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NATIONAL TRANSPORTATION SAFETY BOARD
Investigative Hearing
Norfolk Southern Railway general merchandise freight train 32N
derailment with subsequent hazardous material release and fires,
in East Palestine, Ohio, on February 3, 2023

Agency / Organization

American Society of Mechanical Engineers

Title

Exhibit 6- Tarawneh, JTSEA, September 2012

Docket ID: **DCA23HR001**

Thermal Modeling of a Railroad Tapered-Roller Bearing Using Finite Element Analysis

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In the railroad industry, distressed bearings in service are primarily identified using wayside hot-box detectors (HBDs). Current technology has expanded the role of these detectors to monitor bearings that appear to "warm trend" relative to the average temperatures of the remainder of bearings on the train. Several bearings set-out for trending and classified as nonverified*, meaning no discernible damage, revealed that a common feature was discoloration of rollers within a cone (inner race) assembly. Subsequent laboratory experiments were performed to determine a minimum temperature and environment necessary to reproduce these discolorations and concluded that the discoloration is most likely due to roller temperatures greater than 232 °C (450 °F) for periods of at least 4 h. The latter finding sparked several discussions and speculations in the railroad industry as to whether it is possible to have rollers reaching such elevated temperatures without heating the bearing cup (outer race) to a temperature significant enough to trigger the HBDs. With this motivation, and based on previous experimental and analytical work, a thermal* finite element analysis *(FEA) of a railroad bearing pressed onto an axle was conducted using ALGOR 20.3^{TM}. The* finite element *(FE) model was used to simulate different heating scenarios with the purpose of obtaining the temperatures of internal components of the bearing assembly, as well as the heat generation rates and the bearing cup surface temperature. The results showed that, even though some rollers can reach unsafe operating temperatures, the bearing cup surface temperature does not exhibit levels that would trigger HBD alarms.* [DOI: 10.1115/1.4006273]

Keywords: railroad bearing thermal modeling, tapered-roller bearing heating, internal bearing temperatures, discolored rollers, excessive roller heating, thermal finite element analysis

Introduction

Tapered-roller bearings (see Fig. 1) are the most widely used bearings in railroad cars. When operated under satisfactory load, alignment, and contaminant free conditions, the service life is exceptionally long. As a general rule, bearings will outlast the wheel life, and survive several reconditioning cycles prior to being retired. At the end of their life, bearings will initiate fatigue, particularly subsurface fatigue, rather than wearing out due to surface abrasion. Fatigue failures, or spalling, can lead to material removal at the raceway surface which in turn will cause grease contamination and increased friction that manifests itself as heat within the bearing. Excessive heat will lower the viscosity of the lubricant, which reduces the thickness of the fluid film that separates the rolling surfaces. As a consequence, metal-to-metal contact occurs, which can hasten the onset of premature bearing failure. To identify distressed bearings in service, bearing health monitoring equipment is employed by the railroads to warn of impending failures as a method to ward off potentially catastrophic events, such as derailments. The most common method of monitoring bearing health is by conventional wayside hot-box detectors which are strategically located to record bearing cup temperatures as the train passes. These devices are designed to identify those bearings which are operating at temperatures greater than 105.5 °C (190 °F) above ambient conditions. An extension of this practice is the tracking of temperature data and comparing individual bearings against the averages of the remainder along a train (Karunakaran and Snyder [1]). Identifying those bearings which are "trending" above normal allows the railroads to track bearings which appear to be distressed without waiting for a hot-box detector (HBD) to be alarmed.

As a diagnostic aid, bearings which are identified as hot are removed from service for later disassembly and inspection. In most cases, the cause of bearing overheating can be attributed to one of several known modes of bearing failure such as: spalling, water contamination, loose bearings, broken components, damaged seals, etc. However, in some cases, these early set-out bearings do not exhibit any of the commonly documented causes of bearing failure and are, therefore, classified as *nonverified*.

