X-ray linear detector arrays (LDAs) have been an ideal choice for inline and offline nondestructive testing (NDT) in the tire industry. Novel digital X-ray detectors have recently been developed for enhanced tire quality control. They are based on a new intelligent digital platform, which is targeted to improve image quality, increase the maximum scanning speed, and save on the overall system cost by both electronics and software design. Furthermore, they also provide remote firmware upgrades, diagnostics, and other advanced features. This paper presents the working principles of a typical industrial X-ray imaging system in the tire industry. It describes a new U-shaped detector, and explains how to improve the production efficiency as well as detection abilities in X-ray tire inspection systems. To illustrate, examples of applications in X-ray tire inspection systems are presented for various types of tires.

Introduction
X-ray inspection systems have been deployed in industrial NDT applications over many decades. The integration of the latest technologies from an X-ray source and LDA to a computer and inspection software have made X-ray inspection systems easy to use, safe, and fast. In the past, these factors limited their adoption for industrial applications. Nowadays, these factors have also broadened the scope of X-ray inspection systems beyond research and development applications, and more and more into the realm of inline production testing.

Overview of Tire X-ray Inspection Applications
Tire inspection has already become an important issue in the tire industry in order to improve tire quality and safety. For this purpose, NDT techniques have been employed to test a material for surface or internal flaws without interfering in any way with its suitability for service (Valavanis and Kosmopoulos, 2010). Typically, several existing technologies are used, including visual inspection, acoustic emission, and ultrasonic testing (Anouncia and Saravanan, 2006). The overall effects available for these methods are either quite limited or appropriate only for a specific type of defect (Zhang et al., 2013). On the other hand, X-ray is considered to be the most promising technology for tire defect detection and has been widely used in manufacturing processes (Zhang et al., 2013). X-ray has proven to be the most effective technique
due to its advantage in that surface and internal discontinuities, as well as significant variations in composition, can be detected. Although several inspection techniques are used during the tire manufacturing process, examination by X-rays is considered to be the final quality check of the finished tire. An example of a dual-station X-ray tire inspection system is presented in Figure 1.

X-ray inspection is a well-established NDT technique in the tire industry and is used in a number of applications for quality control and to ensure high levels of quality and safety. X-ray may be applied to prototypes during the development phase as well as for spot-checking or even 100% coverage inline production testing. To ensure all tires are structurally sound and reliable right out of production, X-ray is used to inspect the internal parts of the tire for any underlying discontinuities that could take place during initial use.

Nowadays, large commercial truck and bus tires, as well as some passenger and light truck tires, are inspected in inline production by X-ray machines; however, X-ray tire inspection is not just applied for the final check of a brand new tire. High-priced tires for trucks, earthmovers, aircraft, and so on have their treads commonly replaced, with some of these products being re-treaded several, or even up to 10, times in the case of an airplane tire. From a commercial point of view, it is a reasonable step to analyze the performance of the inner structure of the tire by X-ray before applying the costly re-treading process.

Working Principle of a Typical X-ray Tire Inspection System

Based on the type of tires as well as requirements of inspection systems, there are several typical designs of X-ray inspection systems. In the tire tread and protruding wire inspections, an X-ray LDA is used with a standard X-ray source as the most typical X-ray inspection. It captures a single line at a time (horizontal), and requires the tire to be moved or rotated in order to create the vertical direction of the image. For large commercial truck and bus tires, as well as some passenger and light truck tires, in order to provide the best production efficiency and image quality, the LDA is shaped to approximate the contour of a tire from bead to bead as a U-shaped detector. By placing a panoramic X-ray source inside the tire and rotating the tire during inspection, an entire tire image can rapidly be collected in a single pass with the U-shaped detector; therefore, this is a popular usage nowadays in X-ray inline production testing. The operating principle of a typical imaging system with a U-shaped detector is presented in Figure 2.

For extra-large off-the-road tires, a single, long X-ray linear detector is utilized to reduce the overall system cost. The tire X-ray inspection systems require three or five rotations of the tire to gather necessary information to generate an image by moving the X-ray linear detector along the contour of a giant tire. The image is then generated for at least three sections for analysis: upper sidewall, tread, and lower sidewall.

Development Trend of X-ray Inspection Systems in the Tire Industry

Thanks to the strong demands of inline production testing, the tire industry market is driving X-ray tire inspection system development not only to offer maximum precision and reliability, but also to improve production efficiency. As the X-ray inspection systems are generally operated on an inline basis, they are part of a large production line, where every idle minute costs money. Therefore, the target is always to keep maximum uptime as well as reduce cycle time.

