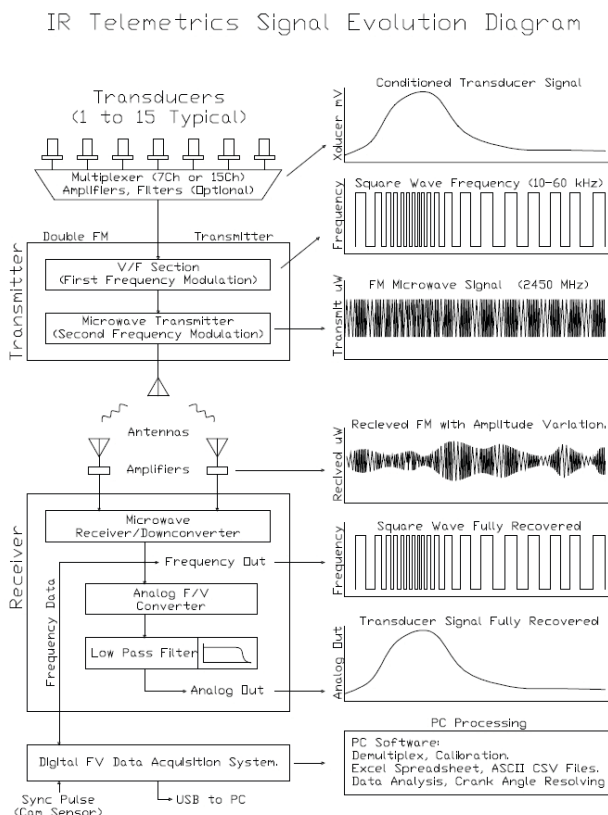


Figure 7 Schematic of the telemetry system.