Upon closer disassembly and inspection, it has been observed that many of these nonverified bearings contain discolored rollers in an otherwise normal bearing. The discoloration of the steel is visual evidence that these rollers have been exposed to temperatures greater than what is expected during normal operating conditions. Hence, initial work performed by the authors of this paper focused on determining conditions that would replicate the discoloration observed in the rollers. A laboratory furnace was used to heat numerous rollers to elevated temperatures in various

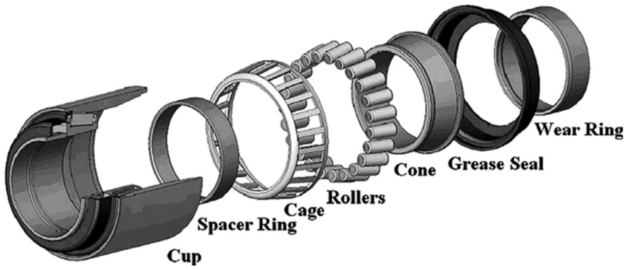

Fig. 1 Detailed component view of a typical railroad tapered-roller bearing

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Table 1 Numerical values for the properties and parameters appearing in Eqs. (1)–(3)

Property	Film temperature	Thermal conductivity[a]	Kinematic viscosity[a]	Velocity	Characteristic length	Prandtl number[a]
Symbol	T_f	k	ν	V	L_c	Pr
Units	K	$\mathrm{W \cdot m^{-1} \cdot K^{-1}}$	$\mathrm{m^2 \cdot s^{-1}}$	$\mathrm{m \cdot s^{-1}}$	m	None
Value	310	27.0×10^{-3}	16.9×10^{-6}	6.0	0.1572	0.706

[a] All thermal properties were obtained at T_f from Ref. [34], Appendix A, p. 941.

Table 2 Summary of the performed *finite element* (FE) simulations. The average cup temperatures provided in the table were obtained by averaging six nodes simulating the thermocouples placed around the circumference of the middle of the cup 60 deg apart.

Case No.	Description of heating scenario	Q_{total} (W)	Q_{roller} (W)	Maximum average roller temperature (°C)	Average cup temperature (°C)
1	Normal operation. All 46 rollers are heated equally to produce $T_{\text{cup}} = 50\,^\circ\text{C}$ (see Fig. 5)	529.0	11.5	55.0	50.2
2	One welded roller. 45 rollers heated to normal operation conditions; one roller abnormally heated	672.5	155.0	120.8	57.5
3	Six welded rollers. 40 rollers heated to normal operation conditions; six rollers on one cone assembly abnormally heated (see Fig. 6)	712.0	42.0	75.9	59.0
4	Twisted cage bar. 44 rollers heated to normal operation conditions; two adjacent rollers abnormally heated (see Fig. 7)	1086.0	290.0	218.2	79.2
5	Added debris. One cone assembly (23 rollers) heated to normal operation conditions; the other cone assembly abnormally heated	908.5	28.0	83.3	68.6
6	Two hot rollers. 44 rollers heated to normal operation conditions; two rollers, one on each cone assembly, abnormally heated	754.0	124.0	110.7	59.7
7	Two hot rollers. 44 rollers heated to normal operation conditions; two rollers, one on each cone assembly, abnormally heated (see Fig. 8)	1484.5	489.3	291.8	90.2
8	Three hot rollers. 43 rollers heated to normal operation conditions; three consecutive rollers abnormally heated (see Fig. 9)	1287.4	264.3	232.0	88.5
9	Four hot rollers. 42 rollers heated to normal operation conditions; four consecutive rollers abnormally heated	1438.2	238.8	233.4	96.8
10	Misaligned roller. 45 rollers heated to normal operation conditions; one roller abnormally heated	1249.0	731.5	388.6	80.0
11	Abnormal operation. All 46 rollers are heated equally to produce $T_{\text{cup}} = 72\,^\circ\text{C}$	979.8	21.3	80.4	71.9
12	Abnormal operation. All 46 rollers are heated equally to produce $T_{\text{cup}} = 80\,^\circ\text{C}$	1163.8	25.3	90.8	80.7
13	Abnormal operation. All 46 rollers are heated equally to produce $T_{\text{cup}} = 130.5\,^\circ\text{C}$ (see Fig. 10)	2208.0	48.0	149.5	130.5

