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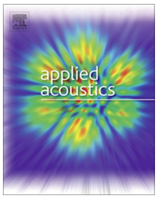

Impact-acoustic evaluation method for rubber–steel composites: Part I. Relevant diagnostic concepts

Gheorghe Bunget [a,*], Qin Shen [a], Frank Gramling [b], David Judd [b], Thomas R. Kurfess [c]

[a] Clemson University International Center for Automotive Research, United States
[b] Michelin Americas Research Company, United States
[c] The Woodruff School of Mechanical Engineering, Georgia Tech, United States

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ABSTRACT

Recycling and retreading is critical for reducing costs and energy consumption for the manufacture of tire casings. An effective retread requires tire casings with good structural integrity and no internal damage. This paper presents an impulse-acoustic nondestructive technique to investigate internal defects in rubber–steel composites such as truck tires. The technique employs a light impactor that taps the structure to be inspected, measuring the impact force with a load cell and analyzing the resulting sound recorded with a microphone in order to discriminate defective regions from defect free regions. Acoustic signatures of both the defective and non-defective side walls of a tire were recorded. The acoustic signatures of were analyzed and the peak amplitude and decay rates demonstrated a suitable correlation in the presence of internal delaminations. This paper seeks to presents an understanding of the fundamental principles underlying the individual measurement and analysis techniques. The results of this investigation show that the acoustic responses can be used to identify the presence of internal delaminations and also may potentially be used to determine their size and location. The effort is part of a project to develop an automated inspection system for truck tires to determine the integrity of the base structure before a retreading operation is performed.

1. Introduction

Tire retreading involves stripping off the old tread from a worn tire and overlaying a new tread on the old tire carcass. Truck tire casings are relatively expensive, and in most cases, little damage of a non-repairable nature occurs to the internal part of the tire, or casing, during normal use permitting the tire to be safely retreaded multiple times. The retreading operation brings significant cost saving while lowers the tire's environmental impact as it extends the life span of the tire. It is estimated that it saves 80% of the raw materials and energy required for manufacturing a new tire and saves hundreds of millions of gallons of oil worldwide. About 15 gallons of crude oil is saved for each reused truck tire casing, as opposed to manufacturing a new tire [1]. Therefore retreading tires reduces significantly the operating costs of truck fleet carriers. It has been documented that retreaded truck tires represent a savings of over $2 billion annually for commercial trucking companies in US [2]. Also, retreading reduces the quantity of rubber waste to be discarded. Worn out tire casings have a significant impact on landfills since it takes about 900 years to naturally degrade rubber. The tire retreading industry is reported as the largest sector of remanufacturing industry in US in terms of the number of retreading plants [3].

However, tire debris along the highways generated primarily by heavy trucks running retread tires has been an ongoing debate over the incidence and traffic safety for some time [4]. Retreaded tires are used in critical applications such as for military and commercial aircraft and school busses. As such, when a retreaded tire fails due to an internal delamination, the results can be catastrophic. Therefore, old tire casings need to be tested for such defects before their retreading operation. An effective retread necessitates a tire casing with good structural integrity, without internal damage.

The evaluation of the structural health of tire casings before the retreading operation has been the focus of several investigations during the last decades. Internal delaminations and separations between the layers of a tire are undesirable in terms of tire durability. Shearographic interferometry was used to identify and measure the internal separations between layers of a tire [5–7]. The interior surface of a tire is mapped in 8 or 9 consecutive sections under normal atmospheric pressure and then under vacuum conditions. The internal delaminations will spread apart during vacuum,

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[*] Corresponding author.

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producing raised areas resembling bubbles on the interior surface. A sophisticated computer program then digitally overlays and compares the two sets of photos recorded in normal pressure and vacuum. The alterations of these images indicate the presence and size of internal defects. One drawback of interferometry techniques is that the separations located outside the steel belt are not detected. Another drawback is that shearography methods do not appear to correlate strongly with tire age [5]. Furthermore, shearography technology is expensive, requires highly qualified personnel, and therefore cannot be included automated lines to check every individual tire.

For several decades now, various ultrasonic methods have been developed to perform non-destructive inspection of tires. Ultrasound techniques are making use of roller and air-coupled transducers either in pulse-echo or transmission mode, both in uninflated [8], and inflated tires [9]. Pulse-echo ultrasonic techniques with air-coupled transducers were also investigated with poor flaw detection. More recent ultrasonic techniques take advantage of using an array of air-coupled transducers in transmission mode [10,11]. Yet, the ultrasound equipment suffers from a number of disadvantages, including the difficulty of obtaining accurate tire defect data and of interpreting the test results which in some prior art equipment is presented on an oscilloscope. Recently, an acousto-ultrasonic inspection technique was demonstrated to have potential in detecting belt damage in steel-belted radial tire sidewalls and delaminations in the thread bands and defects in the bead area [12].

