USE OF PHASED ARRAYS FOR ULTRASONIC TESTING OF RAILROAD WHEELS

Cameron Lonsdale
Standard Steel
500 North Walnut Street
Burnham, PA, USA

Paul A. Meyer
Krautkramer-Branson, Inc.
50 Industrial Park Road
Lewistown, PA, USA

ABSTRACT

This paper describes the application of phased array technology to the ultrasonic inspection of railroad wheel rims at the production facility of a major North American wrought steel wheel manufacturer. Railroad wheels are now experiencing greater loads and more demanding service conditions than ever before and ultrasonic inspection is therefore a critical function. Further, the Association of American Railroads (AAR) requires that all railroad wheel rims must be inspected for rejectable indications at the manufacturer prior to shipment. Phased arrays, which have been successfully used for medical diagnostic applications and for inspection of welded steel tubing, allow for steering and focusing of sound beams within the part to be inspected. Phased arrays also allow for a computerized, flexible testing system with greater efficiency and effectiveness. The basic principles of phased array technology are described, along with the many advantages of using phased arrays for the ultrasonic testing of newly manufactured railroad wheels.

INTRODUCTION

Steel monobloc wheels are obviously a key component for the railroad industry and are found under nearly 1.3 million freight cars and 20,000 locomotives in service in North America (AAR, October, 1998). Most freight cars have eight wheels while locomotives normally have either eight or twelve wheels, depending on the type. With increased wheel loads and improved car and locomotive utilization, wheels are in more demanding railroad service than ever. For example, the allowable gross rail load for North American freight cars is 286,000 pounds and new locomotives are now being produced that weigh in excess of 415,000 pounds. There is now discussion within the railroad industry about increasing the gross rail load of freight cars even further, to perhaps 315,000 pounds, so that products can be moved more profitably. Diesel-electric locomotive horsepower levels have increased dramatically in recent years with 4,400 horsepower models now in regular production and 6,000 horsepower locomotives may be supplied to railroads soon. Also, locomotives now have greater wheel/rail adhesion than ever before and passenger railroad speeds are increasing. Finally, in addition to the high static mechanical loads imposed upon the wheel by the gross rail load, dynamic loads caused by wheel flats and thermal loads from on-tread service braking are important sources of stress.

In service train accidents due to broken wheels are a relatively rare occurrence, although such accidents are generally very expensive since they occur during train operations. A review of Federal Railroad Administration (FRA) data reveals that the number of train derailments caused by broken wheel rims has trended downwards in recent years (FRA, 1999). This trend is likely due to the removal of inferior straight plate wheels from service, the removal of untreated wheels (softer, non-rim quenched wheels) from service and continuous improvements in wheel manufacturing practices. The reduction in failures comes at the same time that wheel service demands are increasing. Figure 1 shows the number of derailments caused by broken wheel rims from 1985 through September of 1999 (FRA, 1999).

