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A HEGESZTÉS, RAGASZTÁS ÉS MECHANIKUS KÖTÉSEK HATÁSA A HULLÁMTERJEDÉSRE GÉPJÁRMŰ KAROSSZÉRIÁKBAN

THE EFFECT OF WELDING, ADHESIVE BONDING, AND MECHANICAL FASTENING TECHNOLOGIES ON WAVE PROPAGATION IN AUTOMOTIVE BODIES

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ABSTRACT

The propagation of vibration waves in vehicle bodies, originating from mechanical defects, is fundementally influenced by the joints used in the vehicle during manufacturing. Classical diagnostic methods focus on direct powertrain measurements, which often fail to detect broad-spectrum structural faults due to the complex, inhomogeneous paths that the waves must travel through. This research explores an approach in which the Time Delay of Arrival (TDoA) method is used to localize unknown fault sources on the chassis, with a goal of an approximate accuracy of 50 × 50 cm. To accurately calibrate the TDoA models, a Transfer Path Analysis (TPA) was conducted on downscaled, simple laboratory specimens.

1. INTRODUCTION

Classical vibration diagnostic methods have long been used in mechanical equipment to identify the location and cause of mechanical faults. These methods primarily focus on known vibration sources, such as direct measurements of rotating powertrain components (engines, transmissions), and heavily rely on prior suspicion of a part failure. However, a modern vehicle is a highly complex structure, made up of thousands of individual components. During operation, several active vibration excitation mechanisms (engine excitation, rolling noise, aerodynamic effects) are present simultaneously, masking critical fault signals.

Acoustic and mechanical waves do not propagate cleanly through a homogeneous medium within a vehicle. The path between the source of the fault and the sensor trying to detect it is inhomogeneous; the waves must travel through components of various materials and geometries and joints of differing physical properties. A hidden or broad-spectrum mechanical fault (such as a developing crack, or a loose fastener) often lacks a discrete, easily distinguishable frequency. This makes using classical Fast Fourier Transform (FFT) based analysis virtually impossible for detecting these faults.

The objective of our research is to develop a diagnostic method based on Time Delay of Arrival (TDoA) capable of localizing unknown fault sources from broad-spectrum impact vibrations on the chassis [1]. The goal is to achieve localization accuracy of 50 × 50 cm on the vehicle and its main elements. However, for wave propagation algorithms to function accurately enough for this, it is essential to understand how different types of joints transfer, dampen and distort these mechanical waves.

2. WAVE PROPAGATION AND JOINTS

When an excitation (vibration) enters the body of the vehicle, it must inevitably pass through the various joints connecting the sheet metal parts and other components of the vehicle. These joints act as “transfer gates” that determine the energy and frequency composition of the transmitted wave. Considering the principles of continuum mechanics, local alterations in stress and strain fields at a structural node can drastically change the phase velocity and damping of passing elastic waves (e.g. bending and Lamb waves) [2, 3].

The most common joint types used in the automotive industry are the following:

- Resistance spot welding (RSW): this is the most common joint type, used for about 80% of the joints within a car body; a single vehicle can contain thousands of spot welds. This technology creates localized fusion points between plates, providing a rigid metallic connection and therefore excellent vibration transfer, while energy dissipation remains low [2, 3].
- Mechanical fastening (Bolts and Rivets): these are preferred when welding is not feasible (for example, multimaterial structures, aluminium-steel connections). Vibration transfer here is predominantly determined by the friction between the surfaces and the preload force of the bolts.

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- Adhesive technologies: these provide massive visco-elastic damping. This significant energy dissipation severely attenuates high-frequency waves, greatly complicating diagnostic wave propagation analysis [2].

3. LITERATURE REVIEW

The propagation of elastic waves in plate structures is significantly influenced by the type of joint connecting the structural components. Since joints introduce discontinuities in stiffness and material properties, they modify wave transmission, attenuation, and scattering, directly affecting vibration-based structural health monitoring (SHM) and non-destructive testing (NDT) [4][10].

