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Measurement of residual stresses in rails using Rayleigh waves

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Abstract. This paper presents a new nondestructive approach for evaluating the residual longitudinal stresses in rails. The developed approach utilises the acoustoelastic effect to infer the longitudinal stress from the measured speed of Rayleigh waves propagating along the longitudinal direction. The measured Rayleigh wave speed along the longitudinal direction is shown to vary significantly across the height of the rail section, which can be directly correlated to the residual stress profile in the rail section. Unlike existing residual stress measurement techniques, such as hole-drilling or sectioning, the developed approach can be potentially applied for the in-situ residual stress measurement, without taking the rail out of service.

Introduction

Residual stress determination in rails is paramount for accurate life prognosis and assessment of fatigue damage [1]. Traditional methods for stress evaluation include the sectioning method, hole-drilling, and X-ray diffraction. However, these methods require the rail to be taken out of service during evaluation. Additionally, cutting and hole-drilling are destructive techniques, which limits their usefulness for field measurements, while X-ray diffraction is expensive [2] and unable to differentiate between micro- and macro-residual stresses, making measurements potentially unreliable [1]. Ultrasonic methods, which utilise the acoustoelastic effect, can potentially provide accurate, nondestructive residual stress measurement and can be applied in-situ.

Use of the acoustoelastic effect to measure stresses has been well documented in literature. Previous studies have utilised longitudinal waves for through-the-thickness evaluation, and critically refracted longitudinal waves for sub-surface stress interrogation [3]. The major drawback of such methods is the limited interrogation distance achievable with bulk (longitudinal and shear) waves. Guided waves are a type of ultrasonic wave capable of propagating long distances without significant attenuation [4], and therefore may be more suitable for stress monitoring applications. In particular, Rayleigh (surface) waves have previously been used to determine applied stresses in aluminium structures [5].

Rayleigh waves can be generated via mode conversion of longitudinal waves using a wedge. The difference in material properties between the wedge and rail specimen causes the longitudinal wave generated by an ordinary ultrasonic transducer to refract into a Rayleigh wave, which travels along the surface of the rail. The wedge angle required for Rayleigh wave generation is determined using Snell's law (Eq. 1, where c_{L_w} is the longitudinal wave speed in the wedge and c_R is the Rayleigh wave speed in the rail). The Rayleigh wave can be detected either using another wedge transducer, or using non-contact instruments, such as an air-coupled transducer or Laser Doppler vibrometer. Due to the non-contact nature of the measurements, the latter two methods avoid the experimental scatter associated with inconsistent contact conditions [6].

$$\theta_w = \sin^{-1}\left(\frac{c_{L_w}}{c_R}\right) \tag{1}$$

Theory

The theory of acoustoelasticity relates the speed of a wave to the stress state of the material through which it propagates. This phenomenon was first reported in bulk waves by Hughes and Kelly [7] in the 1950's, and was later expanded to include Rayleigh waves by Dowaikh [8] in 1990. For a Rayleigh wave, the dependence between stress and wave speed can be expressed as [8]:

$$\begin{aligned} &\alpha_{22}(\alpha_{11} - \rho_0 c^2)[\gamma_2(\gamma_1 - \rho_0 c^2) - (\gamma_2 - \tau_2)^2] \\ &\qquad = [\alpha_{12}^2 + \alpha_{22}(\rho_0 c^2 - \alpha_{11})][\alpha_{22}\gamma_2(\alpha_{11} - \rho_0 c^2)(\gamma_1 - \rho_0 c^2)]^{\frac{1}{2}} \end{aligned} \tag{2}$$

where $\alpha_{11} = \mathcal{J}\mathcal{A}_{01111}, \alpha_{22} = \mathcal{J}\mathcal{A}_{02222}, \alpha_{12} = \mathcal{J}\mathcal{A}_{01122}, \gamma_1 = \mathcal{J}\mathcal{A}_{01212}, \gamma_2 = \mathcal{J}\mathcal{A}_{02121}, \tau_2$ is the stress in the x_2 direction, c is the wave speed, and ρ_0 is the stress-free density. For small values changes in stress, this equation can be represented by:

$$\Delta c_R = k\Delta\sigma \tag{3}$$

where k is a constant that relates the change in wave speed to a change in stress and has units m/s/MPa. The constant, k, is typically negative for aluminium and mild steel, implying that an increase in wave speed corresponds to an increase in compressive stress. However, it has been documented that for grades of rail steel, k is positive, such that an increase in wave speed corresponds to an increase in tensile stress [9]. Thus, measurement of the Rayleigh wave speed in the longitudinal direction at various heights on the rail can be used to determine the distribution of tensile and compressive residual stresses.