relatively slow (i.e., flows with a $\text{Re} \leq 100$). Furthermore, a sensitivity analysis was carried out to assess the effect of the axle convection coefficient on the reported results; the results differed by less than 5% when the axle convection coefficient was increased by 20%.

The only parameter needed to calculate radiation from the axle to the ambient was emissivity, and it was measured to be about 0.96 from previous experimentation (Tarawneh et al. [24]). Again, a sensitivity analysis was performed on the emissivity value used in this study, which revealed that the results differed by less than 1% when the emissivity value was lowered by 20%.

Finally, to simulate heat generation within the bearing assembly, heat flux was applied to the circumferential surface of the rollers, as depicted in Fig. 3. The appropriate heat flux value was determined through a trial-and-error process starting with an overall heat input of 11.5 W per roller (normal operation conditions) and increasing this input until the desired external cup temperature was achieved. The acquired heat input per roller was then divided by the surface area of the roller to obtain the heat flux value. Here, it is assumed that the rollers are the source of heat within the bearing which is justified considering the mass of the roller (0.145 kg) relative to the mass of the bearing cup (11.53 kg) and cone (3.9 kg). To illustrate this, consider an abnormal operation condition in which debris gets wedged between a roller and an adjacent cage bar causing the roller to become fully or partial jammed and resulting in excessive sliding friction between the roller and the cup and cone raceways. Since the mass of the roller is very small compared to the mass of the cup and cone, it is safe to assume that it will heat at a much faster rate than the other two components, thus, becoming the heat source.

Discussion of Results

Thirteen different bearing heating scenarios, summarized in Table 2, were simulated for this study. The first five cases are based on previous experimental work conducted by Tarawneh et al. [2], whereas, the remaining eight cases simulate hypothetical heating scenarios that can result from abnormal roller operation leading to excess frictional heating. The results of both, the FE analysis and the previously validated lumped-capacitance theoretical model (Tarawneh et al. [3] and [23]), are presented and compared hereafter. An in-depth discussion is reserved for six of the thirteen simulated cases, with the purpose of highlighting pivotal information that can help answer the question posed earlier in this paper; i.e., is it possible to have rollers reaching 232 °C (450 °F) within a cone assembly without heating the bearing cup to a temperature that will trigger the HBDs?

FE Model Validation. As stated earlier, the first five heating scenarios listed in Table 2 were intended to replicate five of the

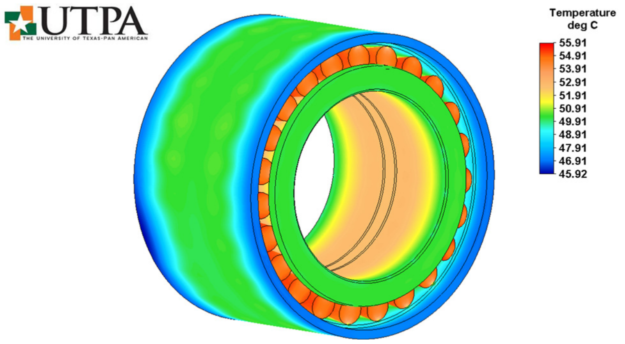

Fig. 5 Thermal FE analysis results for *normal operation conditions*. Axle was suppressed from the visual results to provide a better temperature visualization of the bearing surface (heating scenario 1 in Table 2).

