

Ultrasonic Inspection of Reconditioned Railroad Bearing Components – Year 2

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16. Abstract Reconditioned freight-rail tapered-roller bearing cups may contain subsurface material variations that are not identified by surface-focused reconditioning inspections. Work in Year 2 evaluated ultrasonic shear backscatter with spatial-variance and Gumbel-distribution outlier analysis as a method for identifying regions associated with subsequent spall formation. Sixteen cups were scanned, including eight classified as defective and eight as non-defective by Eddy current array (ECA) inspection. Candidate spall formation regions were identified using 99.99% Gumbel bounds and prioritized by spatial clustering and signal timing. The cups were then evaluated on laboratory dynamic test rigs at the University of Texas Rio Grande Valley under simulated full load at 137 km/h (85 mph). The selected ultrasonic outlier regions of the defective cups corresponded to observed spall locations. Three representative ones were elaborated on in this work. Results suggested that the shear-wave focal region was too deep to identify some defects reliably, motivating subsequent surface-wave evaluation.			
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List of Abbreviations

Association of American Railroads (AAR)
Eddy Current Array (ECA)
Microelectromechanical Systems (MEMS)
Probability Density Function (PDF)
Rolling Contact Fatigue (RCF)
U.S. Department of Transportation (USDOT)
University of Nebraska-Lincoln (UNL)
University Transportation Center for Railway Safety (UTCRS)
University of Texas Rio Grande Valley (UTRGV)
Variable Frequency Drive (VFD)

Disclaimer

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1. Introduction

Freight-rail tapered-roller bearings operate under repeated contact loading and can deteriorate through rolling contact fatigue (RCF), particularly within loaded raceway regions [1]–[3]. Reconditioned bearing components are returned to service after inspection and restoration; however, standard reconditioning practices primarily identify surface-level indications and provide limited information about subsurface material condition. This work evaluates ultrasonic nondestructive evaluation methods for identifying subsurface regions that may be associated with subsequent spall formation. Year 1 established differences in ultrasonic signatures between new and reconditioned bearing cups. Year 2 extended the work by mapping ultrasonic shear-backscatter response across reconditioned outer raceways (cups), applying statistical outlier analysis, and comparing selected regions with outcomes from laboratory simulated service-life tests at the University of Texas Rio Grande Valley (UTRGV). The Year 2 objective was to evaluate whether the ultrasonic and statistical method could identify regions associated with subsequent spall formation and to assess whether the selected focal depth was appropriate for that objective.

2. Summary

The work for Year 2 centered on the evaluating of sixteen reconditioned bearing cups, eight classified as defective and eight as non-defective by Eddy current array (ECA) inspection. Ultrasonic shear-backscatter scans were acquired with the focal region targeted near the case-hardened layer, approximately 1.27 mm (0.050 in.) below the surface. Spatial variance was calculated for each raceway, and 99.99% Gumbel-distribution bounds were used to identify statistical outliers. Candidate regions were prioritized when multiple outliers occurred within 0.5 mm (1 pixel) of one another and when the signal maximum occurred within 2 μ s of the peak spatial variance. These criteria were used to select regions for loading zone selection.

The cups were assembled into bearings and tested on four-bearing dynamic rigs at UTRGV under a simulated fully loaded condition of approximately 153 kN (34,400 lbf) per bearing and a simulated train speed of 137 km/h (85 mph). Each initial test accumulated approximately 193,000 km (120,000 simulated miles). The selected shear-wave outlier regions for the cups indicated as defective corresponded to locations where spalls formed during testing. Several cups classified as non-defective by ECA completed the initial 120,000 simulated miles without spalling. Overall, the results suggest that the original shear-wave focal region was too deep to identify some near-surface damage reliably as the amplitudes of what would be the spalled area, were not always the most prominent. Surface-wave scans were therefore conducted, and an analysis code was developed to evaluate their spatial-variance response. Planned work will compare the surface-wave analysis retrospectively with completed service-life outcomes and will evaluate outer rings containing controlled thermally altered regions produced by localized heating.

