Measurement of the Modulation Transfer Function for a Backscatter Radiography System Used in Nondestructive Examination

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INTRODUCTION

Since the 1990's, North American railroads have been experiencing increased traffic densities, resulting in trains traveling at higher speeds with more passengers, along with heavier axle loads. As a result, considerable pressure has been placed on the existing railroad infrastructure, leading to increased demands in inspection and maintenance of rail structural components. While track inspection encompasses all railroad structural components, significant focus has been paid to the second most costly capital expense, which are crossties. Traditional tie inspection methods have been limited to the examination of the external tie surface through visual means with a human inspector. These techniques are subjective, unreliable, and extremely inefficient. Currently, automated methods of tie inspection exist, which employ machine vision technology to create a three-dimensional image of the track, subsequently removing the variability and achieving speeds necessary to avoid interruption of traffic. Since wood ties generally degrade from the bottom upward, understanding the subsurface composition is of utmost importance in achieving the most reliable and safe tie inspection techniques. In order to meet these needs, a backscatter radiography scanning system was developed for the automated inspection of wood crossties.

Backscatter radiography is a nondestructive examination technique, which utilizes the detection of Compton-scattered x-rays to form an image. It has become an invaluable tool in the industrial arena owing to its ability to place the x-ray source and the detector on the same side of the imaged object, along with its ability to provide density information of bulk materials. Backscatter imaging has found applications in the aerospace industry, where it was used for corrosion detection of aircraft components [1], or in examining the spray-on-foam-insulation (SOFI) surrounding the space shuttle's fuel tanks [2]. It has also found utilization in security applications that deal with the screening of sea containers, vehicles, luggage, and even people [3].

The image quality of any scanning system is one of the most important metrics, which must be characterized and understood in order to achieve optimal results. The best descriptor of quality is spatial resolution, which is most commonly described by the modulation transfer function (MTF). Several methods exist to test the MTF of conventional transmission radiography systems, but these cannot be directly applied to backscatter radiography due to the inherent differences in how their images are formed. The goal of this study was to alter the transmission MTF measurement methods so that accurate and reliable results can be obtained for the backscatter system. Test tools were developed in order to carry out these measurements, with the ultimate goal of providing a target for annual quality assurance testing of the equipment.

MODULATION TRANSFER FUNCTION

The modulation transfer function (MTF) of an imaging system is the most complete description of the spatial resolution properties for that device. The MTF is the magnitude response to sinusoids of different spatial frequencies, and it provides a quantitative description of the degradation of contrast with increasing spatial frequencies. In practice, the MTF is usually determined along one dimension from the line spread function (LSF), as shown by Equation 1

$$MTF(f) = \frac{\left|\int_{-\infty}^{\infty} LSF(x)e^{-i2\pi fx}dx\right|}{\left|\int_{-\infty}^{\infty} LSF(x)dx\right|} \qquad (1).$$

The LSF can be determined by the detector response to either a slit or gradient over the response to a sharp edge. The difficulty in aligning the narrow slit with the x-ray beam is often the deterrent in using this method, and the edge response is used instead.

Edge Method

The edge spread function (ESF) is the response of an imaging system to a sharp edge. Differentiating the ESF will produce the LSF, from which the MTF can be determined through use of Equation 1. The advantages of the edge method include high precision, particularly exceling at low spatial frequencies, along with its simplicity and speed of data acquisition. Its downfalls are based on the differentiation step, which enhances high frequency noise into the MTF measurements [4].

Bar-Pattern Method

In situations where a quick and easy estimate of the spatial resolution is required, such as in routine quality assurance testing, the edge method is not appropriate. A more convenient test uses a bar target composed of equal line and space width. The square-wave response to this bar-pattern is called the contrast transfer function (CTF) and it is not equivalent to the sine-wave response for which the MTF is defined. The CTF is a function of the fundamental spatial frequency and is measured by the difference in the peaks and valleys of the output response profile. For a square-wave pattern of infinite extent, Equation 2 can be used to calculate the MTF from the measured CTF [5].

$$MTF(f) = \frac{\pi}{4}\left\{ CTF(f) + \frac{1}{3}CTF(3f) - \frac{1}{5}CTF(5f) + \frac{1}{7}CTF(7f) - \cdots \right\} \qquad (2)$$

The fundamental spatial frequency f is defined as the inverse of the bar-to-bar spacing. The increasing frequency of evaluation with each successive term in the series expansion indicates that for evaluation at higher frequencies, fewer terms need to be used since no modulation values exist above the cut-off frequency. The cut-off is defined by the frequency at which the measured MTF goes to zero. Equation 2 can therefore be approximated with the use of only one term at frequencies larger than 1/3 of the cut-off [6].