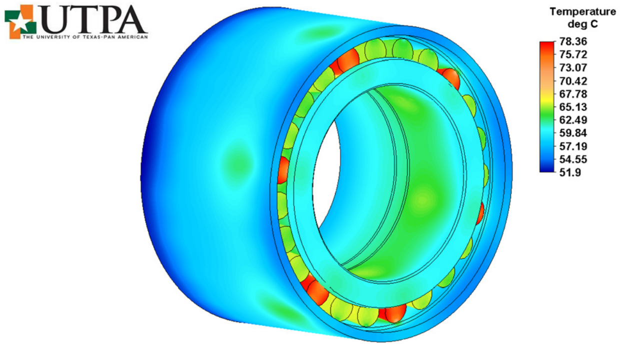

Fig. 6 Thermal FE analysis results for *six welded rollers in one cone assembly* (heating scenario 3 in Table 2)

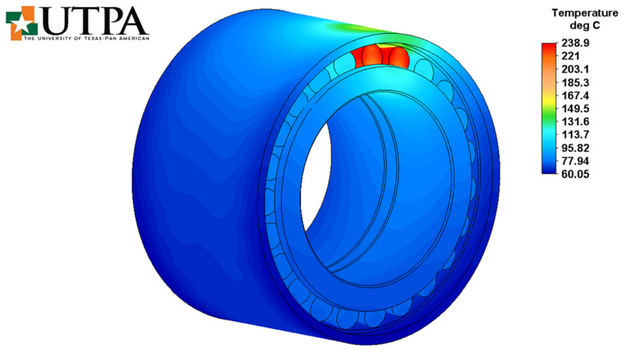

Fig. 7 Thermal FE analysis results for *twisted cage bar* (heating scenario 4 in Table 2)

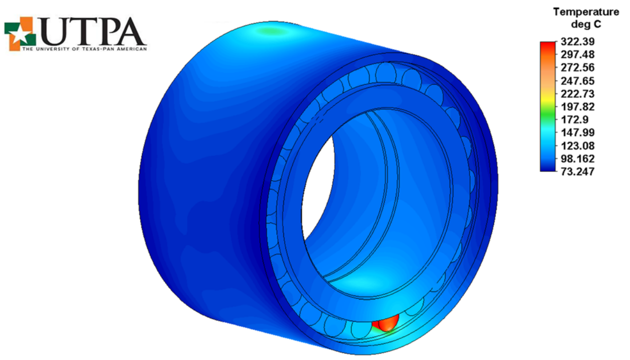

Fig. 8 Thermal FE analysis results for *two hot rollers (one on each cone assembly)* (heating scenario 7 in Table 2)

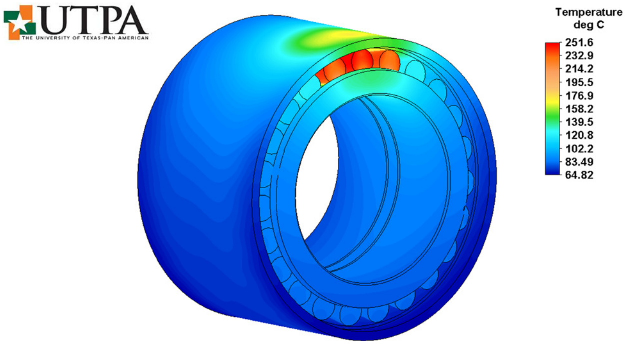

Fig. 9 Thermal FE analysis results for *three consecutive hot rollers* (heating scenario 8 in Table 2)

