UNIVERSITY OF MISKOLC
FACULTY OF MECHANICAL ENGINEERING AND INFORMATICS
INSTITUTE OF MACHINE AND PRODUCT DESIGN

PREDICTION AND LOCALIZATION OF MECHANICAL DAMAGE OF VEHICLE POWERTRAINS USING DIAGNOSTICS METHODS

PHD THESIS

PREPARED BY:
József Balázs Kriston
Certified Mechanical Engineer

ISTVÁN SÁLYI DOCTORAL SCHOOL OF MECHANICAL ENGINEERING SCIENCES
TOPIC AREA: DESIGN OF MACHINES AND STRUCTURES
RESEARCH GROUP: PRODUCT DEVELOPMENT AND DESIGN

HEAD OF DOCTORAL SCHOOL:
Vadászné Prof. Dr. Bognár Gabriella
DSc, Full Professor

TOPIC AREA LEADER:
Vadászné Prof. Dr. Bognár Gabriella
DSc, Full Professor

SCIENTIFIC SUPERVISOR:
Dr. Jálics Károly
Director of Institute, Associate Professor

Miskolc
2026

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1. INTRODUCTION

Vibrations occurring in vehicles can originate from various sources, including the engine, suspension components, wheels and tires, as well as powertrain elements. These vibrations may initially manifest as minor inconveniences—such as an increased play in the steering wheel—or progress into more serious concerns later, including degradation of vehicle handling, accelerated wear of components, and deterioration of fuel efficiency and power output. To ensure that vehicles remain safe and efficient, diagnosing and mitigating vibration problems is essential.

The human auditory organ is a highly sensitive and versatile 'instrument', but it does not provide information that can be stored and processed later. Sound perception often varies from person to person, even when exposed to the exact same noise or sound. Consequently, it is impossible to determine certain faults solely through human perception, especially those providing more differentiated acoustic patterns. However, a noise judged as unpleasant does not necessarily indicate a vehicle malfunction; human sound perception is highly subjective. A specific noise may be annoying to some individuals while others do not notice it at all. Perception depends on numerous parameters, such as spatial distribution, spectral distribution, duration, energy level, etc.

Due to eventual degradation and wear of mechanical elements during operation, the emitted noise and vibration values deviate from the designed nominal operating state. Monitoring these parameters for diagnostic purposes helps specialists reduce maintenance costs, preserve the planned service life, and schedule maintenance operations effectively.

Taking the above into account, the objective of our investigation is to develop a vibration-based measurement system capable of distinguishing between normal and faulty operating states, as well as localizing the faulty components within the vehicle structure. Since industry requires a method that is rapid, simple, and cost-effective, an important prerequisite must be established for the measurement method: disassembly of the motor vehicle is not permitted. A further goal is to assign the most appropriate vibroacoustic method to specific types of vehicle faults to optimize their diagnosis.

2. LITERATURE REVIEW

Assessing current research trends, it can be stated that in most cases, vehicles are not investigated as complete systems, but rather at the subsystem/component level under laboratory conditions. For the analysis of individual components (engine, gearbox, etc.), test rigs are utilized; thus, a portion of the research involves designing vibroacoustically correct test equipment (e.g., using magnetic brakes for load applications, flexible couplings, etc.). In most cases, the faults are artificially induced (e.g., via long-term operation, accelerated aging, or physical intervention), and the structural architecture and operating conditions of the vehicle are fully known in every instance.

Research focuses primarily on finding appropriate condition indicators for vehicle faults and proving their reliable applicability. At the same time, very few works can be found that operate with a statistically sufficient database. As a result, the generalization of results for other types of passenger cars remains uncertain.

The malfunctions investigated are highly comprehensive, including but not limited to gear defects, crankshaft bearing failures, engine faults, auxiliary equipment failures, chassis/suspension defects, etc. Studies highlight those operating conditions, namely the instantaneous state of the vehicle, speed-load relationships, temperature, etc.—exert a significant influence on measurement results and on the sensitivity of various condition indicators to faults. Research also demonstrates that the position and orientation of the sensors have a decisive influence on the detection of certain faults. Modelled after fault identification performed by the human ear, there are some attempts—though limited in number—to apply psychoacoustic metrics for diagnostic purposes.