BACKSCATTER RADIOGRAPHY

Unlike conventional transmission radiography, Compton Backscatter Imaging (CBI) techniques rely on the detection of x-ray photons backscattered in the target object. The technique typically uses an x-ray source and detector, which are both highly collimated, and placed on the same side of the object. The intersection of the x-ray beam and the detector's field-of-view form the measurement volume from which the backscatter signal originates. The number of detected x-rays depends on both the number of scattered x-rays, and the attenuation of their path within the material. In the energy ranges of commercially available x-ray tubes, Compton scattering is the predominant photon interaction. Contrast is therefore the result of differences in electron densities of scanned materials.

Since the detected backscatter signal requires photons to both traverse and escape the target material, the geometry of the measurement volume, including its size, shape, and position within the sample, play a significant role. The output contrast will therefore be dependent on both the electron density of the material and the geometrical setup of the system. As a result, the accuracy of MTF measurements is highly dependent on the appropriate target material and thickness, along with their orientation and relationship to surrounding materials. Previous experiments built a bar-pattern target in which the thickness of lead was insufficient to provide adequate signal contrast. Also, measurements were performed with the target placed over both ballast and wood ties. Since the scattering probability for ballast is much less than that of wood, the signal from lead bars located in these areas were over-modulated. These two factors combined to produce output profiles with unresolvable peaks that were contaminated with large amounts of noise.

METHODS

System Description

The necessity for fast scanning speeds (20 mph) required the construction of a system in which the utilization efficiency of the x-ray source was maximized. The scanning technique capable of this in backscatter radiography is known as the push-broom method [7]. It uses a fan beam of x-rays coupled to a linear detector array. The arrangement allows for the simultaneous measurement of all scatter voxels irradiated by the fan beam. The system is composed of a 450-kVp industrial x-ray tube, which is mounted to a Hi-Rail vehicle. The linear array is located within the focal plane of the x-ray tube, and it obtains a scan line perpendicular to the system's motion. The translational motion of the imaging system and the continuous operation of the x-ray tube create a two-dimensional image. The linear motion of the scanning system is referred to as the along-scan direction, while the perpendicular orientation is known as the across-scan direction. All tests were conducted under normal tube operating conditions, with scan speeds of 15 mph.

Bar-Pattern Measurements

A custom bar-pattern was designed in order to carry out the MTF measurements on this backscatter radiography system. The rectangular bars were constructed out of 0.64 cm thick lead that ranged in width from 0.50 cm to 5 cm. These lead bars were embedded into medium-density fiberboard (MDF) by routing out rectangular bars to match the dimensions of the line-pairs. Ten discrete spatial frequencies in line-pairs per centimeter were generated: 0.10, 0.11, 0.13, 0.14, 0.17, 0.20, 0.25, 0.33, 0.50, and 1.0. Each spatial frequency consisted of four identical line-pairs in order to provide better statistics for each measurement. Since a large number of line-pairs were tested that were of extensive widths, it was not possible to put them all on one target piece. As a result, one spatial frequency was placed per 48.3 cm x 12.7 cm MDF board. Doing so ensured that no line-pairs would be placed near the rails, since the decreased intensity of off-axis radiation could misleadingly cause a over-modulated signal in these line-pair responses.

The bar-pattern tests were performed with two orthogonal orientations of the target, which provided measurements of the one-dimensional MTF for both the along-scan and across-scan direction of motion. Due to the complexities of backscatter contrast generation, the placement of these tools was a key factor in obtaining accurate results. When testing for the across-scan axis, the target was placed in the center of the rails atop and parallel to the wood crossties. The along-scan measurements required the tools to be placed perpendicular to the ties and in the center of the track, with careful attention paid so that only wood ties, and not ballast, were beneath the lead bars.

Analysis of the images required drawing a rectangular region of interest (ROI) around the line-pairs such that it sampled a major portion of their area. The peripheral regions of the bars were avoided since it included scatter from surrounding materials. Each ROI produced an output pulse composed of four peaks and four valleys for each spatial frequency tested. These successive peaks can differ perceptibly in intensity due to noise. Therefore, an average of the minimum and maximum signals were calculated as a means of reducing the influence from these spurious events that could possibly contaminate the MTF calculated.

Edge Method Measurements

A fully absorbing lead edge (1.25 cm thick, 7.62 cm long) was placed so that the center of its edge is at the intersection of the central axis of the x-ray beam with the track. The edge is oriented either parallel or perpendicular to the wood crossties, depending on which direction the MTF is being measured for. A slight angle (1.5°-3°) is given to the edge device in order to generate an oversampled ESF that has a data interval smaller than the pixel pitch size [4].

The image processing techniques used to acquire the MTF from the edge images consist of several steps, with the calculation of the oversampled ESF based on a method described by Buhr *et al* [8]. First, an ROI is drawn around the portion of the image containing the edge transition. The edge locations are determined for each row, along with the angle of the edge transition, producing the actual edge line. The raw data from the ROI is then projected along this line into sub-pixel bin widths of 0.1p, where p is the width of the detector pixels, producing the oversampled ESF. The ESF is then smoothed by fitting a third-order polynomial equation to the oversampled ESF. The smoothed

ESF is then differentiated to obtain the LSF. The LSF was then Fourier transformed and its absolute value normalized at zero frequency to obtain the MTF.