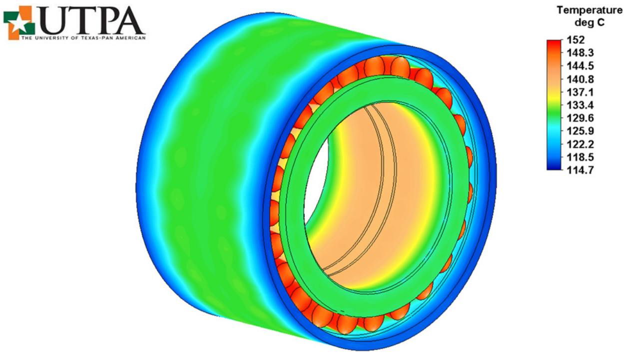

Fig. 10 Thermal FE analysis results for all rollers heated equally to produce a 130.5 °C average cup temperature (heating scenario 13 in Table 2)

excessive frictional heating. The simulation results illustrate how the two misaligned rollers reach an operating temperature of 218.2 °C (425 °F), whereas, the average cup temperature does not exceed 80 °C, which is only 30 °C above that of a bearing in normal operation. Therefore, even though the latter bearing contains two hot rollers operating at unsafe temperatures, conventional track-side HBDs will not trigger an alarm since these devices will only alert when a bearing cup temperature is 105.5 °C (190 °F) above ambient temperature. Rollers operating at very high temperatures will degrade the lubricant and can cause grease starvation, which may lead to bearing seizure and eventual catastrophic failure.

The abovementioned FE model simulations are based on dynamic bearing testing that was previously conducted in the laboratory. The FE model results provide internal temperature data that could not be obtained experimentally due to instrumentation limitations associated with placing temperature sensors inside a rotating bearing. To further investigate the effect of hot rollers on the temperature of the bearing cup, which is the surface scanned by the infrared wayside HBDs, several hypothetical heating scenarios were explored; three of which are discussed hereafter.

The question posed earlier in this paper as to whether it is possible for certain rollers to heat to temperatures above 232 °C (450 °F) within the bearing and go undetected by the HBDs can be answered by looking at the results of simulations 7–10. Simulation 7 in Table 2, shown in Fig. 8, models the case in which two rollers, one on each cone assembly, are operating abnormally. The

Table 4 Relevant temperatures obtained through the FE simulations

	Simulations	Finite element—temperature results				
		Cup 1st raceway (°C)	Cup 2nd raceway (°C)	Cup average (°C)	Roller average (°C)	Roller max (°C)
1	Normal operation	50.3	50.3	50.2	55.0	55.0
2	One welded roller	58.7	56.2	57.5	61.7	120.8
3	Six welded rollers	60.6	57.5	59.0	63.7	75.9
4	Twisted cage bar (two hot rollers)	86.2	73.5	79.2	80.5	218.2
5	Added debris (one raceway)	71.9	65.5	68.6	71.1	83.3
6	Two hot rollers	59.8	59.8	59.7	65.7	110.7
7	Two hot rollers	90.4	90.4	90.2	100.6	291.8
8	Three hot rollers	96.6	81.2	88.5	88.9	232.0
9	Four hot rollers	107.9	87.6	96.8	94.9	233.4
10	Misaligned roller	81.8	76.9	80.0	89.1	388.6
11	Abnormal operation ($T_{cup} = 72\,°C$)	72.0	72.0	71.9	80.4	80.4
12	Abnormal operation ($T_{cup} = 80\,°C$)	80.9	80.9	80.7	90.8	90.8
13	Abnormal operation ($T_{cup} = 130\,°C$)	130.8	130.8	130.5	149.5	149.5

motivation behind this simulation is to determine the roller temperature and heat rate associated with a bearing cup temperature of 90 °C, which is still about 40 °C below the hot-box alarm threshold assuming an ambient temperature of 25 °C. The results indicate that, in order to produce a 90 °C bearing cup temperature, the two hot rollers must generate a heat rate of 489 W if the remaining 44 rollers are assumed to be operating normally (producing 11.5 W each). The roller temperature associated with this heat rate is about 292 °C, which is hot enough to produce distinct roller discoloration without triggering the HBDs.

