Improvement of Axle Bearing Monitoring Systems Through the Use of High Speed Imaging for Directing Acoustic Beamforming

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Improvement of axle bearing monitoring systems through the use of high-speed imaging for directing acoustic beamforming

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Axle bearings on railway vehicles are a key and safety-critical component of each wheelset. The early detection of bearing faults is of paramount importance from a safety perspective, but is also essential for efficient and well-targeted maintenance regimes. Recent advances in bearing monitoring technologies have moved away from thermal and towards acoustic sensing techniques. Through the use of arrays of microphones combined with beamforming processing, it is possible to track a particular bearing during a train's passage and thereby improve the data quality and thus processing outputs. This paper presents an approach in which the acoustic beamforming is steered to match the passage of the axle bearings as they are tracked through a test site using high-speed imaging.

The imaging system presented identifies and tracks key components of the vehicle. From this, alignment and speed information can be passed to the beamforming process to allow it to target and track the axle bearings. The Imaging Speed Monitoring System (ISMS) presented in this paper makes use of a high-speed camera to measure the real-time train speed in order to solve the microphone array alignment problem. Feature extraction and object tracking techniques have been applied to the data from the ISMS to generate vehicle speed profiles and to allow alignment with key components, such as the axle bearings.

1. Introduction

Safety is a key issue in the operation of the railway. Realising its importance, railway companies conduct regular inspections of the railway infrastructure as well as vehicles. Among the vehicle components, rolling element bearings are one of the most critical components.

Although generally tolerant to non-ideal conditions, minor problems can sometimes cause bearings to fail rapidly and unpredictably. Faulty bearings can result in serious accidents, such as train derailment. Therefore, the condition monitoring and maintenance of bearings is essential.

Maintenance is another important issue in the railway system. Periodic/manual inspection can be used to identify defects, but automatic in-service inspection allows consideration of the condition of the system.

This leads to improved reliability, but also the potential for condition-based maintenance (CBM). Using CBM, maintenance intervals can be extended, maximum component lives attained and disruption from unscheduled maintenance avoided.

This paper builds on previous work, carried out by Entezami *et al*[1], in the area of in-service trackside acoustic-based axle bearing inspection. In the previous work, acoustic beamforming has been used to focus on the axle bearings during the passage of a vehicle.

This requires a precise alignment and measurement of vehicle speed, which has previously been achieved through the use of a series of lightgates. This paper presents an alternative approach to vehicle tracking based on visual inspection.

2. Acoustic bearing monitoring

Historically, trackside axle bearing fault detection has been thermal. Hot axle box detectors (HABDs) have been in use since the 1960s. However, HABDs rely on the thermal effects associated with bearing failures and so often only report comparably imminent failures. For example, Barke's 2005 paper describes a case where a HABD was passed (normal condition, no alarm triggered) and the bearing failed just 96 s later[2]. This is one of the major shortcomings of standalone hot axle box detectors; another shortcoming is their low sensitivity to incipient damage[3].

The development of acoustic bearing defect monitoring has become popular to overcome these shortcomings of hot axle box detectors. Among the acoustic bearing defect detectors, vibration and acoustic emission sensors are well-known and widely used.

However, in certain circumstances where physical access to the bearing is limited or difficult, acoustic microphone array inspection systems can be used instead[4]. Laboratory-based experiments have been undertaken at the Birmingham Centre for Railway Research and Education (BCRRE) at the University of Birmingham[4].

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Low-cost, commercial off-the-shelf (COTS) microphones and recording equipment were used to collect and store the audio signals from bearings in both healthy and faulty conditions. Vibration sensors were used as a reference while developing the system. The signals have been analysed in both the time and frequency domains in order to verify the effectiveness of the system in identifying bearing faults.

In the previous study, laboratory testing helped with understanding the way that faults develop within bearings.

The experiments were, however, undertaken in a relatively ideal environment. Therefore, field tests were used to expand the verification to real-world scenarios. Tracking the movement of the vehicle and listening to a certain source of the acoustic signal from the train was one of the main challenges in the field tests[1]. The method used in this work was based on work by Zechel *et al*[5]. A microphone array was used to provide both steering and directionality.

An analysis of the results obtained in the laboratory has shown that acoustic inspection methods can provide early stage bearing fault detection and diagnosis in a controlled environment. The field tests have indicated a considerable amount of environmental noise being emitted and therefore highlighted the importance of using an acoustic microphone array to track the source of a particular audio signal[1].

The Imaging Speed Monitoring System (ISMS) is proposed to support the acoustic microphone array inspection system by enhancing the performance of the audio source tracking element.