Bolted joints exhibit strongly nonlinear behaviour because wave propagation depends on bolt preload, contact pressure, and friction between the mating surfaces. A properly tightened bolt provides high contact stiffness and efficient wave transmission, whereas preload loss leads to micro-slip, increased damping, and reduced wave amplitude. These characteristics make guided waves particularly suitable for detecting bolt loosening and monitoring joint integrity [8]. Furthermore, Lamb wave studies have shown that changes in contact conditions significantly influence wave transmission through bolted [1].

Riveted joints provide a permanent connection with stable long-term stiffness because they are not affected by preload relaxation. However, localized deformation around the rivets, residual stresses, and manufacturing tolerances create multiple wave transmission paths, resulting in increased scattering and more complex vibration responses. Fatigue damage around rivet holes further modifies local stiffness and wave propagation characteristics, making guided waves effective for damage detection in riveted structures [11].

Spot-welded joints generally offer the highest stiffness and the most efficient transmission of elastic waves because the connected plates are metallurgically fused together. Consequently, intact spot welds produce cleaner wavefronts with relatively low attenuation, making them well suited for Time Difference of Arrival (TDoA) and guided-wave-based damage localization. However, fatigue cracks developing in the Heat Affected Zone (HAZ) reduce joint stiffness, increase wave scattering, and degrade signal quality [7].

Overall, previous studies indicate that welded joints provide the most efficient wave transmission, riveted joints introduce moderate scattering due to localized stiffness variations, and bolted joints exhibit the highest damping because of frictional energy dissipation. Understanding these differences is essential for accurately modelling wave propagation and improving the reliability of vibration-based structural health monitoring systems.

4. EXPERIMENT SETUP AND METHODOLOGY

Full vehicle diagnostic measurements produce noisy data. During a diagnostic wave propagation event, the mechanical waves bounce off hundreds of structural nodes, causing reverberation and severe interference. Under these conditions, it is impossible to isolate the effect of a singular joint type on the TDoA algorithm.

To solve this, we simplified our model for calibration. Using Transfer Path Analysis (TPA) applied to a set of controlled, simplified laboratory specimens, we can measure the pure inertance (Frequency Response Function – FRF) of isolated automotive joints, furthermore, the wave propagation in the specimen in the time domain.

5. SPECIMEN DESIGN

Two steel plates () were used during our experiment, measuring 600 × 400 x 1 mm and 400 × 400 x 1 mm, respectively (figure 1.). The steel plates were made of S235JR structural steel. The plates were each assembled with a 20 mm overlap and secured along a line of joints at the same distribution (except the adhesive joint, which was done along the whole overlap).

The joint types used in our experiments are as follows:

- M6 bolt and nut connection
- 6mm blind rivets
- Spot welds

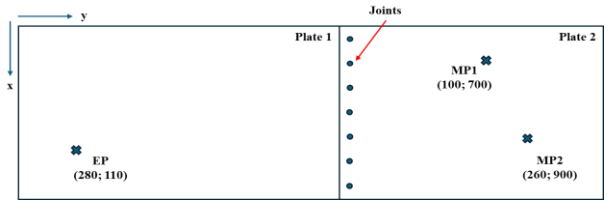


Figure 1. Schematic of the experimental setup, with measurement points (MP1 & MP2) and the excitation point (EP)

For the time domain tests for the wave propagation, a simple steel plate was used to get reference data of a blank steel plate without any joints.

6. THE EXPERIMENT

The experiment was done with the following equipment:

- Shaker: TIRAvib small electrodynamic shaker with a maximum excitation force of 9 N, with the included power amplifier
- Miniature impact hammer: 20 g weight
- Data acquisition (DAQ): Brüel & Kjaer Photon+, 4 channel DAQ system
- PCB 288D01 impedance head
- 2 Brüel & Kjaer 4397A accelerometers

The accelerometers were fixed to the steel plate with beeswax, which has very good vibration transferring properties, and it makes it easy to attach and remove the sensors.