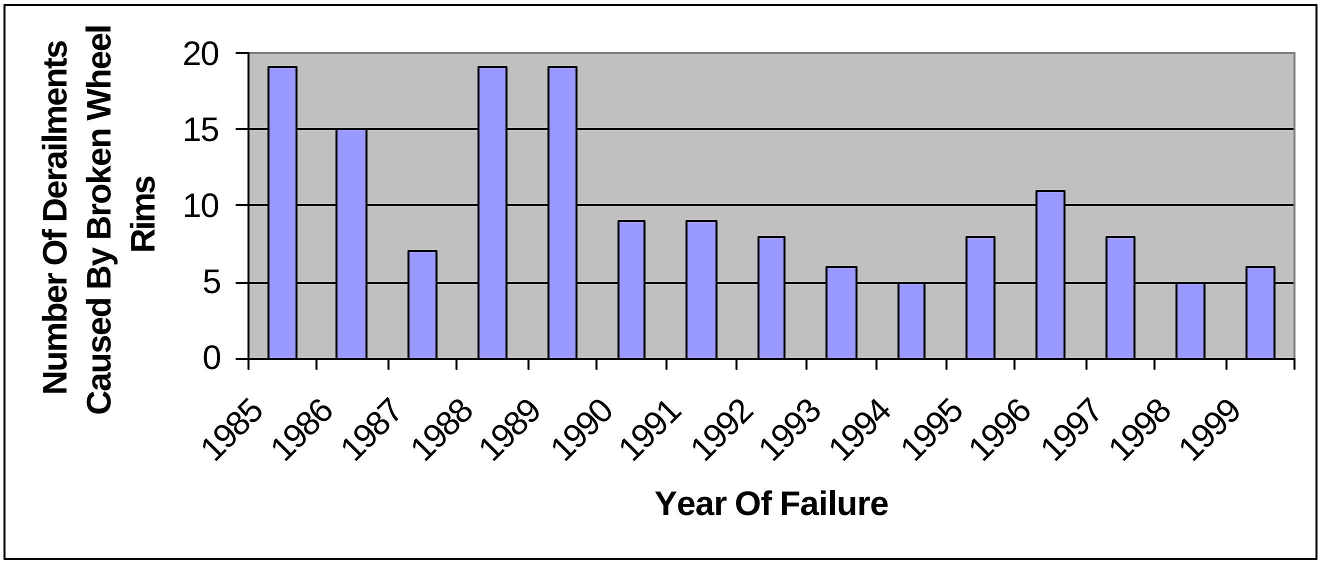

Figure 1. Number of broken wheel rims that caused derailments, 1985 – September 1999.

Further wheel performance data are provided by Association of American Railroads (AAR) car repair billing (CRB) data (AAR, 1999). When a wheel is replaced on a freight car by a railroad or independent car repair facility, a car repair bill is created to account for the repair and insure that the party performing the repair is paid for the work. Not all North American wheel removals are included, but the data are believed to be fairly good. CRB data are kept for various "why made codes" which indicate why a wheel was removed. "Shattered rims," a progressive fatigue failure seen in some wheel rims, are identified as AAR why made code 71. The number of shattered rims has decreased in recent years, as shown by Figure 2, which are AAR CRB data for shattered rims removed during the period 1988-1998

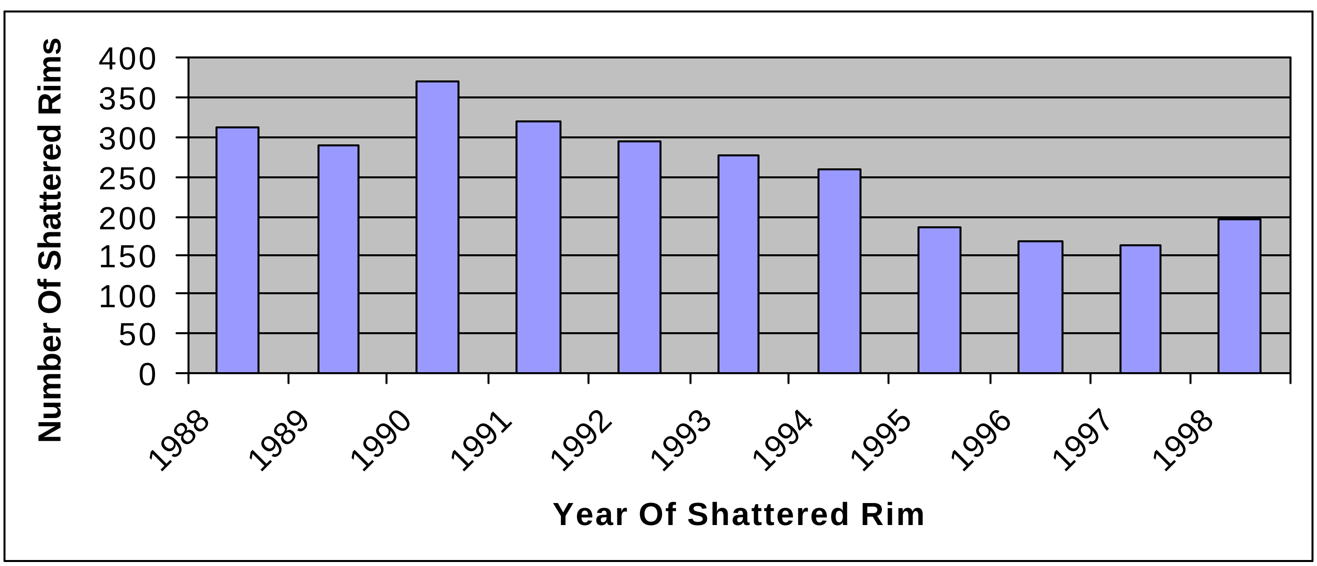

Figure 2. AAR CRB data for shattered rims, 1988-1998.

