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ESTIMATING THE OUTER RING DEFECT SIZE AND REMAINING SERVICE LIFE OF FREIGHT RAILCAR BEARINGS USING VIBRATION SIGNATURES

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ABSTRACT

The railroad industry currently utilizes two wayside detection systems to monitor the health of freight railcar bearings in service: The Trackside Acoustic Detection System (TADS™) and the wayside Hot-Box Detector (HBD). TADS™ uses wayside microphones to detect and alert the conductor of high-risk defects. Many defective bearings may never be detected by TADS™ since a high-risk defect is a spall which spans more than 90% of a bearing's raceway, and there are less than 20 systems in operation throughout the United States and Canada. Much like the TADS™, the HBD is a device that sits on the side of the rail-tracks and uses a non-contact infrared sensor to determine the temperature of the train bearings as they roll over the detector. These wayside detectors are reactive in the detection of a defective bearing and require emergency stops in order to replace the wheelset containing the defective bearing. These costly and inefficient train stoppages can be prevented if a proper maintenance schedule can be developed at the onset of a defect initiating within the bearing. This proactive approach would allow for railcars with defective bearings to remain in service operation safely until reaching scheduled maintenance.

Driven by the need for a proactive bearing condition monitoring system in the rail industry, the University Transportation Center for Railway Safety (UTCRS) research group at the University of Texas Rio Grande Valley (UTRGV) has been developing an advanced onboard condition monitoring system that can accurately and reliably detect the onset of bearing failure using temperature and vibration signatures of a bearing. This system has been validated through rigorous laboratory testing at UTRGV and field testing at the Transportation Technology Center, Inc. (TTCI) in Pueblo, CO. The work presented here builds on previously published work that demonstrates the use of the advanced onboard condition monitoring system to identify defective bearings as well as the correlations developed for spall growth rates of defective bearing outer rings (cups). Hence, the system uses the root-mean-square (RMS) value of the bearing's acceleration to assess its health. Once the bearing is determined to have a defective outer ring, the RMS value is then used to estimate the defect size. This estimated size is then used to predict the remaining service life of the bearing. The methodology proposed in this paper can prove to be a useful tool in the development of a proactive and cost-efficient maintenance cycle for railcar owners.

INTRODUCTION

The cargo load of each freight railcar is supported by the railcar's suspension components: springs, dampers, axles, wheels, and tapered-roller bearings. Of these components, the bearings are the most susceptible to failure due to the heavy cargo loads they support at high speeds.

The tapered-roller bearing typically used in freight railcar services has three different fundamental components: rollers, inner rings (cones), and outer ring (cup). These components, shown in Figure 1, allow for near-frictionless operation under heavy loads and high speeds. However, when one of the aforementioned components develops a defect, the effectiveness of the near-frictionless rotation is compromised, which may lead to increased frictional heating depending on the size and location of the defect.

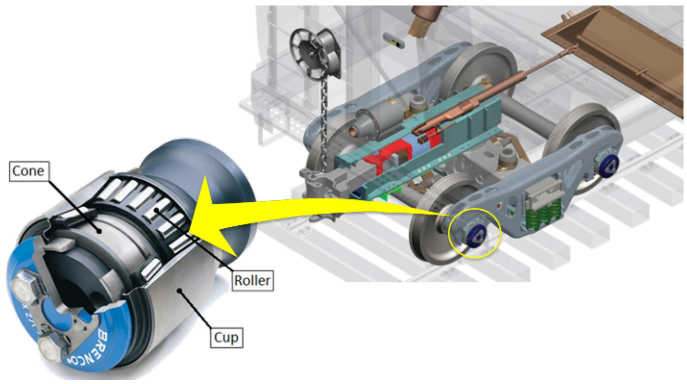

Figure 1. Tapered-Roller Bearing Components [1]

The defects can be categorized into one of three categories: localized defect, distributed defect, or a geometric defect. Two examples of localized defects that include pits, cracks, or spalls on a single component of the bearing are illustrated in Figure 2 (left). A distributed defect is when multiple bearing components have localized defects or a single component with multiple defects that are distributed throughout its surface such as a water-etch defect, pictured in Figure 2 (right). Bearings that are out of tolerance due to manufacturing issues or due to geometric inconsistencies are examples of geometric defects.