3. Ultrasound Experiments and Analysis

Year 2 used the same general ultrasonic immersion-scanning procedure established in Year 1. Each outer raceway (cup) was placed on a rotating fixture in the immersion tank, and the stage was leveled. The transducer was mounted on a 90° fixture to produce the calculated oblique angle of incidence. Figure 1 presents the scanning configuration. After the scan profile was defined and saved, the cup was rotated through 360° at each axial position. The transducer mount was then indexed vertically, with the index adjusted to follow the cup taper. This sequence was repeated until the full raceway was covered, and the same procedure was applied to both raceways of each cup.

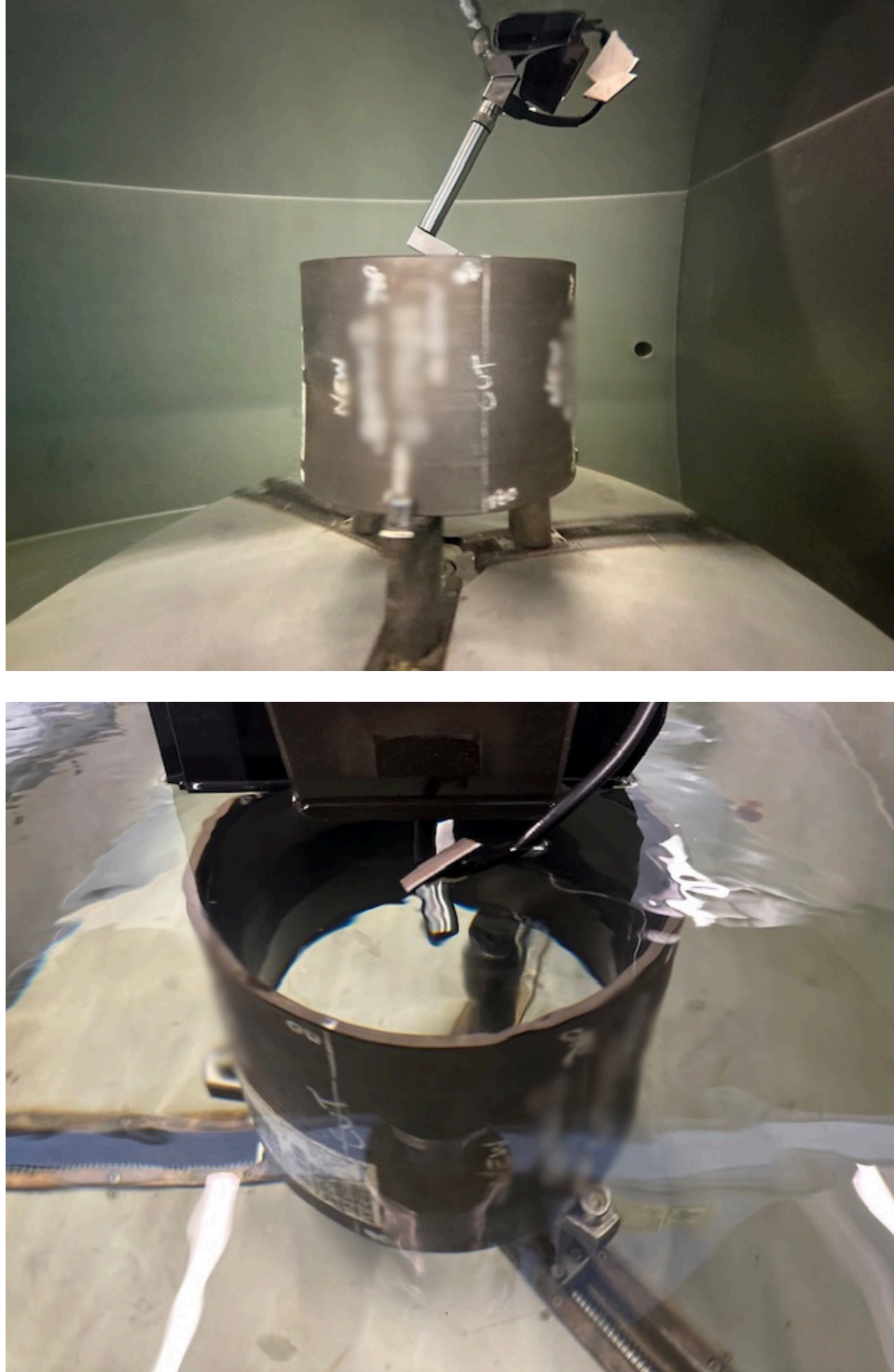


Figure 1. Ultrasonic immersion-scanning setup for an outer raceway (cup) at UNL.