RESULTS

The MTF values calculated with the edge and bar-pattern methods are plotted for both the across-scan and along-scan directions in Figure 1. Comparing the results from the bar-pattern method for both directions show good agreement between spatial frequencies of 0.01 lp/mm and 0.025 lp/mm, with curves of similar shape. The lower MTF values for spatial frequencies less than 0.0l lp/mm could be caused by the how the tool was placed. The large span of the lead bars for these smaller spatial frequencies resulted in some overlap of the lead onto ballast sections of the track. As a result, the signal is over-modulated since the small scattering probability of ballast does little to enhance the signal. Also, at these frequencies lower than 0.01 lp/mm, the across-scan direction has a steeper falloff, indicating a direction-dependent MTF which can be attributed to the differing sources of blur between the two directions. In the across-scan direction, the MTF is dominated by the finite size of the detector pixels, while the along-scan direction depends on the finite width of the fan beam and the additional component of blur introduced by the linear motion of the system.
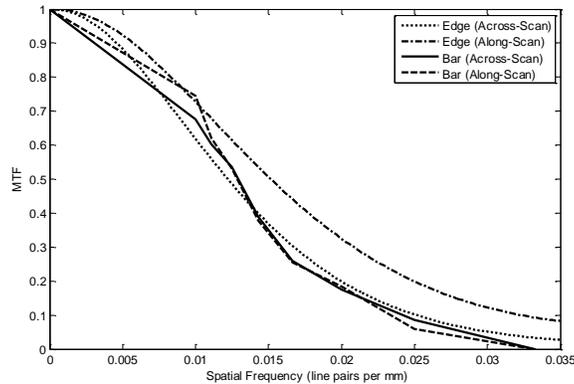

Figure 1: Calculated MTF values using the edge or bar -pattern method for the across-scan and the along-scan direction of system motion.

Comparing the results between the two methods, the MTF curves from the bar-pattern method in both directions show good agreement with the across-scan edge results. The largest difference is seen with the along-scan direction edge results, whose MTF curve is higher than the other three. The result can be attributed to how the edge spread function was sampled differently between the two directions. As required by IEC 62220-1, the ESF should be measured over a large range, in order to observe the long-range spread effects [8]. In the across-scan direction, the ROI spanned a length of almost 91 cm between the lead and wood edge. In the along-scan direction, the edge covered the width of a wood tie in the direction of motion, resulting in an ROI that could only span a distance of 18 cm. As a result, the long-range and slowly rising tails of the ESF were missed in these shoulder regions, producing a considerably higher and erroneous MTF for the along-scan direction.

As a means of comparison between the methods, the limiting spatial resolution is used, which is defined by the spatial frequency at which the MTF falls to a value of 10%. The limiting resolution for the bar-pattern target is 0.024 lp/mm and 0.023 lp/mm for the across-scan and along-scan direction, respectively, resulting in a mean difference of 4%. These results were verified by identifying the limiting spatial resolution visible within the actual bar-pattern images. The last resolvable line-pair was the 2 cm lead bars, which equates to 0.025 lp/mm, indicating the validity of these MTF curves. The liming resolution for the edge method is 0.025 lp/mm and 0.031 lp/mm for the across-scan and along-scan directions, respectively. The 25% difference between the two values is expected due to the insufficient sampling of the long-range ESF.

CONCLUSIONS

In this work, two methods of measuring the MTF of a backscatter radiography system were presented. While both the edge and bar-pattern method are two well-defined techniques for transmission imaging, the unique image

formation in backscatter created additional complexities that had to be accounted for. The ability of materials below the test tool to contribute to the overall detected backscatter signal produced an added complexity in obtaining accurate results.

The results for the bar-pattern method show good agreement between the two directions of motion, with limiting spatial resolutions matching that of the subjectively determined smallest resolvable line-pair. The major advantage of this technique lies in the fact that the calculated results can be verified against the scanned images. While this method is the simpler and easier choice for measuring the MTF, it can suffer in the low spatial frequency range due to the approximation of a sine wave with a square wave response. The method also suffers from low precision, noise, and coarse sampling of an otherwise continuous MTF.

The result for the edge method proved the importance of using a long measurement range to sample the edge response in order to obtain accurate MTF data. While the across-scan direction produced results in good agreement with the bar-pattern method and the visual limiting spatial resolution, the along-scan data resulted in an MTF curve much higher than the other three measured. The use of a small measurement range in this direction was caused by the inability to measure the signal over areas of ballast. As a result, the measured ESF has been cutoff in the extended tail portion, leading to a systematic overestimation of the calculated MTF.

An accurate and reliable measurement of the MTF is key to understanding the spatial resolution properties of an imaging system. In the case of backscatter radiography, it was determined that the accuracy of the MTF results rely heavily on the surrounding material, proving that proper test tool placement is a more important consideration than which method is actually used.

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