Experimental Methodology

Generation of the Rayleigh wave was achieved using a wedge-transducer assembly. A high frequency wave was used to ensure that the Rayleigh wavelength was significantly smaller than the minimum rail thickness ($16\ mm$ in the web) and therefore satisfied the approximate half-space conditions required for the generation of a Rayleigh wave. A 2.25 MHz ($\lambda_R \approx 1.3\ mm$), 20 cycle rectangular windowed sine wave was generated using a Tektronix arbitrary function generator and amplified to 320 V_{pp} through a RITEC GA-2500A gated amplifier. A piezoelectric transducer was used to generate a longitudinal wave, which was converted into a Rayleigh wave using a $52°$ polyethylene wedge. The surface of a 1 m sample of new 60 kg/m rail was prepared using sandpaper to remove the surface rust and allow for both a) transmission of the wave from the wedge to the rail and b) a reflective surface for the laser-based measurements. The wedge was coupled to the surface of the rail using light motor oil and secured in place using a clamp. Measurement of the Rayleigh wave was achieved using a Polytec PSV-400-M2-20 scanning laser vibrometer, which measures the out-of-plane displacement of the wave. An initial alignment scan was performed to ensure that the Rayleigh wave propagation occurred in the longitudinal direction. The time of arrival of the wave was then measured at nine locations along a 100 mm segment of the line of propagation. The process of aligning the wedge and measuring the time of arrival was repeated for seven different heights along the rail, as shown in Fig. 1a. The experimental setup can be seen in Fig. 1b, and the wedge-transducer assembly can be seen in Fig. 1c.

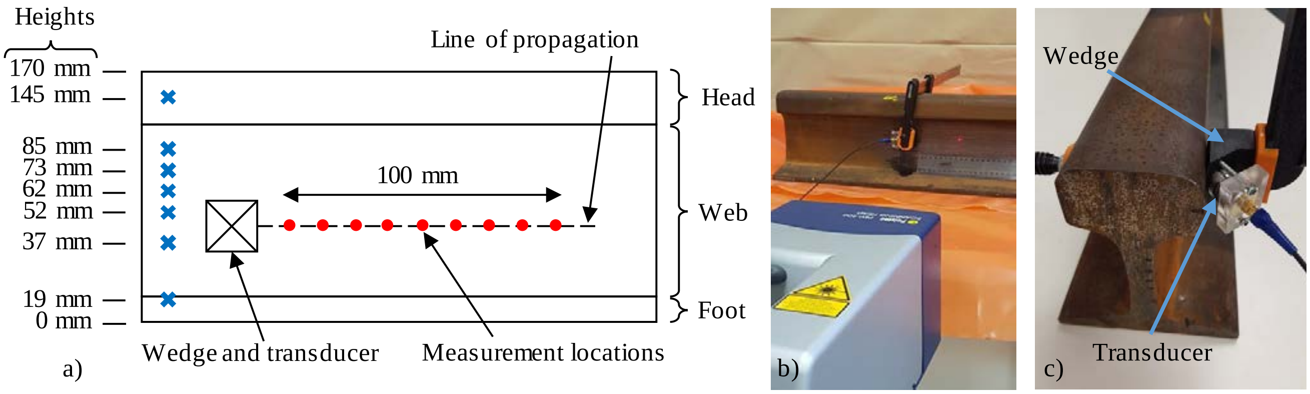

Fig. 1: a) Schematic diagram of measurement locations, wedge position, and line of propagation; b) Experimental setup; c) Wedge-transducer assembly on head of rail.

The time of flight between measurement locations was determined using the cross correlation algorithm. The Rayleigh wave speed was obtained by plotting the time lag, corresponding to the maximum correlation between the first measurement point and subsequent points, against the propagation distance. A linear regression line was then used to determine the speed of the wave. Example waveforms recorded at locations 1 and 9 are shown in Fig. 2, and determination of wave speed using a regression slope is shown in Fig. 3.