Sixteen cups were scanned: eight classified as defective by ECA (labeled as MxV1–MxV8) and eight classified as non-defective by ECA (labeled as MxV9–MxV16). Approximately 31,000

A-scans were collected per raceway. For shear backscatter, the recorded signal included the front-wall response, grain-noise region, and backwall response. Analysis focused on grain-noise behavior using a time gate centered on the transducer focal zone. C-scan maps were assembled from the A-scans to represent spatial changes in amplitude across each raceway. The uppermost and lowermost C-scan regions exhibited elevated amplitudes associated with the tapered lips of the raceway and were excluded from the analysis. To reduce the likelihood that isolated responses from particulates in the immersion medium would be treated as persistent indications, cups classified as non-defective were scanned two to three times.

The spatial variance of the shear-backscatter signals was calculated using

$$\Phi(t) = \frac{1}{N} \sum_{i=1}^N [V_i(t) - \bar{V}(t)]^2, \quad (1)$$

where N denotes the number of signals per raceway, $V_i(t)$ represents the signal at spatial position i , and $\bar{V}(t)$ represents the ensemble mean. The peak of each spatial-variance curve occurred near the transducer focal depth.

Figure 2 presents top- and bottom-raceway spatial variance curves for MxV4, MxV5, and MxV6, all of which were classified as defective by ECA. Variance curve amplitude and arrival time varied by raceway; each raceway was therefore evaluated independently, and the red segments mark the $\sim 6 \mu\text{s}$ analysis window.

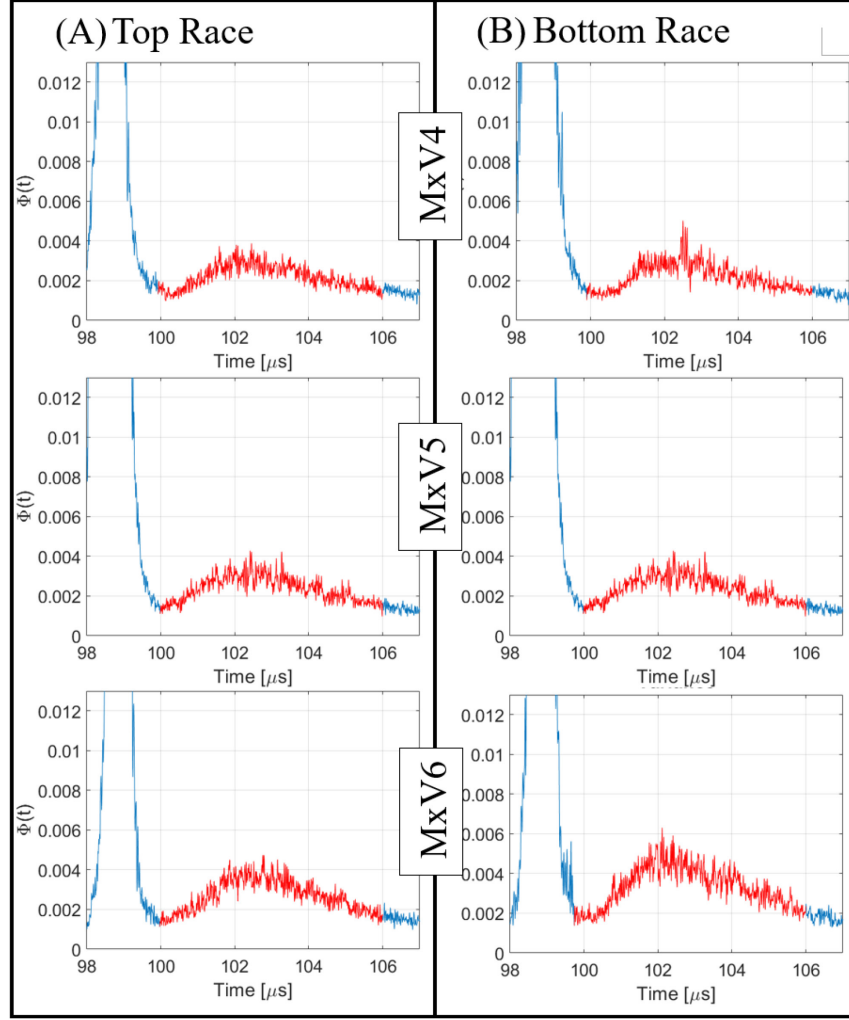


Figure 2. Spatial-variance curves for MxV4, MxV5, and MxV6 during Year 2.