The measurement setup for the FRF recording is the following:

- frequency range: 0-3200 Hz
- sampling frequency: 7800 Hz
- number of FFT lines: 6400 (0,5 Hz resolution)
- number of averages: 20 (linear)
- excitation signal: white noise (50% burst, 50% off the sampling time)
- window: rectangular
- recorded: averaged time signals, autopower and crosspower, H1 frequency response functions (FRF/inertance) and coherences

The measurement setup for the time domain recording is the following:

- sampling frequency: 100.000 Hz
- number of averages: 3 (linear)
- excitation signal: hammer impact
- window: rectangular
- recorded: averaged time signals

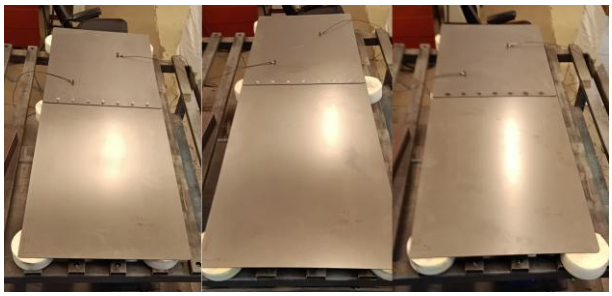


Figure 2. Bolted (left), Riveted (middle) and Welded (right) plates

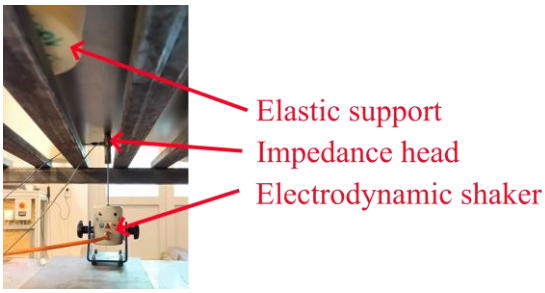


Figure 3. The experiment setup

For the experiment, the plates were placed on six elastic foam supports, which provided compliant boundary conditions and reduced vibration transmission between the plates and the supporting structure.

The plates had an impedance head glued to the downward facing side of the plate for measuring force and acceleration in the same sensor. For the time domain test the impedance head was detached from the plate, and a hammer impact was applied on the same place. The theory behind that is well described in the literature [3], [10].

7. RESULTS AND INTERPRETATION

The test results are discussed in both the frequency and time domains. First, the frequency response functions are examined (Figure 4). When the results are interpreted, significant differences can be observed in the vibration transfer of the different joints at both measurement points. The vibration transfer curves obtained for the bolted and riveted joints are found to be much more similar (blue and green curves). In both cases, lower-amplitude peaks are observed at the resonant frequencies, indicating increased damping (energy dissipation).

In contrast, the vibration transfer curve of the spot-welded plates (red curve) indicates a much stiffer joint, with many more sharp peaks (lower damping, higher quality factor) appearing across the measured frequency range. Here, damping is the lowest, and energy flows through the joint more freely with less distortion.

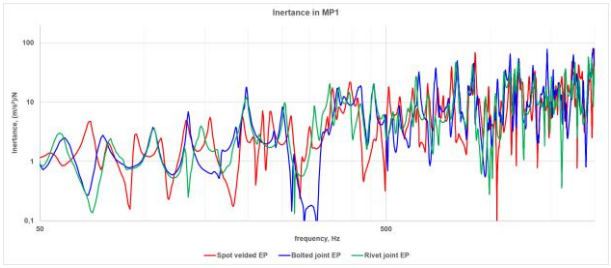


Figure 4. Results at measuring point 1 (MP1)

A time domain result is shown in figure 5. The diagram shows the acceleration time signal in MP1 on the bolted specimen. After the impact the acceleration signal decays approx. in 0.5 s to zero. The time signals on all other specimens look similar, but this representation does not allow further investigation. It is necessary to zoom the initial range of the curves. The zoomed curves of three different joint configurations and a blank steel plate subjected to the same impact excitation are shown in figure 6.

