Mode-mixing-induced second harmonic A0 mode Lamb wave for incipient damage localization

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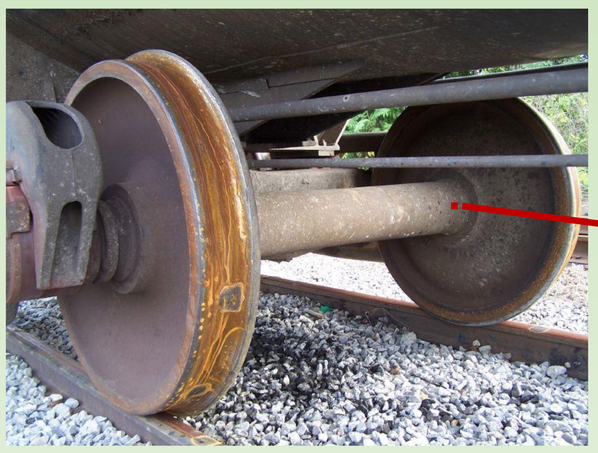
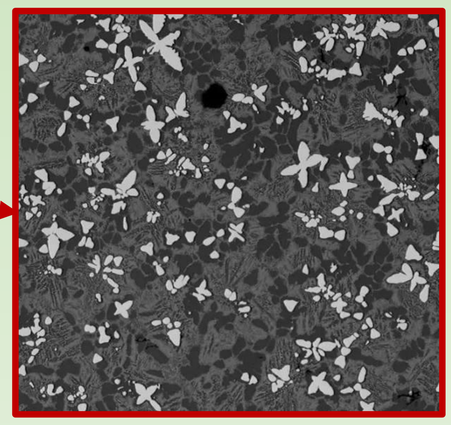
Motivations

The presence of damage in railway systems, exemplified by train axles, in whatever form it is manifested, can significantly jeopardize their operation and safety without timely awareness. Therefore, it is crucial to detect the appearance of initial damage in the early stage, which can enhance the safety and extend residual lifetime of structures in service, as well as effectively drive down exorbitant maintenance costs. In virtue of their high sensitivity to material microstructural changes, nonlinear guided waves show promise for incipient damage inspections, which can significantly facilitate the maintenance decisions. Despite various work on incipient damage detection, research on incipient damage localization with nonlinear guided waves is relatively scarce as a more advanced level. In this study, by examining a PZT-activated plate system where multiple primary wave modes coexist, we discover a second harmonic A0 mode Lamb wave (2^{nd} A0 wave) that is new to the current state-of-art of the second harmonic guided waves. Through combining a previously developed theoretical model with the 2^{nd} A0 wave-based measurements, a dedicated algorithm is proposed to achieve a high-resolution damage localization using a simple measurement system.