Figure 2. Examples of a localized defect (left) and a distributed defect (right)

Bearing Condition Monitoring Systems

The railroad industry currently utilizes two different types of wayside detections systems to monitor the health of the freight car bearings in service: The Trackside Acoustic Detection System (TADS™) and the wayside Hot-Box Detector (HBD).

TADS™ utilizes wayside microphones to detect high-risk defects in bearings and alert the conductor as the train passes by the system. A "growler" is an example of a high-risk defect in which spalls occupy more than 90% of the bearing component's rolling surface. The system is proficient in determining end-of-life bearings. However, there are less than 20 systems in service throughout the United States and Canada and TADS™ is not capable of detecting defective bearings with small defects [2]. The latter suggests that many bearings may spend their entire service life without passing through a TADS™ station, and many other bearings with small defects will go undetected as they pass through TADS™.

Hot-box detectors (HBDs) are the most utilized bearing condition monitoring systems in operation in North America with over 6,000 in use in the United States and are placed every 40-rail km (25 mi) to 64-rail km (40 mi) on average. HBDs use non-contact infrared sensors to measure the temperature radiated from the bearings, wheels, axles, and brakes as they roll over the detector. The HBD will alert the train operator of any bearings running at temperatures greater than 94.4°C (170°F) above ambient conditions. However, bearings operating at temperatures above the average temperature of all bearings on the same side of the train, as detected by multiple HBDs, are said to be "warm trending" [3]. Warm-trended bearings are flagged without triggering an HBD alarm and are subsequently removed from service for later disassembly and inspection.

A study that compared the temperature profiles for defect-free (healthy) bearings to those of bearings with defective inner (cone) and outer (cup) rings was carried out by the UTCRS research team in 2016 [4]. The study demonstrated that the operating temperature was not a good predictor of bearing health since bearings with defective inner and outer rings operated at temperatures that are comparable to those of healthy bearings [4]. The latter led to the development of an advanced onboard condition monitoring system that uses accelerometers in addition to temperature sensors. This system demonstrated a correlation between an increase in the vibration levels within the bearing and the deterioration of the bearing's condition [5]. As such, this study combines new research on defect size versus vibration levels and recently published spall growth rate data [6-7].

EXPERIMENTAL SETUP & PROCEDURES

To acquire all the required data needed for this study, the University Transportation Center for Railway Safety (UTCRS) designed and fabricated two dynamic bearing test rigs shown in Figure 3. Both test rigs can accommodate Class F (6 ½" × 12") and Class K (6 ½" × 9") tapered-roller bearings. A fully-loaded railcar applies a load of 153 kN (34.4 kip) per bearing, and each tester is equipped with a hydraulic cylinder that allows each test bearing to be loaded up to 175% of a fully-loaded railcar if desired. The data provided in this paper was collected utilizing three loading conditions: 100% of full-load, which corresponds to a fully-loaded railcar, and 110% and 125% of full-load, which both simulate an overloaded railcar. The test rigs are equipped with a 22 kW (30 hp) variable speed motor which allows the bearings to be tested at different velocities. However, a wheel speed of 796 rpm or a track speed of 137 km/h (85 mph) was used for this study. The bearings are air-cooled utilizing two industrial-size fans that produce an air stream traveling at an average speed of 5 m/s (11.2 mph). The defective area of the raceway is placed in the 90º position shown in Figure 4 in order to apply maximum load to the spall. The latter practice has been proven to cause the defect to propagate at the fastest possible rate, thus, providing a worst-case scenario.

Figure 3. A picture of the single bearing test rig (left), and the four-bearing test rig (Right)