The data in Figures 1 and 2 suggest that wheels are indeed failing less frequently. However, several recent, major, wheel related derailments on railroads in the western United States, along with other wheel failures on locomotives, have led to increased scrutiny for wheels. Some of these failures were attributed to manufacturing related problems such as inclusions and porosity within the wheel rim. Therefore, both wheel manufacturers and North American railroads began to look critically at the methods used to inspect new wheels.

AAR ULTRASONIC SPECIFICATION

Ultrasonic inspection of railroad wheel rims for rejectable indications following manufacturing is required according to the AAR Manual of Standard and Recommended Practices (AAR, 1998). The AAR ultrasonic specification was adopted in the late 1960's and had remained essentially the same until 1999 when a group was established to facilitate revision. Ultrasonic scanning in the axial direction (across the rim section) and the radial direction (from the tread surface) had been prescribed since the specification's inception. The old AAR inspection specification required that one radial reference hole and one axial reference hole be drilled in the center of the rim for calibration purposes. Both holes were to be drilled as 1/8-inch diameter flat bottom holes, with the radial reference hole parallel to the rim face and the axial reference hole perpendicular to the rim face.

New revisions to the AAR ultrasonic specification (not yet in effect at the time of this writing) require that several additional calibration holes be drilled in the wheel rim and include the following major changes:

- Scanning shall be performed using an automated scanning system.
- A distance amplitude correction (DAC) is used for both the radial and axial scans.
- Additional holes are drilled in the rim to improve volumetric coverage of the scan.
- The rejection criteria are tightened to 50% of the signal response from the reference standard.

These revisions will soon go into effect and are expected to improve the quality of the ultrasonic inspection performed by railroad wheel manufacturers, who participated fully in the process. The new specification's indication rejection criteria are twice as stringent as the old one and volumetric coverage of the rim is significantly greater.

THEORY AND DEVELOPMENT OF PHASED ARRAYS

Ultrasonic phased array systems are not new - they have been available since the mid 1970's. But at that time the cost of the electronics necessary to operate these systems was prohibitively high. More recently, reduced computing and electronics costs have made these systems more practical.

In a phased array system there is a transducer containing many individual elements. Additionally, there are several instrument channels each capable of independently operating a transducer element. Precise timing, or phasing, of the individual channels is necessary for effective operation of the system. Applying a linear time delay to successive elements in the system will cause the sound beam to be steered to one side as shown in Figure 3.