Train axle

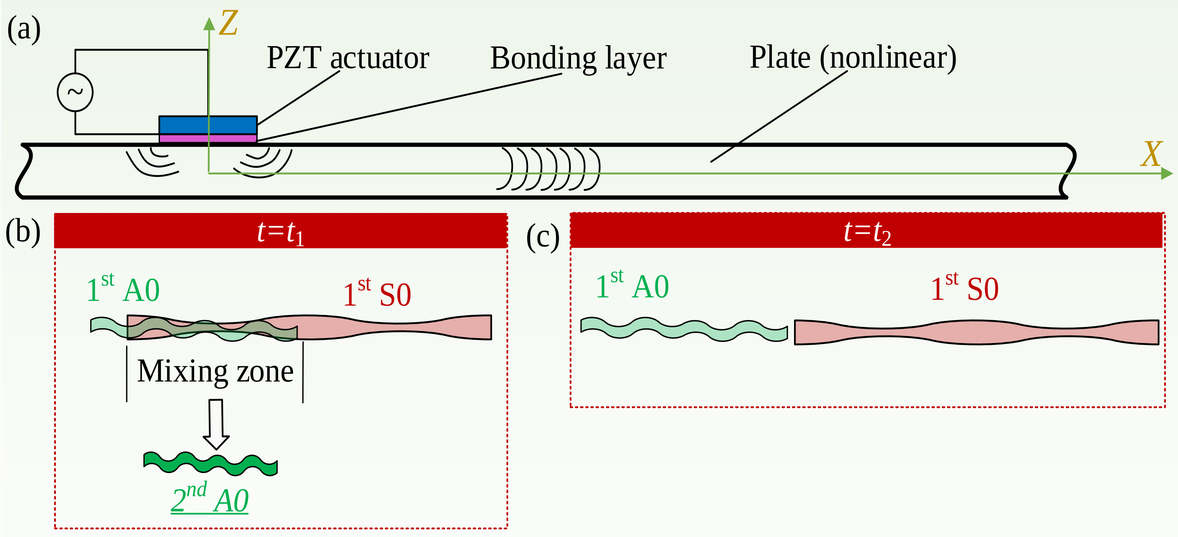
Microstructural defects



Incipient damage

Characteristics of the second harmonic A0 wave generation

While the PZT-activated primary S0 and A0 mode Lamb waves (1^{st} S0 and 1^{st} A0 waves) propagate in a weakly nonlinear plate in a symbiotic manner, nonlinear Lamb waves are generated alongside the primary wave propagation. In this case, both the 1^{st} A0 and 1^{st} S0 Lamb waves generate the second harmonic S0 mode Lamb waves as a result of their self-interactions. In addition, the mutual interaction between the 1^{st} A0 and 1^{st} S0 waves also takes place, generating a 2^{nd} A0 mode Lamb wave, which is highlighted in this work.

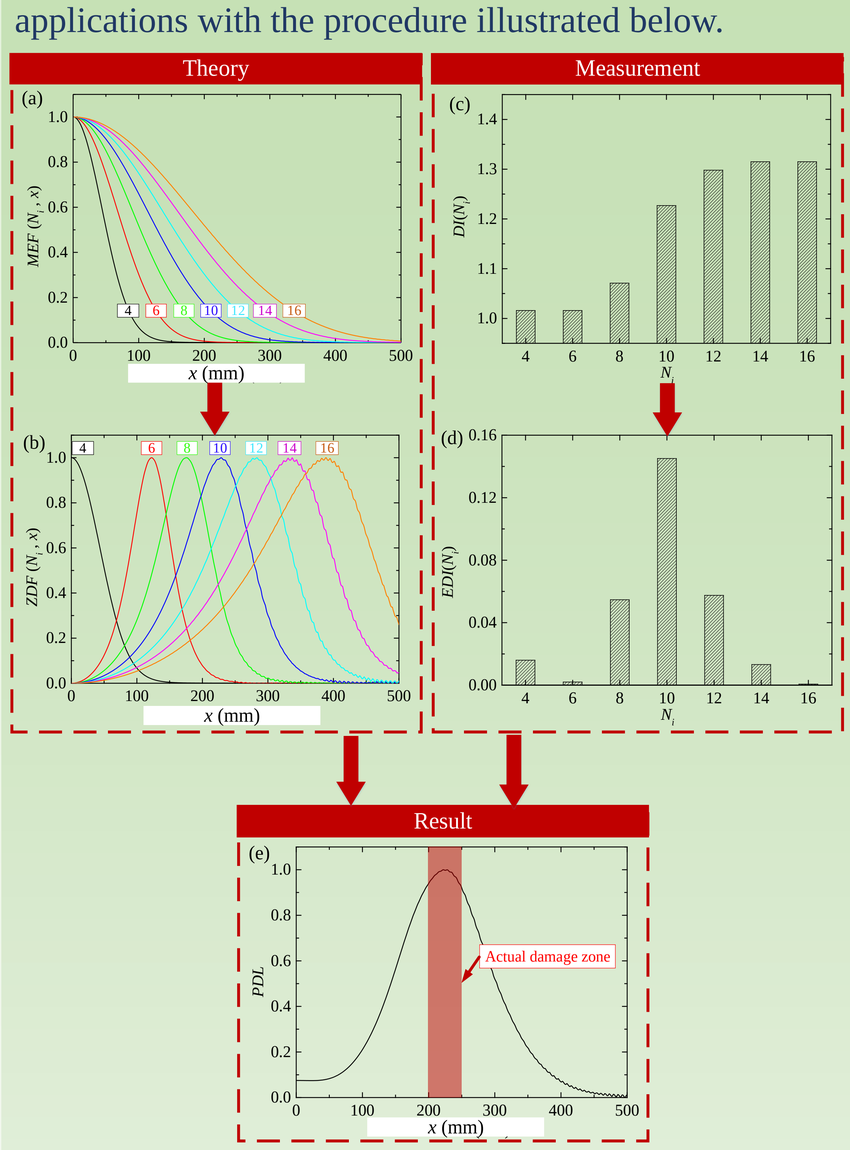


(a) Schematic of the PZT-driven system; (b) characteristics of nonlinear wave generation at the beginning ($t=t_1$) when the 1^{st} A0 and S0 waves mix in the plate; (c) characteristics of nonlinear wave generation as time goes on ($t=t_2$) when the 1^{st} A0 and S0 waves separate in the plate.