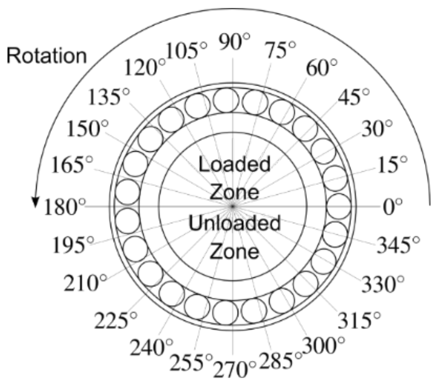

Figure 4. Bearing schematic and spall placement locations

The Single Bearing Tester (SBT) shown in Figure 3 (left) accommodates a single railroad tapered-roller bearing in a cantilever setup, which closely mimics the bearing loading conditions on a freight railcar. A bearing adapter was specially machined to accept four 70g accelerometers placed in the Smart Adapter (SA) and Mote (M) locations at the inboard and outboard sides of the bearing, one 500g accelerometer placed in the Radial (R) location on the outboard side, and four K-type bayonet thermocouples, two inboard and two outboard. A picture of the modified bearing adapter showing the Smart Adapter (SA), Mote (M), and Radial (R) locations is provided in Figure 5. In addition to the four thermocouples affixed to the bearing adapter, there are seven K-type thermocouples placed equidistantly around the circumference of the bearing outer ring (cup) and held in place tightly via a hose clamp.

The Four-Bearing Tester (4BT) shown in Figure 3 (right) accommodates either four Class F or Class K bearings pressed onto a test axle. The axle and bearing setup for the 4BT is given in Figure 6. In order to replicate field service conditions, only data collected from the middle two bearings (B2 and B3) were used for this study since they are both top-loaded. Thus, the middle two bearing adapters were machined to accept two 70g accelerometers placed in the outboard (SA) and (M) locations, one 500g accelerometer placed in the outboard R location, two K-type bayonet thermocouples, and one regular K-type thermocouple aligned with the two bayonet thermocouples and placed midway along the bearing cup width, held tightly by a hose clamp.

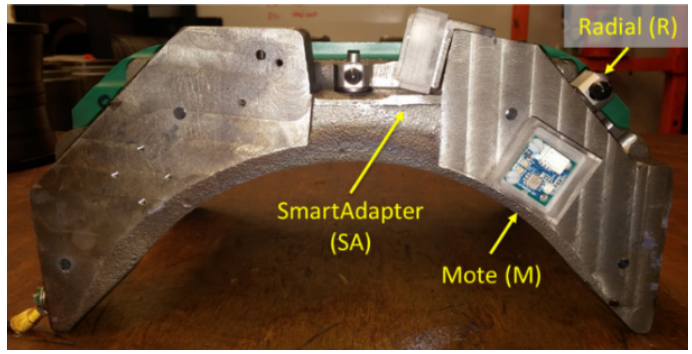

Figure 5. Modified bearing adapter showing sensor locations

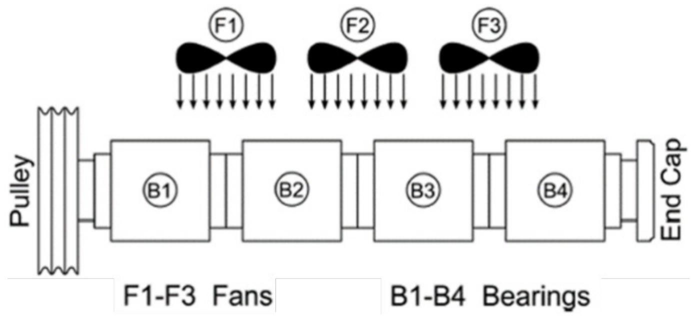

Figure 6. Top view of four-bearing tester (4BT)

A National Instruments (NI) PXIe-1062Q data acquisition system (DAQ) programmed using LabVIEW™ was utilized to record and collect all the data for this study. A NI TB-2627 card was used to collect the thermocouple temperature data at a sampling rate of 128 Hz for half a second, in twenty second intervals. An 8-channel NI PXI-4472B card was used to record and collect the accelerometer data for this study. Accelerometer data was recorded and collected at a sampling rate of 5,120 Hz for sixteen seconds, in ten-minute intervals. The root-mean-square of the accelerometer data was then used for the analysis.

Subsequent to vibration level changes during an experiment, the test is stopped, and the bearings are pressed off. They are then completely disassembled, cleaned out, and undergo a thorough visual inspection. Castings of the spalled areas are made using a low-melting, zero-shrinkage bismuth alloy. To create the casting, tacky tape is applied around the edges of the defect area to create a mold border for the molten alloy, which melts at 80°C (176°F). The molten bismuth alloy is then poured into the cavity to obtain a casting of the spalled region. This process is depicted in Figure 7.