The Gumbel distribution was applied to the previously calculated spatial variance to define statistical bounds. The probability density function (PDF) for the signal $A(t)$ is defined as

$$f_N(A(t)) = \frac{1}{a_N(t)} \exp \left\{ \frac{-A(t) - b_N(t)}{a_N(t)} - \exp \left[\frac{-A(t) - b_N(t)}{a_N(t)} \right] \right\}, \quad (2)$$

where the constants used in Equation (2) are defined as

$$a_N(t) = \frac{\Sigma(t)}{\sqrt{2 \ln(N)}}, \quad (3)$$

and

$$b_N(t) = \left[\sqrt{2 \ln(N)} - \frac{\ln(\ln(N) + \ln(\pi))}{2 \sqrt{\ln(N)}} \right] \Sigma(t). \quad (4)$$

$\Sigma(t)$ denotes the standard deviation of the ensemble. The amplitude of the fitted signal can be calculated as

$$\langle A(t) \rangle = \left[\sqrt{2\ln(N)} - \frac{\{\ln(\ln(N) + \ln(\pi) - 2\gamma)\}}{2\sqrt{2\ln(N)}} \right] \Sigma(t). \quad (5)$$

The theoretical upper and lower bounds of the signal ensemble are then defined as

$$U^{theory}(t) = \left[\sqrt{2\ln(N)} - \frac{\ln \left\{ \ln(N) + \ln(\pi) + 2\ln \left[-\ln \left(1 - \frac{1-\alpha}{2} \right) \right] \right\}}{2\sqrt{2\ln(N)}} \right] \Sigma(t), \quad (6)$$

and

$$L^{theory}(t) = \left[\sqrt{2\ln(N)} - \frac{\ln \left\{ \ln(N) + \ln(\pi) + 2\ln \left[\frac{-\ln(1-\alpha)}{2} \right] \right\}}{2\sqrt{2\ln(N)}} \right] \Sigma(t). \quad (7)$$

Here, γ denotes the Euler-Mascheroni constant ($\gamma \approx 0.5772$), and α defines the confidence level.

$\Sigma(t)$ is related to the spatial variance by $\Sigma(t) = \sqrt{\Phi(t)}$ [4].

Using Equations (2)–(7), statistical bounds were calculated for regions of the ultrasonic shear-backscatter signal that exhibited a nominally uniform scattering profile. A 99.99% confidence bound was selected to reduce the number of candidate outliers. The following examples summarize results for three cups classified as defective by ECA. For MxV4, the ECA inspection conducted by MxV Rail indicated a top-raceway defect at approximately 33.75° and 22 to 33 mm from the bottom of the raceway. Figure 3(A) presents the C-scan outlier map. After application of the Gumbel upper bound, candidate outliers were further prioritized when the signal maximum occurred within 2 μ s of the peak spatial variance and when an outlier was located within 0.5 mm (1 pixel) of at least one other outlier. The red rectangle in Figure 3(A) identifies the higher-priority cluster used to select the loading region at 30.59° . Figure 3(B) presents the selected outlier, and Figure 3(C) presents the corresponding A-scan. Figure 3(D) identifies a higher-amplitude outlier

that was excluded from priority consideration because its signal maximum occurred outside the specified 2 μ s interval.