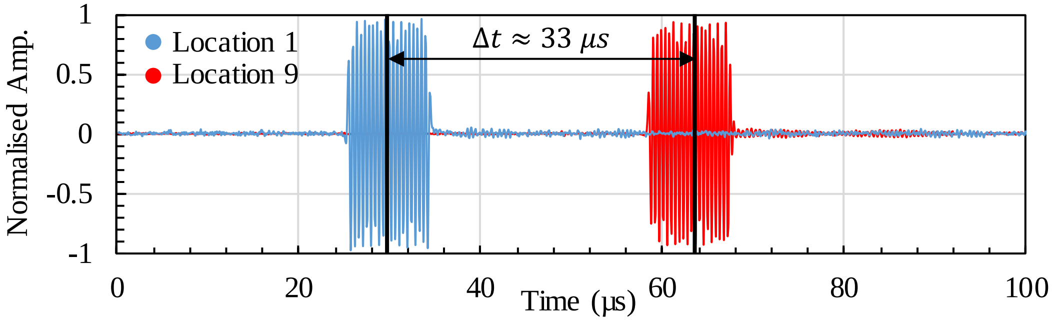

Fig. 2: Normalised amplitude of Rayleigh wave recorded by the vibrometer arriving at locations 1 and 9. The approximate time lag between the two wave arrivals is 33 μs.

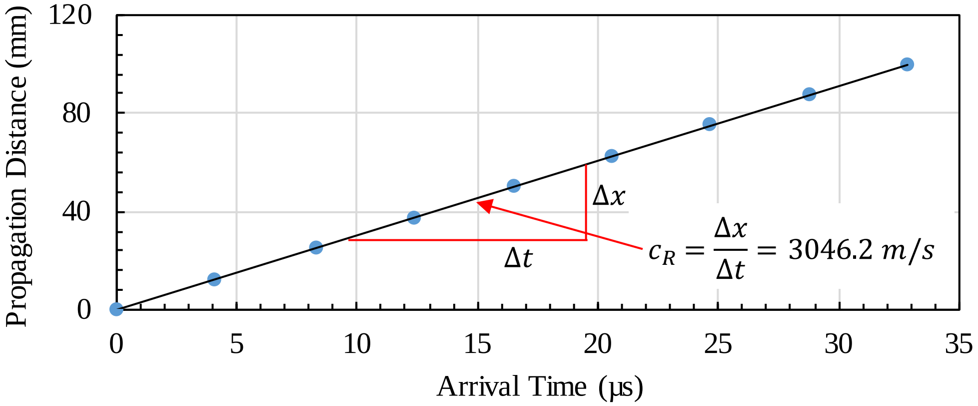

Fig 3. Determination of Rayleigh wave speed at a height of 19 mm.

Results

Figure 4 shows the out-of-plane displacement of the Rayleigh wave recorded by the vibrometer during an alignment scan. It can be seen that the wave travels with no angular deviation longitudinally along the rail, which is necessary to ensure that changes in wave speed are caused purely due to longitudinal residual stresses. It can also be seen that the wedge transducer generates a narrow Rayleigh wave beam, approximately 10 mm in width, which travels along the longitudinal direction. The width of the Rayleigh wave is small in comparison to the height of the rail cross-section, which enables stress measurements to be made at several positions along the head, web and foot of the rail. This feature provides a significant advantage over some other stress measurement techniques, which lack the resolution offered by a narrow-beam Rayleigh wave along the height of the rail. Particular care was taken when aligning the wedge-transducer assembly, as small angles of misalignment can cause an artificial change in wave speed due to the error in measured propagation distance. Similarly, care was taken to ensure that the stand-off distance between the vibrometer head and line of propagation on the rail specimen was constant for different measurement heights. Due to the low number of averages taken during the alignment scan, noise errors are evident, as identified in Fig. 4. Such errors were avoided during time of flight scans by increasing the number of signal averages to 2000.

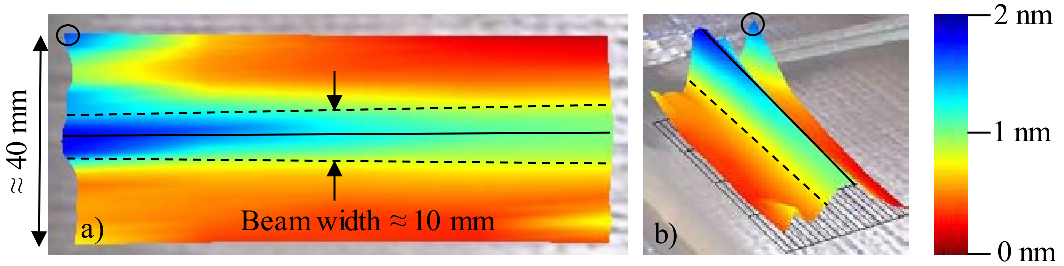

Fig. 4: a) 2D view of typical alignment scan showing out-of-plane displacement, beam width, and line of propagation; b) Isometric view of alignment scan. An obvious noise error has been identified.