After the casting hardens, it is removed from the cavity and painted to highlight the borders of the spalled region. Spall sizes were measured using optical techniques coupled with digital image analysis, as well as, with a manual coordinate measuring instrument with the resulting field of points manipulated in

MATLAB™. In more detail, the casting impression is photographed, and the images are post-processed in MATLAB™ to enhance the contrast. The enhanced images are imported to Image Pro-Plus®, where measurements of area and other pertinent geometric parameters are made.

Figure 7. Casting procedure using Bismuth; spalled surface outlined with tacky tape (left); Bismuth alloy cast (right)

RESULTS AND DISCUSSION

Several experiments with defective outer ring raceways were carried out to study the effect that the defect size has on the vibration levels within railroad bearings and to develop defect size growth rate models in order to estimate the remaining service life of the bearing. The data in Figure 8 was acquired by averaging the last two hours of vibration data of the defective bearing operating at a speed of 137 km/h (85 mph) and under a load ranging between 100% and 125% of full-load and comparing it against the defect size. This data is the result of over a decade of testing performed at UTRGV. Table 1 lists the different defect area growth rates acquired from a parallel study also performed at UTRGV [7].

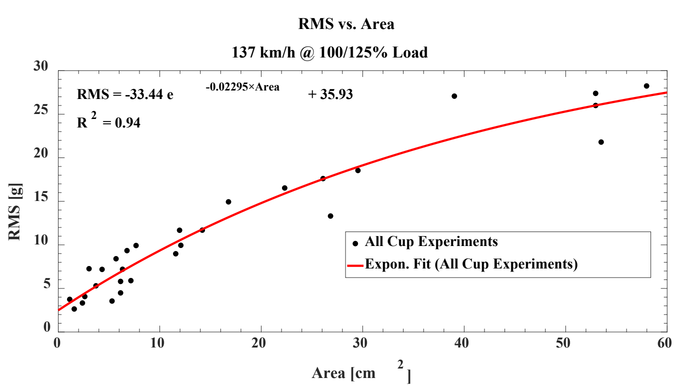

Figure 8. RMS versus cup spall area correlation

Table 1. Spall growth rates of defective outer rings

Spall Size	Min. Growth Rate [cm^2/km]	Average Growth Rate [cm^2/km]	Max Growth Rate [cm^2/km]
<13 cm^2	0.07×10^{-4}	1.01×10^{-4}	3.83×10^{-4}
>13 cm^2	1.09×10^{-4}	3.41×10^{-4}	6.52×10^{-4}

Example Case: Laboratory Experiment 200

In Experiment 200, a class K bearing with a pitted inboard raceway on the outer ring (cup) was run on the 4BT. The bearing, with an initial raceway shown in Figure 9 (left), was placed in the B2 position on the 4BT (refer to Figure 6). The spall, positioned in the maximum load region to produce a worst-case result, propagated throughout the course of the experiment and grew to a size of 9 cm^2 (1.4 in^2), as depicted in Figure 9, after 81,590 km (50,698 mi). This defect size corresponds to approximately 2.5% of the 367.28 cm^2 (56.93 in^2) area of a single class K outer ring (cup) raceway.

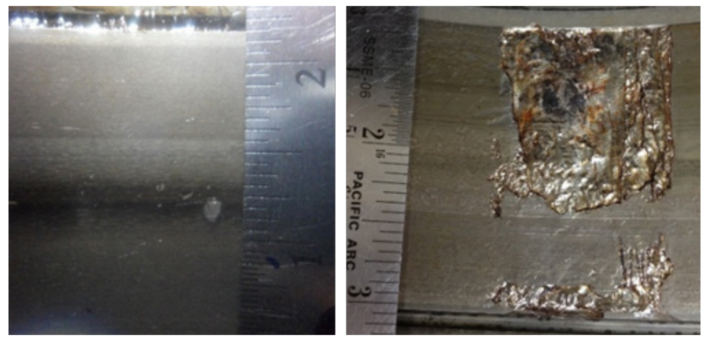

Figure 9. Initial cup raceway with small pits shown (left) and resulting cup spall in the same region (right) [ruler is in inches]

Figure 10 presents the vibration and temperature profiles of Bearing 2 (B2) operating at 110% of full-load and 796-wheel rpm (corresponding to a track speed of 137 km/h) during Experiment 200. The bearing was deemed defective using the UTCRS-developed bearing condition monitoring vibration thresholds. Any bearing operating with a vibration signature having an RMS value that is above the "Maximum Threshold" has been verified to be defective. As demonstrated in a previous study, an increase in the vibration levels signifies an increase in defect size [5]. This vibration increase can be seen around the 150-hour mark in Figure 10. The oscillations in the vibration levels shown after the 150-hour mark are signs of spall growth.