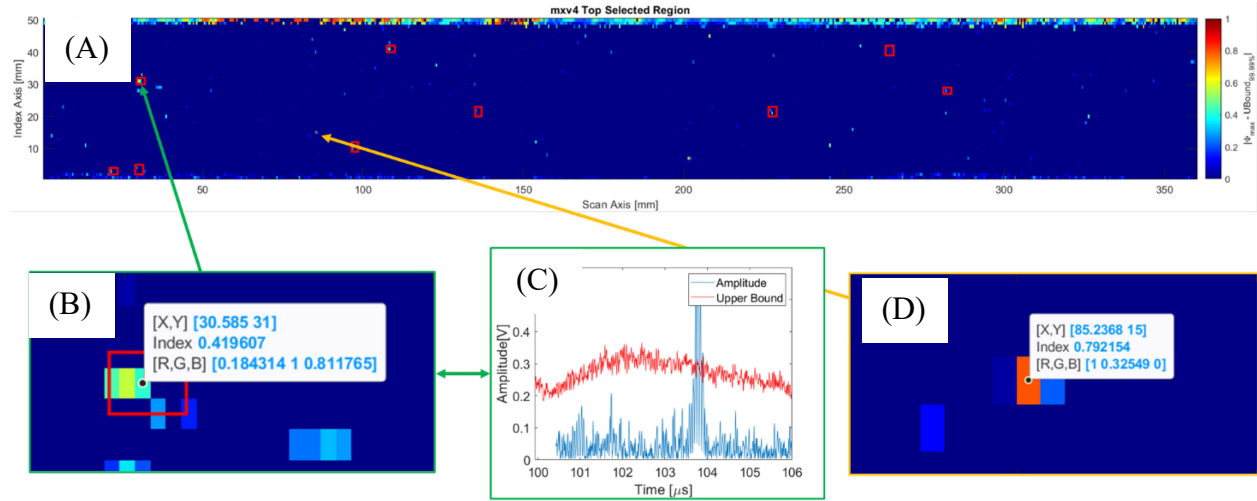


Figure 3. Outlier analysis for the MxV4 top raceway using Gumbel-distribution-derived bounds.

Figure 3(A) identifies pixels whose amplitudes exceeded the 99.99% upper bound; the red-outlined regions satisfy both additional prioritization criteria. The outlier in Figure 3(B) defined the selected loading location, and a spall subsequently formed within that region during service-life testing. Figure 3(C) presents a representative signal that crossed the upper bound within 2 μ s of the peak spatial variance. Figure 3(D) presents a high-amplitude outlier that was excluded by the timing criterion.

Figure 4(A) presents the MxV5 C-scan outlier map. The ECA inspection conducted by MxV Rail indicated a defect near 225°. The ultrasonic analysis identified a candidate region near 217.6°, where a notable cluster of adjacent outliers was present, as illustrated in Figure 4(B). This region was selected as the loading location for the service-life test.

Figure 4(A) identifies pixels whose amplitudes exceeded the 99.99% upper bound, and the red-outlined regions satisfy both additional prioritization criteria. The outlier cluster in Figure 4(B) defined the selected loading location; a spall subsequently formed within that region.

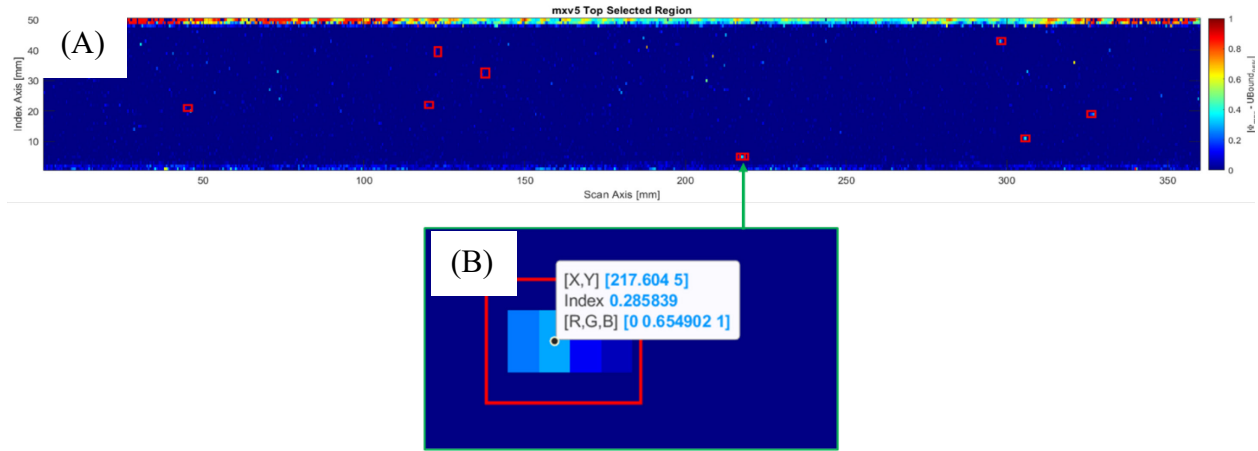


Figure 4. Outlier analysis for the MxV5 top raceway using Gumbel-distribution-derived bounds.