The effect of residual stress on the Rayleigh wave speed can be seen in Fig. 5a. There is a clear increase in wave speed in the region of the rail head and rail foot, implying regions of tensile stress. Conversely, the web of the rail appears to feature mostly compressive stresses, as indicated by the slower wave speed. These results are in qualitative agreement with the results of Webster et. al. [10], also presented in Fig. 5b, which were obtained using neutron scanning techniques for new and used rail specimens.

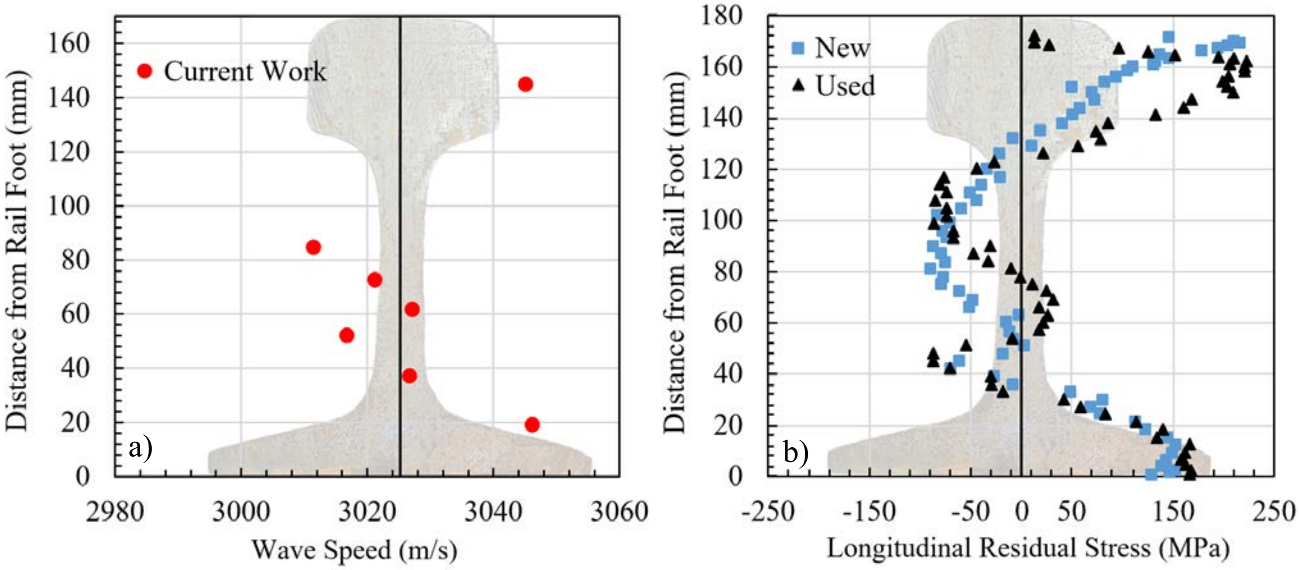

Fig. 5: a) Results of the current work, showing the variation in wave speed along the height of the rail; b) Results of the Webster et. al. [10] showing the residual stress measured using neutron scanning techniques.

Further work is required to determine the residual longitudinal stress profile from the experimental results for the Rayleigh wave speed presented in Fig. 5b. The conversion constant k in Eq. (3) could be determined by inducing a known applied stress in the specimen and measuring the change in wave speed. The preliminary experimental results demonstrate the feasibility of using Rayleigh wave acoustoelasticity for longitudinal residual stress measurements in steel rails. The potential benefits of the developed approach include fast, cost-effective, nondestructive stress measurements that can be applied in-situ.

Conclusion

This paper demonstrates the application of the acoustoelastic effect towards a new approach for residual stress determination in steel rails. An experimental technique is developed for the measurement of Rayleigh wave speed along the longitudinal direction at various positions along the rail cross-section. These measurements can be used, in principle, to determine the residual longitudinal stress distribution in the rail cross-section. Further experimental work is required to calibrate the Rayleigh wave speed to the longitudinal stress according to the theory of acoustoelasticity. The preliminary experimental results of the present study indicate that the shape of the residual stress distribution as measured using Rayleigh wave acoustoelasticity is consistent with previous findings, which use neutron scattering.

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