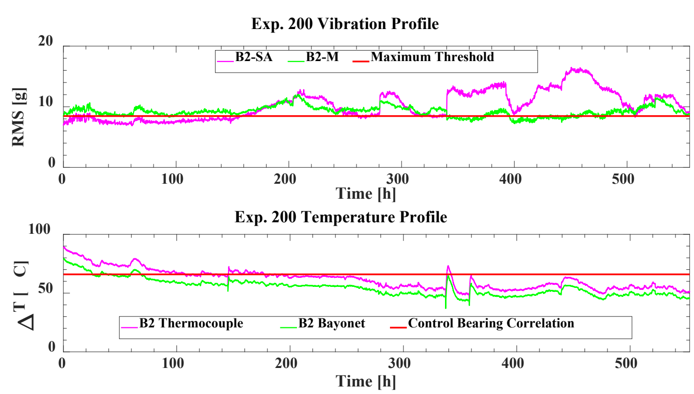

Figure 10. Vibration and temperature profiles for Experiment 200.

Contrary to the vibration increase, the operating temperature above ambient (ΔT) decreased around the 150-hour mark. This decrease in temperature is generally a by-product of an increase in defect size. Meaning that the spall region provides a pocket for the grease to accumulate, which in turn lowers the operating temperature of the bearing once the grease goes back into circulation. The B2 temperature profiles are below the Control Bearing Correlation, which would signify a healthy bearing [4].

The last two hours of the experiment were averaged in order to correlate the RMS of the vibration level to the defect size of the bearing. Table 2 provides the averages of the last two hours of operation while Table 3 gives the defect size and growth rate estimations. Conservatively, it would take approximately 267,000 km (166,000 mi) of operation for the cup spall to grow to 183.64 cm^2 (28.46 in^2) or 50% of a single cup raceway surface area using the maximum growth rate of 6.52×10^{-4} cm^2/km. Using the average defect area growth rate from the experiment, it would take approximately 1,580,000 km (~980,000 mi) to reach a defect area covering 50% of a single cup raceway. These estimations allow railcar operators enough time to develop a proactive maintenance schedule that minimizes costly and unnecessary train stoppages and delays.

Table 2. Average values for the final two hours of Experiment 200 for Bearing 2 (Average ambient temperature was 20°C or 68°F).

Track Speed [km/h]/[mph]	Load [%]	ΔT [°C / °F]	Control ΔT [°C / °F]	RMS [g]
137/85	110	48.2/86.8	66.0/118.8	9.1

Table 3. Defect size estimation and growth rate for Bearing 2.

RMS [g]	Defect Size [cm^2]	Calculated Defect Size [cm^2]	Percent Error [%]	Average Growth Rate [cm^2/km]
9.1	9.0	9.59	6.6	1.10×10^{-4}

This defective class K bearing was then moved to the SBT, where it ran an additional 31,295 km (19,446 mi) over two experiment iterations. The spall propagated from 9 cm^2 (1.4 in^2) to about 21 cm^2 (3.26 in^2), as shown in Figure 11, with an average growth rate of 3.81×10^{-4} cm^2/km.

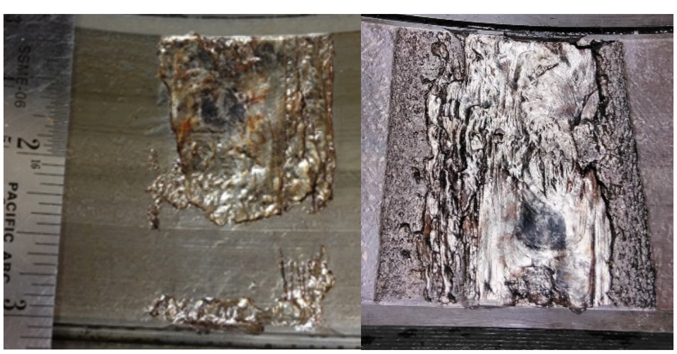

Figure 11. Initial cup spall (left) and final cup spall (right) for Experiment 201A.