3. The microphone array alignment problem

To separate the individual bearing sounds, and to eliminate the Doppler effect resulting from the movement of the train, acoustic beamforming is used. In order to do this, the geometry of the system and the speed of the train must be known. Real-time speed monitoring is preferred. The sub-system to align and direct the acoustic beamforming in[1] comprises three sets of Infrared lightgates.

The lightgates are installed beside a section of the rail with a fixed distance between them. They provide the time and location when the train passes by each point. The speed can therefore be monitored by knowing the distance and time. However, the speed detected by the lightgates is the average speed between each pair. This relatively coarse accuracy leads to deviations in locating the acoustic signal with the microphone array. Furthermore, the lightgate installation is close to the track, which complicates any installation or approvals processes.

The ISMS supports the acoustic microphone array inspection system through a less invasive speed measurement for the beamforming algorithm and, through greater resolution, can be used to enhance the quality of the targeting and thus the recorded signals.

4. Field test using a high-speed camera

Field tests to verify the performance of the Imaging Speed Monitoring System (ISMS) were carried out at the Rail Alliance test facility at Long Marston with the support of Motorail Logistics.

The test facility consists of a 5 km loop of rail. Tests were carried out using a Class 117 DMU and a mobile railway laboratory carriage, as shown in Figure 1.

Tests were carried out at a variety of speeds ranging from 8 km/h (simulating shunting) to 50 km/h. The ISMS and lightgate systems were used in parallel to allow a direct comparison of performance. A general overview of the test system is shown in Figure 2.

Figure 1. Test train

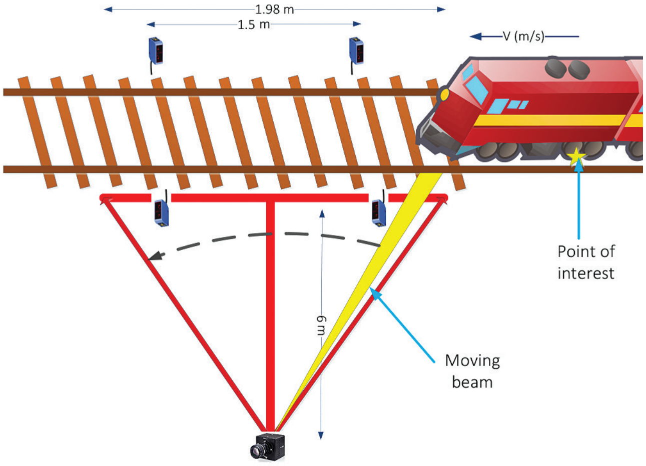

Figure 2. Field test plan overview

4.1 *High-speed camera selection*

One of the key components in the ISMS is the camera. Considering the high speed of in-service trains, the camera should be capable of clearly capturing fast-moving objects, *ie* it should have a fast shutter speed (short exposure time). However, a high shutter speed reduces the amount of light passing through the aperture and, at the same time, the bogie where the bearing is located is in a low illumination environment because it is below the train body. Therefore, another requirement is that the camera should be extremely sensitive to light in relatively low illumination conditions. Having considered these two key features, a monochrome high-speed camera was selected for use in the ISMS.

4.2 *Results and analysis*

An example image captured by the ISMS high-speed camera is shown in Figure 3. It is a monochrome image containing the two poles (1.5 m apart) with the lightgates mounted on them. The image shows that the bearing lid has significantly different features from the components around it.

In this case, the clarity of the target object means that pre-processing of the image is not necessarily needed and feature detection for the bearing lid can be directly applied.

The feature detection technique used is the circle Hough transform (CHT)[6]. The Hough transform, named after its original inventor[7], is a technique that focuses on the edge features

Figure 3. Example image captured by the high-speed camera

of an image[8]. The original algorithm by Hough made use of grey-level information, but did not use orientation information of the edge[6]. Several years later, Ballard's work uses magnitude and direction to represent the severity and orientation of the local grey-level change[6]; this is also known as the circle Hough transform. Using this technique, the detected bearing lid is highlighted by the dashed curves in Figure 3.

Having obtained the bearing location information in the image, the real-time speed of the train can be calculated by comparing the pixel change of the bearing lid centre in consecutive frames. At the same time, the lightgates system is used to measure the train speed as a reference system.

The two impluses in Figure 4 represent a single axle passing through the two pairs of lightgates.

The average train speed between the two pairs of lightgates is calculated by using the fixed distance divided by the difference in the times that the wheel blocked the infrared signal, which was about 48 km/h in this test.