According to the primary wave mixing characteristics, the effective wave mixing zone for the 2^{nd} A0 wave generation is confined within a certain area surrounding the PZT actuator. Therefore, through tactically tuning the size of the wave mixing zone, damage detection can be carried out zone by zone to finally realize damage localization along the wave propagation path with only one transmitter-receiver pair, which can hardly be achieved by any existing guided-wave-based methods.

Design of an incipient damage localization algorithm

Based on the generation mechanism of the mode-mixing-induced 2^{nd} A0 wave, a dedicated algorithm is further designed to achieve this goal for practical applications with the procedure illustrated below.



MEF: mixing-zone estimation to evaluate the mixing zone of the primary S0 and A0 Lamb waves generated by a PZT actuator

ZDF: zone determination function to define an effective zone for damage localization

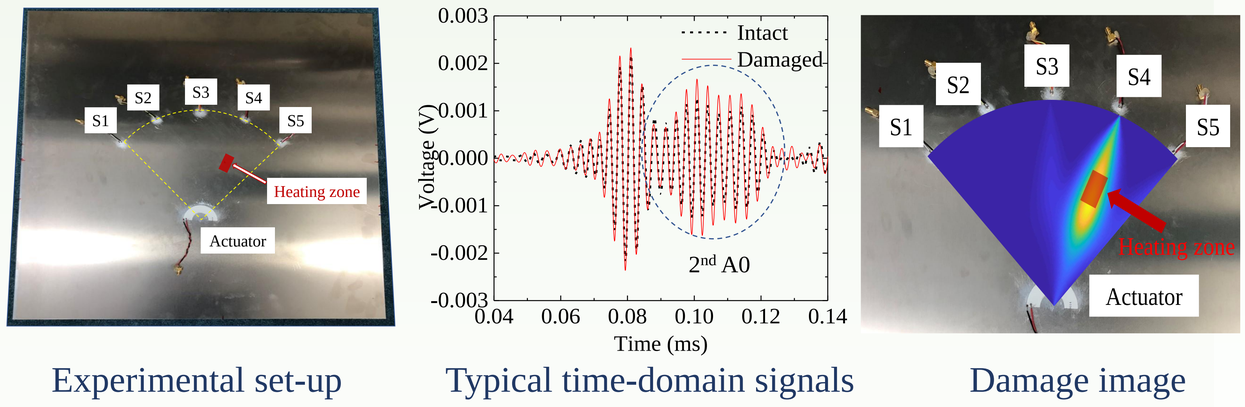
DI: damage index from measurements

EDI: effective damage index

PDL: probability of damage localization

Incipient damage localization application

Experiments are carried out to locate an incipient damage as an application case. A half-ring PZT actuator and five square PZT sensors are bonded on a 2024-T3 aluminum plate, covering a quarter-circular inspection area. The plate is locally heated at 400 °C for 4 hours, which has proven effectiveness to create incipient damages/microstructural changes with the heating area. A pair of excitations with inverse phases are used in the superposition method for the second harmonic extraction. A pair of typical signals before and after introducing the damage is presented, showing significant increase in the 2^{nd} A0 wave amplitude. Finally, with the developed damage localization algorithm, the *PDL* is calculated and damage image is obtained. It can be seen the identified damage zone matches very well with the actual heating zone.



Experimental set-up | Typical time-domain signals | Damage image

In conclusion, experiments demonstrate the feasibility of the proposed damage localization algorithm achieved with a simple physical system.

Reference

[1] Shan S, Cheng L*. Mode-mixing-induced second harmonic A0 mode Lamb wave for local incipient damage inspection. Smart Materials and Structures, 2020, 29(5): 055020.

[2] Shan S, Cheng L*, Wen F. Design of nonlinear-Lamb-wave-based structural health monitoring systems with mitigated adhesive nonlinearity, Smart Materials and Structures, 2018, 27(10), 105006.

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