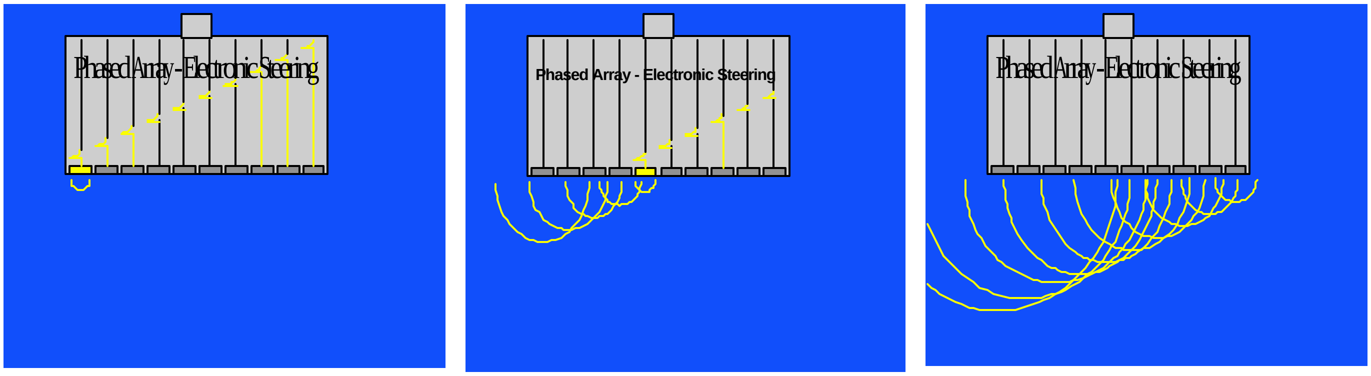

Figure 3. Wavefront steering using linear phase delays.

In a similar manner a nonlinear phase delay can be used to focus the acoustic energy as shown below in Figure 4.

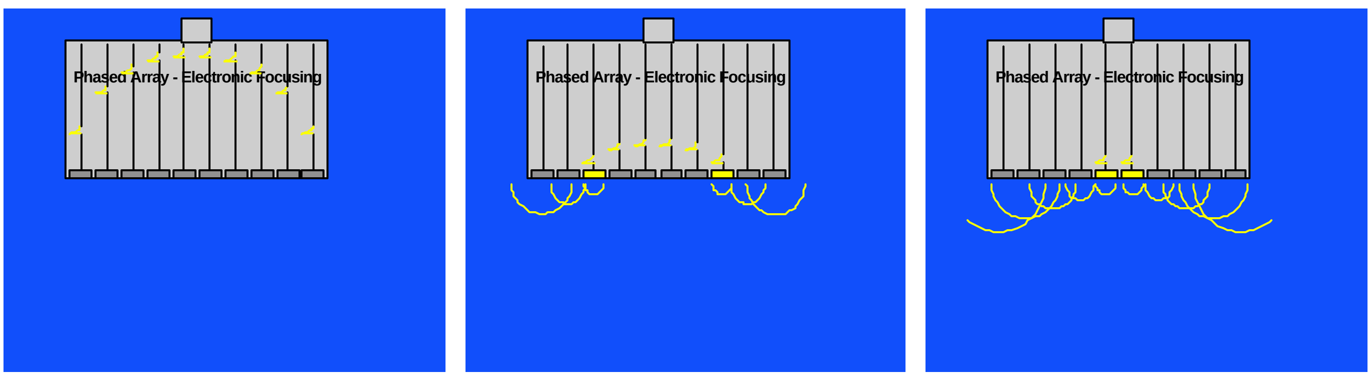

Figure 4. Wavefront focusing using phase delays.

Naturally it is possible to combine these effects permitting detailed interrogation of many regions within the inspected component. These capabilities are limited by wave propagation considerations, however, and must be addressed during the design of the system.

The maximum angle at which the beam can be steered is strongly affected by the design of a single element. When energy is radiated from a single element, it approximates a circular wavefront. The distribution of energy along the wavefront is governed by the ratio of the element width to the wavelength of sound in the radiation medium. As this ratio increases the radiated energy is concentrated more heavily directly in front of the element. Decreasing the ratio distributes the energy more uniformly along the wavefront. It is generally accepted that the maximum effective steering angle occurs at the angle at which the signal amplitude drops 6 dB below the axial peak. Therefore, as larger steering angles are required, the individual elements must be correspondingly smaller to produce sufficient energy in the steered beam at larger angles. It must be kept in mind that as the steered beam enters the steel wheel, refraction occurs steering the sound to an even greater angle.

Focusing effects are governed by diffraction as well as phasing. A group of array elements activated simultaneously will produce a beam with an axial maximum at a distance proportional to

$$d^2 * freq/(4*c)$$

where d is the lateral dimension of the group, *freq* is the frequency of the acoustic signal, and c is the acoustic velocity of propagation. This value is sometimes called the *nearfield distance* or the *natural focus* of the transducer. It is not possible to focus a transducer beyond its nearfield distance, not even by phasing it.