To demonstrate the enhancement of the ISMS over the lightgate reference system, a comparison was made by plotting the speed/time curves of the ISMS and the lightgate systems, which is shown in Figure 5.

The speeds were calculated from the four axles of the railway laboratory carriage and are shown together in a single figure. On the graph, the first two triggers correspond to the two axles of the first bogie, while the second two are caused by the axles of the second bogie.

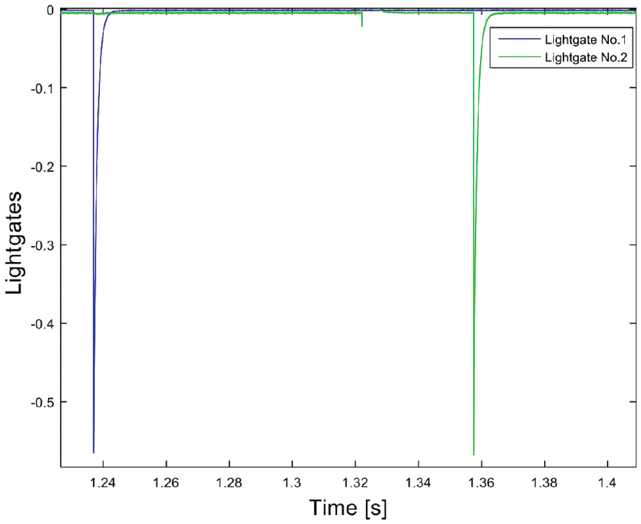

Figure 4. Lightgate signals for a single axle

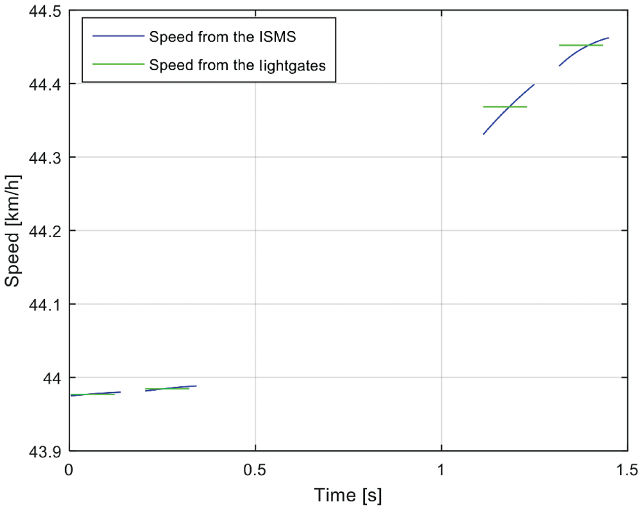

Figure 5. Speed/time curves from the ISMS and the lightgate systems

Both systems indicate that the train was accelerating when it passed through the inspection area. However, while the ISMS can produce a measurement of acceleration from only one axle passing, the lightgate system requires at least two axles to pass before any acceleration can be identified. This is because the ISMS captures multiple frames for each axle, giving multiple speed measurements, whereas the lightgate system captures only two impulses, producing a single speed measurement.

5. Extended ISMS processing

As demonstrated in the case study of the field tests, the ISMS is capable of monitoring the speed of a train and can give a more accurate speed measurement than a lightgate-based system. However, the computer vision technique applied to the data from the field tests was comparably simple as the axle boxes were clearly visible.

Such a technique could not be extended to other scenarios where the axleboxes were less visible. Modern (passenger) trains have components on and around the axle bearing that complicate and restrict the view of the bearing lid, as shown in Figure 7(a). Further experiments to automatically identify partially-occluded axle boxes have been carried out using video of a Class 323 vehicle. The wheel tracking procedure is generally divided into three stages, shown in Figures 7, 8 and 9:

- Stage 1 – Extracting the bogie section in the image;
- Stage 2 – Filtering operation of the bogie section to outstand the wheel profile;
- Stage 3 – Wheel detection.

A flowchart of the working principle is shown in Figure 6. In Stage 1, the original RGB image is degraded into greyscale, then the rail is detected using a Hough line transform[8] and the ballast section below the rail is removed from the image in order to reduce the image size and complexity.

In Stage 2, the important edges are identified in the image, using a Canny operator. This operator was selected because of its reduced susceptibility to noise in the image[9,10].