Based on literature sources, the presence of a fault can be successfully detected in many cases using properly selected parameters; however, its precise source and root cause cannot always be directly determined. Since these are complex structures, correct diagnostics require a deeper analysis, alongside precise knowledge of the structure's geometry, operating principle, and operating conditions. Almost without exception, authors discuss further development possibilities and extensions of their methods at the conclusion of their research. It is recognizable that the field of vehicle vibration diagnostics—although it has developed dynamically in recent decades—is not yet fully mature and offers countless development opportunities [1-33].

3. DESCRIPTION OF THE PERFORMED TPA EXPERIMENT

The vibration transfer capability of the vehicle structure was investigated on a first-generation Ford Focus vehicle. During the experiments, accelerometers (CH1...CH3) were placed on the vehicle body at positions corresponding to Figure 3.1. In addition, to generate frequency response functions (FRF), vibration acceleration was also measured adjacent to the excitation points (CH4). The objective was to demonstrate that structure-borne sound excitation originating from the engine compartment environment reaches the applied measurement positions with sufficient intensity. The excitations were applied at points I1 and I2 of the engine mount. Using an impulse hammer, impacts were delivered at these points on both sides of the engine in all three spatial directions (-X, +Y, and -Z directions according to the vehicle's coordinate system).

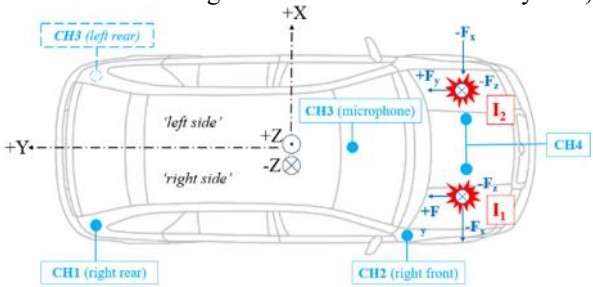


Figure 3.1. *Schematic diagram of the tested vehicle showing excitation and measurement points*

Overall, it can be stated that the applied X, Y, and Z-direction excitations propagate with nearly identical transmission characteristics in all directions when interpreted in the vehicle-fixed coordinate system. For the sake of the experiment, it was assumed that the abnormal excitation to be detected originates from the engine compartment environment. In this case, the CH2 sensor, located closest to the engine, exhibits the best transmission behaviour. Nevertheless, this does not imply that the microphone and the rear acceleration sensors are unsuitable for fault detection. For these measurement points, a limitation of the excitable frequency range must be considered (max. 2 kHz depending on the location of the fault), but they remain suitable for detecting severe malfunctions. Based on the obtained results, measuring on one side of the vehicle is theoretically sufficient for proper diagnostics. However, this is still not recommended, as the fault signal-to-noise ratio resulting from the accelerometer's position can provide information regarding the location of the malfunctioning element.

4. DIAGNOSTIC MEASUREMENT RESULTS

4.1 VW TOURAN GEARBOX NOISE ISSUE

A relatively new (year of manufacture: 2019) turbocharged, direct-injection, 1.5-liter gasoline engine passenger vehicle with front-wheel drive and a 6-speed manual transmission was investigated. After six months of use, the owner began complaining about a specific noise experienced during gear shifts between first, second, and third gears. Based on its nature, the noise can be described as an impact/clash-like phenomenon, and its frequency content can be characterized as broadband noise. The noise was clearly audible both inside and outside the vehicle during gear shifting.