The particular design we use in this inspection system was developed by first defining the maximum distance to a defect. This distance defines the size of the active group of elements necessary to obtain sufficiently narrow beamwidths. The active group, or virtual probe, in this design is 16 mm square. Defect size also dictates the appropriate ultrasonic frequency, selected to be 5 MHz. Steering angle and desired focal characteristics determine the necessary element size, and therefore the number of elements in the group. The 16-mm square virtual probe is divided into 16 individual active elements. The total number of elements in each array (128) was established to permit scanning the entire rim volume of any of the several wheel designs. This makes the size of the array larger than necessary for many tests. Therefore, testing each wheel design requires only a subset of the elements. This also permits the possibility of testing larger future designs while using existing hardware.

THE PHASED ARRAY INSPECTION SYSTEM FOR WHEELS

The phased array ultrasonic inspection system, currently the only such system in the world used for the inspection of new railroad wheels, is installed on two wheel inspection lines at the Burnham plant. The system is now used for the inspection of all wheel rims made by Standard Steel. Since Standard Steel is a wrought wheel manufacturer, many different wheel designs are produced and wheels have several different rim thickness dimensions. Before scanning of a given design can be accomplished, minimum rim dimensions (a data set) must be initially entered into the phased array system. This prevents spurious signals from being generated by geometric differences in wheel rim and tread profiles. After information is entered into the computer and saved, a given data set can be recalled for future testing at the push of a button, or after a bar code label is scanned.

Two ultrasonic probes large enough to test all of the wheel designs are mounted inside the immersion tank of each automated inspection line. The water immersion tank provides for the most effective and efficient couplant of sound into the wheel rim. The wheel rim is immersed in water and the rim is ultrasonically inspected from the back rim face (axial scan) and wheel tread surface (radial scan) as the wheel is rotated through 360 degrees. Each of the two large ultrasonic probes has 128 individual ultrasonic transducers (256 total) that are electrically "fired" as required and perform the actual scanning of the wheel rim. Ultrasonic beams can be steered and focused within the wheel rim and multiple scans can occur during a single wheel rotation. As required by the AAR, an automatic alarm sounds to alert the operator when an indication is detected that breaks the established rejection level.

Included in the phased array systems are water and dust proof cabinets for the computers, air conditioners, two computer hard drives, power supply systems, key pads and bar code label wands. The computer system has several different security levels to facilitate updating of information. For example, only personnel specifically authorized to make changes to wheel design data sets are allowed do so as such changes require a password.

When compared to the old ultrasonic inspection system that used larger "paintbrush" transducers and analog equipment, the new phased array system provides for improved sensitivity (particularly in the near field), improved volumetric coverage, a reduction in the signal to noise ratio, greater inspection flexibility and computer interface capability. The phased array system allows for rapid changing of test configurations for different wheel designs, the ability to perform multiple scans during an inspection, the ability to perform custom and special inspection scans, and has the capability for long-term data storage. Further, operator test set-up time is minimized and inspection consistency has been improved. Operators no longer have to reposition ultrasonic inspection transducers for each different wheel design. The phased array inspection system has been a success. The system is flexible and can be adjusted to account for any changes in requirements for ultrasonic testing.

CONCLUDING REMARKS

With the increased demands of railroad service it is critically important that railroad wheel manufacturers produce a product of the best possible quality. Manufacturers have no control over the severe service environment experienced by a wheel and thus must insure that product inspections are conducted using the best available technology and methods. As a result, state of the art phased array ultrasonic technology was selected for the new wheel inspection systems at the Standard Steel Burnham plant. Additionally, recent tightening of AAR wheel rim ultrasonic test specifications validates the decision to acquire a flexible computer based system with increased sensitivity and improved volumetric coverage.

REFERENCES

Association of American Railroads, *Railroad Facts*, Washington, D.C., October 1998.

Association of American Railroads, *Manual of Standards and Recommended Practices – Wheel and Axle Manual – Section G*, Washington, D.C., 1998.

Association of American Railroads, Car Repair Billing Data, Washington, D.C., 1999.

Federal Railroad Administration, "Train Accidents By Cause From Form FRA 6180.54," http://safetydata.fra.dot.gov, 1999.