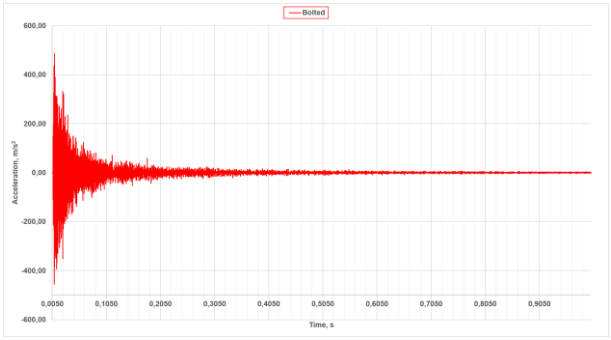


Figure 5. Results at measuring point 1 (MP1) of the bolted specimen

The blue curve represents the excitation force, while the remaining curves correspond to the measured acceleration responses of a continuous steel plate w/o joints (red), a bolted steel specimen (green), a riveted steel specimen (light blue), and a spot-welded steel specimen (orange).

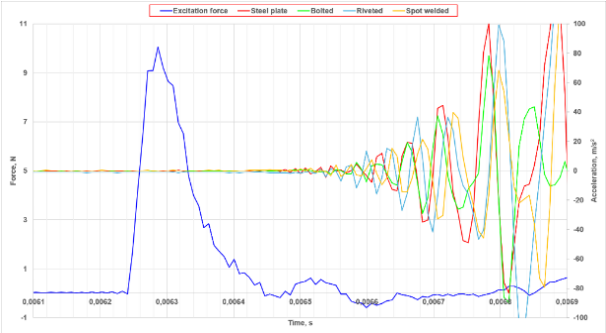


Figure 6. The excitation force signal and the time signals at Measuring Point 1 (MP1)

The excitation force peaks at ~10 N (t = 0.00628 s) as a short-duration impulse. Acceleration responses lag slightly due to elastic wave propagation. A rapid increase in vibration amplitude is observed following the arrival of the main wave packet, after an initial period of low-amplitude oscillations.

Continuous Steel Plate (Red, Reference): Shows minimal wave modification, rapid amplitude growth, a sharp wavefront, and low energy loss due to uninhibited transmission.

Spot-Welded (Orange): Closely mirrors the continuous plate with high stiffness, efficient transmission, low damping, and a clear wavefront ideal for TDoA algorithms.

Riveted (Light Blue): Generates high amplitudes but a more irregular waveform, driven by localized joint deformation, manufacturing tolerances, and scattering across multiple load paths.

Bolted (Green): Exhibits the lowest initial amplitudes, gradual response build-up, and pronounced oscillations. Interface friction and micro-slip introduce significant damping and attenuation.

The joining method directly dictates wave propagation and dynamic performance. The continuous plate and spot weld maximize energy transmission and clarity, whereas riveted joints add structural complexity and bolted connections provide maximum damping via frictional dissipation.

8. SUMMARY

The investigated joint types exhibit distinct vibration transmission characteristics, which affect wave propagation and TDoA-based localization.

In bolted joints, vibration transfer depends mainly on preload, friction, and surface conditions. Preload relaxation reduces clamping force and increases nonlinear damping due to friction and micro-slip.

Riveted joints provide permanent stability without preload loss. However, localized stresses and multiple load paths result in a complex vibration response, with energy dissipated through deformation, contact interactions, and hysteresis.

Spot-welded joints provide high stiffness and low wave attenuation, resulting in clear wavefronts suitable for TDoA diagnostics. However, fatigue cracks in the HAZ or micro-slip may degrade signal quality.

Initial findings indicate that spot welds do not significantly affect wave propagation or TDoA applicability. Future research will therefore focus on reducing arrival-time uncertainty in sensor signals.

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