Figure 5(A) presents the MxV6 C-scan outlier map. The ECA inspection conducted by MxV Rail indicated a defect near 169° and 0 to 11 mm from the bottom of the raceway. The ultrasonic analysis identified a candidate region along approximately 165° , as detailed in Figure 5(B). Figure 5(C) presents the A-scan corresponding to the selected pixel. This outlier satisfied both prioritization criteria. The ultrasonic scan also produced a distinct response at a known repair dimple, identified in Figure 5(D), which was distinguishable from the selected candidate defect indication.

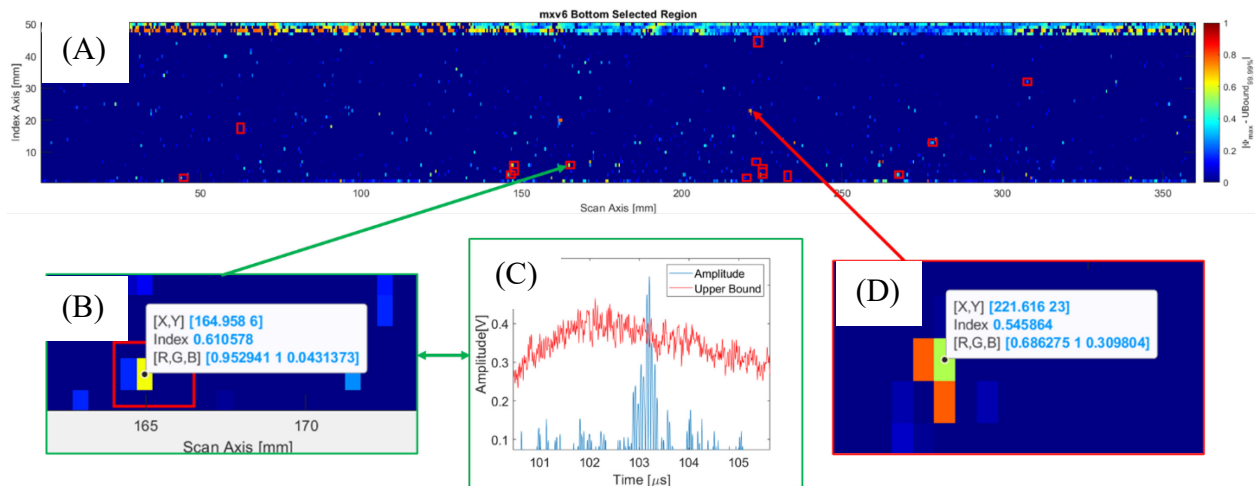


Figure 5. Outlier analysis for the MxV6 top raceway using Gumbel-distribution-derived bounds.

Figure 5(A) identifies pixels whose amplitudes exceeded the 99.99% upper bound, and the red-outlined regions satisfy both additional prioritization criteria. The outlier in Figure 5(B) defined the selected loading location; a spall subsequently formed within that region. Figure 5(C) presents the corresponding higher-amplitude signal crossing the upper bound within 2 μ s of the peak spatial variance. Figure 5(D) presents the ultrasonic response associated with the repair dimple.

4. Simulated Service Life Tests

After ultrasonic scanning, the cups were transported to UTRGV for laboratory simulated service-life testing. Each cup was assembled into a complete bearing using two cone assemblies, one for each raceway, a spacer ring, two grease seals, and two wear rings. Each cone assembly contained a cone, cage, and rollers. Bearings were tested in pairs because the four-bearing dynamic rigs applied top load to the two center bearing positions. The paired bearings were pressed onto custom test axles using a 300-ton hydraulic press and then installed on the UTCRS four-bearing dynamic test rigs. Figure 6 presents the test-rig configuration.

The rigs regulated vertical load through a proportional-integral-derivative controlled hydraulic-cylinder system capable of applying loads up to 150% of the Association of American Railroads (AAR) recommended load. A pulley-and-belt drive system powered by a variable frequency drive (VFD) rotated the axle-bearing assembly. For the expedited service-life tests, the rigs simulated a fully loaded railcar condition of approximately 153 kN (34,400 lbf) per bearing at a simulated train speed of 137 km/h (85 mph). Each initial experiment accumulated approximately 193,000 km (120,000 simulated miles).