Other techniques such as X-ray have been used to identify foreign materials, ply defects, chafer dimensions, bad splices and belt step offs. An X-ray source irradiates selected sectors of the tire and creates a fluoroscopic image of the sectors on an X-ray image intensifier [13]. The disadvantage of X-ray methods is that the equipment is expensive and it requires extra safety precautions mainly due to radiations, even though the hazards to humans from overexposure to penetrating radiation are more fully appreciated currently than in the past.

According to 2002 U.S. Census figures, tire retreading is performed by approximately 600 establishments in US [14]. Generally, tire-retreading services are provided in the establishments of small organizations within the tire industry [3]. However, current technologies require very expensive equipment used by operators who have been specially trained and thus they are not suitable for small retreading organizations. Consequently, diagnostics technologies based on these detection methods are too expensive for small organizations and require highly trained operators. Most of these small retreading facilities use visual inspection which is reasonably fast. However, internal delaminations and holes are often missed due either to human error or to the lack of visible evidence. Therefore, there is a significant need for an inexpensive inspection technique.

One of the most widely used and cost effective vibration based nondestructive techniques is the hammer tap test. Yet, even though it is an inexpensive and simple method, the hammer tap method has several drawbacks. It is subjected upon the hearing and experienced interpretation of the inspector and it does not provide quantitatively data. This is a highly localized technique; a defect is detected only if it is located below the region of the tap. However, the principles of the hammer tap technique could be transferred to a computer-based analysis and interpretation of the acoustic-response characterizing the structural state of tire. This approach has an advantage over the other methods from the standpoint of simplicity of instrumentation. Under impact, the tire vibrates and emits a mechanical wave that propagates in the surrounding medium (air) in a vibrational motion. The whole structure emits this sound with its local natural frequency. A microphone is used to capture the acoustic signature of the structure response when a ball pendulum impacts the tire and the emitted sound can be measured instantaneously.

Most impact-acoustic methods for industrial applications are mainly focused accelerometer sensing of vibration signatures generated by the impact. For example, Sansalone has been pioneered the impact-echo method with applications in civil engineering to detect delaminations in concrete structures and to identify crack depths in concrete [15,16]. This research opened a new field in non-destructive inspection and excellent cost effective sensors were implemented (such as microphones). The use of microphone sensing was forged in the field of agriculture where many researchers made use of the impact-acoustic techniques to assess the quality of various food products. An impact-acoustic method showed high correlation of frequency signature with internal quality of rice kernels [17]. Impact-acoustic investigations with agricultural applications have been carried out with promising results on the internal structure of watermelons [18,19], apples [20,21], peaches [22], potato tubers [23], tomatoes [21], wheat kernels [24], hazelnut kernels [25]. Heirtzler demonstrated the potential of the impact-acoustic method in delamination detection in tires and several discriminator quantities were fused together in a neural network to determine whether a defect was present at the impacted location [26]. Most of this previous related work shows the feasibility of the impact-acoustic techniques to detect internal delaminations and voids.

The objective this research is to develop a simple, low cost (inexpensive) NDE method for detecting and measuring internal flaws and delaminations in the composite structures of truck tires, and to design a demonstrator machine. The present paper is the first in a series of works on impact-acoustic nondestructive evaluation of multiple types of tires with varying sizes of internal delaminations. The current paper introduces the impact-acoustic technique as a diagnostic tool for materials with high acoustic damping properties. It informs the reader about the acoustic parameters that correlate with the internal structural health of the tires. The second paper in the series will discuss the evaluation results of these acoustic parameters when applied over a wide range of tire types. Also, it will identify the specific challenges presented by the surface disturbances such as raised letters/markings when in contact with the impactor. The third paper will show that artificial intelligence is a reliable tool for the analysis and diagnosis of the acoustic parameters when discriminating between surface disturbances and the internal structural damage of the tire. The approach presented in this paper uses a time signal analysis of the acoustic response to identify the presence of damage within the structure. This research focuses on more simplified techniques of feature extraction, data analysis and decision making than in the investigation conducted by Heirtzler.

2. Methodology

As a transducer, the microphone may be modeled as an air coupled acoustic transducer. Conventional transducers (accelerometers and contact acoustic transducers) need to be in contact with the surface to achieve good coupling characteristics. This approach is inefficient for inspecting tires which rotate either intermittently or continuously. For this application, the use of air-coupled microphones instead of contact sensors is an attractive and promising alternative providing the basis for a significant increase in measurement speed. Furthermore, as no coupling liquid is required, measurements are much less dependent on the state of the measurement surface (roughness or markings).

The detection mechanism of the impact-acoustic approach may be explained through a widespread tapping technique. In civil engineering for example, the common method of finding the