The Canny operator is then followed by a series of mathematical morphology operations[11], such as erosion, dilation

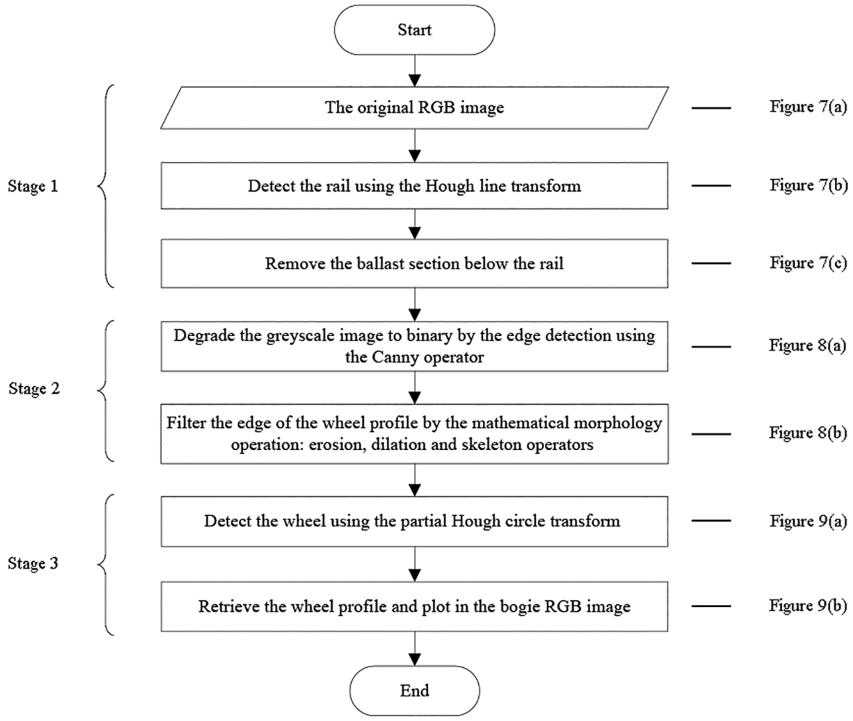

Figure 6. Flowchart of the wheel tracking procedure

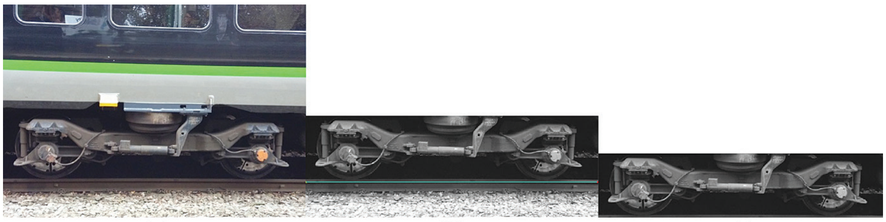
(a) (b) (c)

Figure 7. Stage 1: (a) the original RGB image; (b) the rail detection; (c) remove the ballast section from the image


(a) (b)

Figure 8. Stage 2: (a) edge detection; (b) mathematical morphology operation


(a) (b)

Figure 9. Stage 3: (a) circle detection; (b) wheel profile retrieval

and skeletonisation, to construct an unbroken and clear line representation of the wheel. The result of this process is shown in Figure 8(b). In the Figure, the bearing lid is surrounded by the other components on the wheelset, which makes it difficult to identify and extract it.

In Stage 3, the parts of the wheel that can be seen are used in the detection of the entire wheel. In this case, the bottom part of the wheel shown in Figure 9(a) is used to estimate the position of the whole wheel (Figure 9(b)). The algorithm used is the partial Hough circle transform.

This is similar to the basic circle Hough transform explained above, but uses a parameter threshold to specify the size of a circular sector that can be extrapolated to identify a complete circle.

6. Conclusions and further work

This paper has demonstrated a potential extension to acoustic bearing monitoring systems for use in in-service rail applications. The work presented focuses on the alignment and tracking of the vehicle to support acoustic beamforming techniques. The use of the proposed Imaging Speed Monitoring System (ISMS) uses high-speed imaging and video processing to track the key elements of the vehicle to be targeted by the acoustic techniques. Comparisons of the lightgates and video-based tracking systems have been presented. These show a comparable performance for constant speeds and improved performance for vehicles whose speed varies within a test section. This invasive visual approach should dramatically simplify the installation or approvals processes associated with trackside installation.

The next steps for this approach require the harmonisation and integration of the visual and acoustic systems. Initially, a wider lens will be fitted to the camera to allow the acoustic and visual fields to better overlap. Care will need to be taken to avoid or compensate for distortions at the extremes of such a lens. The existing system integrates the lightgates with the acoustic signals at a hardware level. Although the ISMS has been shown to provide tracking information, this information still needs to be directly integrated with the beamforming algorithms for real-time operation.

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