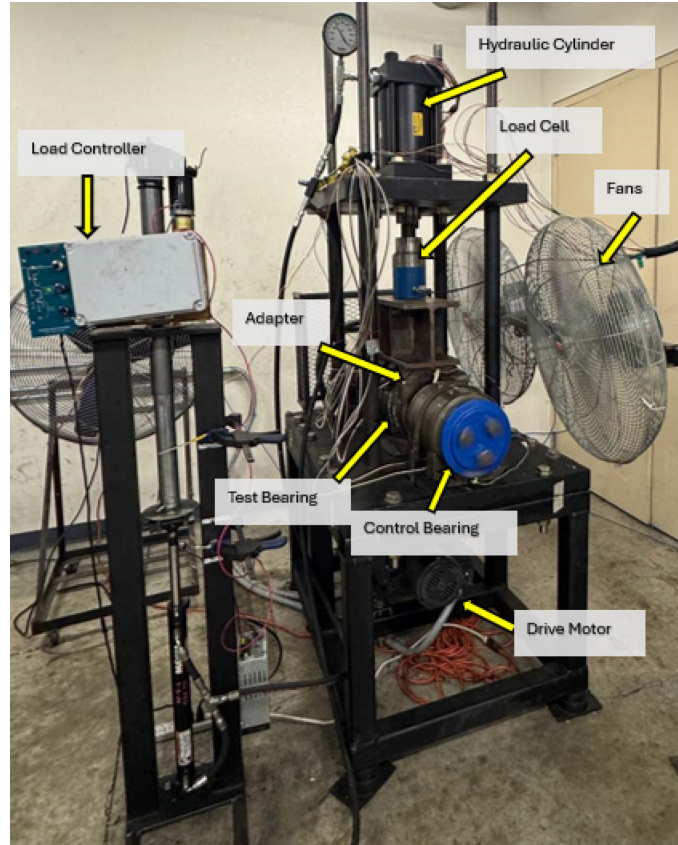


Figure 6. Four-bearing dynamic test rig used for simulated service-life testing.

Vibration, temperature, and load data were recorded throughout the tests. Microelectromechanical systems (MEMS) accelerometers acquired 16-s vibration records every 10 minutes. K-type thermocouples, including bayonet-type, recorded temperature every 20 s. Load-cell data were recorded on the same acquisition schedule as the accelerometer data [5]. The accelerometer sampling frequency and usable bandwidth were not specified in the available Year 2 test record. All sixteen scanned bearings were tested to compare the selected ultrasonic regions with subsequent spall locations. For MxV4, MxV5, and MxV6, the selected statistical outlier regions corresponded to regions where spalls formed. Figures 7 and 8 present the MxV6 bottom-raceway condition before and after testing, respectively. All but one of the cups classified as non-defective by ECA had no outliers that satisfied the selection criteria and completed the initial 120,000 simulated miles without spalling. The one cup that developed a spall, did so on a roller,

which was not one of the subcomponents inspected. Those bearings were later retested to produce a spall for additional comparison.



Figure 7. Pre-test condition of the bottom raceway of MxV6.



Figure 8. Post-test condition of the bottom raceway of MxV6 after spall formation.

5. Conclusions and Future Work

Year 2 results indicate that ultrasonic shear backscatter combined with the Gumbel-based outlier procedure can identify candidate regions associated with subsequent spall formation, but performance was not uniform across the evaluated cups. For the three defective cups discussed in detail, MxV4, MxV5, and MxV6, the selected ultrasonic regions corresponded to the regions where spalls formed during service-life testing. Across the broader evaluated set, ECA indications corresponded with subsequent spall locations more consistently than the shear-wave selections. The available results suggest, but do not establish, that the selected shear-wave focal region was too deep to identify some near-surface damage reliably.

Surface-wave scans were therefore acquired to evaluate a more near-surface measurement approach. Because the surface-wave signals do not provide the same front-wall feature used to align the shear-backscatter data, a modified analysis procedure was developed for the surface-wave measurements. The corresponding bearings had already completed service-life testing before the surface-wave analysis was finalized; therefore, the surface-wave results will be compared retrospectively with the completed test outcomes. Planned work will also evaluate outer rings containing controlled thermally altered regions produced by localized heating at known locations. These tests will provide a more controlled basis for assessing whether the ultrasonic analysis identifies the imposed material changes.

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