The traditional quality inspection process is mostly performed by human inspection. This often results in an inaccurate and undetected inspection result because of visual fatigue. This also leads to low efficiency with high labor costs. Today’s tire manufacturers produce tires that are complex and require sophisticated testing to verify the overall quality of the final product. As a result, a computer-vision-based automatic defect recognition (ADR) technique has also become an important and efficient tool to improve the quality of the products and increase manufacturing efficiency.

Novel X-ray Detectors for Tire Inspection

The requirements for X-ray detectors can be easily summarized based on the development trend of X-ray inspection systems of tire inspection. These are as follows:

- Easy for maintenance
- Ultra-high throughput and speed to improve production efficiency
- Superior X-ray imaging quality for ADR
- Reliability for high temperature and humidity, and robustness for external noise
- Flexible design to support various sizes of tires
- Multi-view system support for dual-station inspection system

A recent product family of U-shaped X-ray LDAs was developed and specially optimized for high-speed digital tire inspection utilizing panoramic X-ray sources (Figure 3). A block diagram of the series products is illustrated in Figure 4.
The series products are based on a novel intelligent digital readout platform, which brings significant advances in both speed and image quality for industrial inline and offline NDT of tires.

New features are user-friendly designed for maintenance, such as remote firmware upgrades, and automatic diagnostics combined with updated compact mechanics. With a gigabit Ethernet (GigE) interface and digital parallel readout structure, it reaches a maximum 1.8 m/s (5.9 ft/s) scanning speed, which can help to reduce the cycle time to approximately 20 s for up to 20% improvement of production efficiency. It also supports a dual-station system by using the GigE interface to allow multiple U-shaped detectors to be controlled by a single computer simultaneously.

By meeting CE Mark certification as well as dust and water-resistant standard IP43, it is optimized with a robust and reliable design for high temperature (0 to 65 °C [32 to 149 °F]), humid, and contaminated environments found in a tire production factory. It has improved the radiation hardness and lifetime of the detector, which helps to minimize lifetime cost of X-ray systems. Improvement of the X-ray response drop with absorbed radiation dose is shown in Figure 5.
The standard series is well suited for quality inspection of various types of tires, from passenger car and truck tires to off-the-road tires. With active lengths from 1382 to 3379 mm (54.41 to 133 in.) the series covers tire bead sizes of 30.48 to 88.9 cm (12 of 35 in.).

Thanks to the latest designs of ultra-low noise, front-end, application-specific integrated circuits as well as the digital readout platforms, it not only reduces the dark noise significantly, but also enables the highest sensitivity level with 0.75 pC gain. Thus, while meeting the high scanning speed requirement, the series can provide image quality to meet the tightest quality requirements. The dynamic range of the U-shaped detectors is doubled as it is presented in Figure 6.

In order to meet the demanding image quality requirements for inline ADR, a stringent hardware assembly control process ensures less than 0.25 mm (0.01 in.) mechanical gap along the entire 0.4 mm (0.02 in.) pitch LDA. Furthermore, an advanced pixel discontinuity correction algorithm was developed to get an edgeless image, as the discontinuity issue on certain detector array joints may disturb inline ADR for tire carcass and belt structure integrity.

The pixel discontinuity correction algorithm utilizes actual measured physical gaps in between detector arrays to recalculate the pixel position of each pixel, and then by inserting one new pixel into each physical gap, the correction values are calculated and stored in a flash memory of the detector hardware as a factory configuration for each U-shaped detector (Figure 7).

Figure 8 gives an example of image quality improvement by comparing the difference when the advanced pixel discontinuity correction is applied to the 0.4 mm (0.02 in.) pitch U-shaped detector.

In order to optimize the image quality further, an upgraded software library supports storing up to 256 offset and gain correction tables based on the optimized configurations for different types of tires. New software functions, including advanced nonlinear calibration, dead pixel correction, automatic troubleshooting procedure, and multiple detector support are also well suited to tire inspection. An example of an X-ray tire image with a 0.4 mm (0.02 in.) U-shaped detector is presented in Figure 9.

Figure 8. Example of a high-resolution tire X-ray scan without and with pixel discontinuity correction.

Summary

This paper presented X-ray tire inspection applications and how recently developed novel X-ray digital detectors meet the application requirements by considering development trends of X-ray inspection systems in the tire industry for both high production efficiency and excellent image performance. The results show that it reached the expected improvements by cooperating with a couple of X-ray tire inspection system manufacturers.

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