In the heating scenario "three hot rollers" (simulation 8 in Table 2), shown in Fig. 9, it is assumed that three adjacent rollers are caught misaligned while entering the loaded zone of the bearing, thus, heating abnormally to an elevated temperature of 232 °C. The main goal of this simulation is to determine the bearing cup temperature associated with this hypothetical heating scenario. The results of this simulation demonstrate that the average bearing cup temperature is 88.5 °C even though there are three hot rollers operating abnormally at an elevated temperature that can cause distinct discoloration in these rollers. Again, the 88.5 °C bearing cup temperature is well below the HBD threshold for an ambient temperature of 25 °C and, therefore, this bearing will most likely continue to operate abnormally while undetected by conventional wayside bearing health monitoring equipment. Simulations 9 and 10 in Table 2 are two other hypothetical heating scenarios that demonstrate how certain rollers can reach unsafe operating temperatures without heating the bearing cup anywhere close to the hot-box alarm threshold.

Finally, simulation 13 in Table 2, shown in Fig. 10, provides an insight into the operating conditions that would lead to a bearing cup temperature of 130.5 °C, which would trigger the HBD alarm. The results reveal that all 46 rollers within the bearing have to reach an operating temperature of 149.5 °C, generating a total heat input of 2208 W, in order for the bearing cup to reach 130.5 °C. This heating scenario demonstrates the extreme operating conditions that must occur before conventional wayside detectors tag that bearing for removal from service.

Conclusions

The purpose of the work presented in this paper is to demonstrate that it is possible to have certain rollers within the cone assemblies operating at unsafe elevated temperatures without heating the bearing cup to levels that would trigger the HBD alarm. A theoretical approach was sought because of instrumentation limitations associated with monitoring internal temperatures of a rotating bearing. To this end, a FE model of a railroad tapered-roller bearing pressed onto an axle was developed. The boundary conditions used for the FE model were derived from previously conducted experimental and theoretical work. The model was validated experimentally and theoretically by comparing the axle temperature obtained from the FE results to that calculated from an analytical expression derived from theory developed in a previous study. The systematic comparison of the axle temperature values revealed that the results agreed to within 2%.

Thirteen different heating scenarios were investigated in this study; five of which were intended to duplicate previously performed dynamic bearing tests. The studied cases varied from normal operation to bearings having certain rollers misbehaving to bearings heating to levels that would trigger HBDs. In each case, the temperatures and heat generation rates within the bearing were determined for a specified external surface cup temperature. The ambient temperature used in all the simulations listed in Table 2 is 25 °C (77 °F).

The FE model results revealed that rollers in a bearing operating normally are only 5 °C hotter than the bearing cup temperature; however, abnormally operating rollers such as stuck or misaligned rollers can reach temperatures that are significantly higher than the bearing cup temperature without heating the cup to levels that will trigger an alert. The latter is of concern because rollers operating at elevated temperatures will have adverse effects on the material properties of the bearing raceways, the cages, and also the grease condition. Considering the fact that most lubricants used in railroad bearings start to degrade when operated at temperatures above 125 °C for prolonged periods, having a few rollers operate at temperatures at or above 232 °C will most likely contribute to the accelerated deterioration of the grease, and in extreme conditions, can result in grease starvation and premature bearing failure. Since conventional wayside bearing monitoring equipment will only alert the railroad if the bearing cup temperature reaches 105.5 °C (190 °F) above ambient, it is likely that certain rollers will continue to operate at unsafe temperatures and go undetected until they cause enough damage to the internal components of the bearing that will raise the bearing cup temperature to alarm levels. At that time, however, it might be already too late to avoid catastrophic bearing failure. The aforementioned raises the question about the need for continuous bearing condition monitoring systems as opposed to conventional wayside detection equipment.

In summary, a validated FE model was developed for a railroad tapered-roller bearing that can provide insight into the operating temperatures of the internal components of the bearing for a specified external bearing cup temperature, which has proven to be a very arduous task to accomplish experimentally. The usefulness of the devised FE model is demonstrated in Table 4, which provides relevant temperature results acquired from the simulations