Figure 12 shows the outboard (OB) vibration and temperature profiles for the experiment at 100% of full-load and a track speed of 137 km/h (85 mph). It is important to note that Table 4 shows the average of the peak temperatures is nearly 15°C (27°F) below the Control Bearing Correlation, whereas, the accelerometers are detecting vibrations significantly higher than the Maximum Threshold. The defect size correlation from Figure 8 overestimates the defect by about 8.4%. Again, assuming the defect propagates at the maximum growth rate of 6.52×10^{-4} cm^2/km, it would take approximately 246,000 km (153,000 mi) for the defect to grow to 50% of a single cup raceway area.

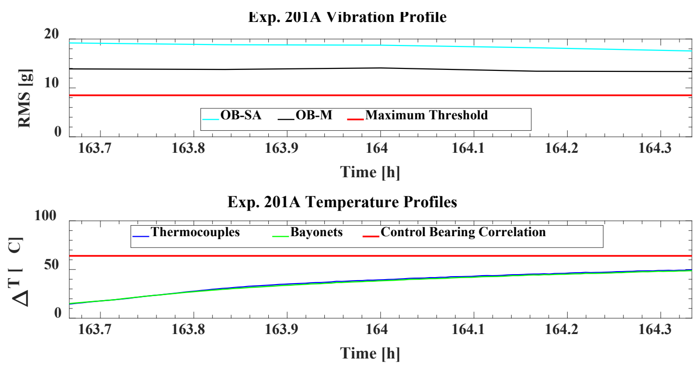

Figure 12. Vibration and temperature profiles for Experiment 201A.

Table 4. Average values of Experiment 201A (Average ambient temperature was 20°C or 68°F).

Track Speed [km/h]/[mph]	Load [%]	ΔT [°C / °F]	Control ΔT [°C / °F]	RMS [g]
137/85	100	49.6/89.3	64.0/115.2	16.1

Table 5. Defect size estimation and growth rate for Experiment 201A.

RMS [g]	Defect Size [cm^2]	Calculated Defect Size [cm^2]	Percent Error [%]	Average Growth Rate [cm^2/km]
16.1	21	22.76	8.4	3.81×10^{-4}

CONCLUSIONS

Current wayside condition monitoring systems are reactive in nature in that they normally detect defective bearings towards the end of their lives. This does not allow for appropriate maintenance cycles throughout the time the bearing is defective. Hot-box detectors (HBDs) rely on temperature measurements alone and are, therefore, not very effective at identifying bearings with defects at early stages of development since the operating temperature of these bearings is usually within the operating temperatures of healthy (defect-free) bearings. Not only have HBDs failed to identify defective bearings that ultimately led to derailments, but almost 40% of bearings removed from service due to warm temperature trending as flagged by HBDs turned out to be defect-free bearings. Hence, temperature measurements alone are not a reliable metric for determining bearing health.

TADS™ are not a good alternative to HBDs due to the low number of units in service as well as the fact that they are programmed to flag "growlers" (*i.e.*, bearings containing a component with a defect that covers 90% of the contact raceway surface area), and the train must be stopped immediately to get the bearing replaced. Had the defective bearings been identified at an earlier stage, proactive maintenance could have been scheduled, which would have avoided the costly train stoppages and service interruptions.

Since the current wayside detection systems are inefficient, a new onboard vibration-based bearing condition monitoring system has been developed at the UTCRS laboratories, and field-tested and validated at TTCI. The new onboard condition monitoring system utilizes accelerometers as well as temperature sensors to track the health of railroad bearings in service through their vibration and temperature signatures. This new system can accurately identify the onset of defect initiation within a bearing and provide good estimates of the defect size. This data combined with the developed defect growth rate models can be effectively used to estimate the remaining service life of a defective bearing. An example of how this process works was provided in this paper for the case of a bearing outer ring (cup) defect. Using this methodology, freight railcar owners can establish proactive maintenance schedules that eliminate unnecessary and costly train stoppages and delays resulting from early bearing removal from service.

ACKNOWLEDGMENTS

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