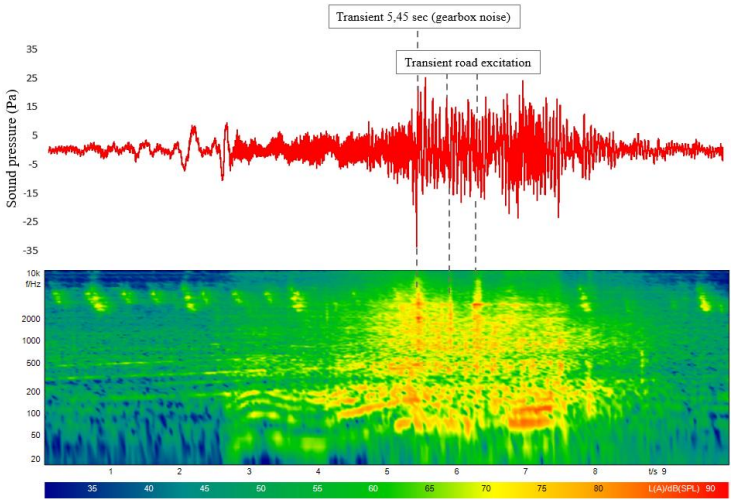


Figure 4.1.1. *Time signal and high-resolution spectrogram of pass-by noise measurement*

As a first step, a pass-by noise measurement was performed to verify the presence and nature of the fault. To gain closer insight into the problem, measurements were also conducted in the static state of the vehicle. Summarizing these results, it can be stated that vibroacoustic methods do not always allow for the full localization of a malfunction within a vehicle's powertrain system. The effectiveness of finding the faulty component depends heavily on the frequency characteristics of the noise or vibration caused by the fault. In the case of broadband excitation, there is no fundamental frequency component originating from structural characteristics that could be used to identify individual

machine elements. Frequency analyses require precise knowledge of the transmission structure and its operating conditions. In our case, the gearbox, as one of the main assemblies of the vehicle, could be identified as the source of the fault by choosing appropriate measurement positions, but the faulty element or elements within the interior of the structure could not be identified in greater detail.

4.2 AUDI REVERSE GEAR NOISE ISSUE

A premium, used, all-wheel-drive, diesel-engine vehicle (approx. 200,000 km mileage) equipped with an automatic transmission and a hydrodynamic torque converter was investigated. The owner complained of a specific whistling noise when operating in reverse gear. The noise was audible during acceleration, during low-speed vehicle creeping in neutral, and during braking to a standstill.

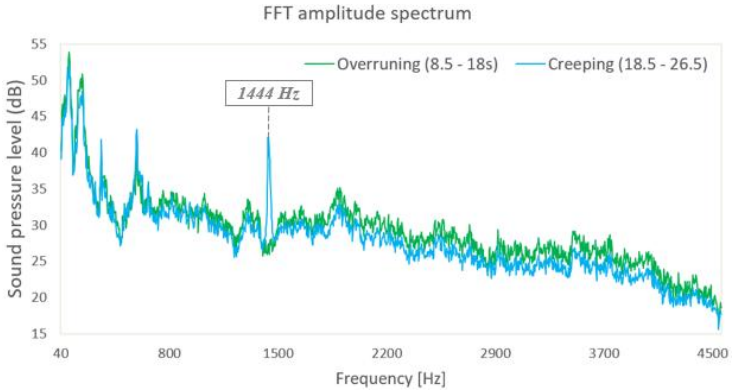


Figure 4.2.1. *FFT amplitude spectrum comparison between overrunning and creeping states*

For a systematic investigation of the problem, microphone-based noise measurements were performed under driving conditions where the noise occurred. The microphone was positioned at head height on the front passenger seat. Measurements were performed exclusively in reverse gear, covering the following driving phases: acceleration, overrunning (engine braking deceleration), creeping at idle speed, and braking. In the operating state where the noise appears, a component at 1444 Hz is visible, standing 18 dB above the background noise level. This magnitude of peak in the spectral distribution results in a clearly audible, tonal sound, which is highly likely to produce the sharp noise reported by the user. Investigation of psychoacoustic parameters

was also performed. Due to the extended duration of the time signal (30 s), specific intervals critical to the operating conditions were extracted:

- Phase 1 (0 – 8.5 s): Acceleration from a standstill
- Phase 2 (8.5 – 18 s): Engine braking from maximum speed to creeping speed
- Phase 3 (18 – 26.5 s): Creeping at idle speed
- Phase 4 (26.5 – 30 s): Braking

In the absence of a baseline reference measurement, two different test phases are compared. In the overrunning state, the noise problem does not manifest, whereas it is audible during creeping.

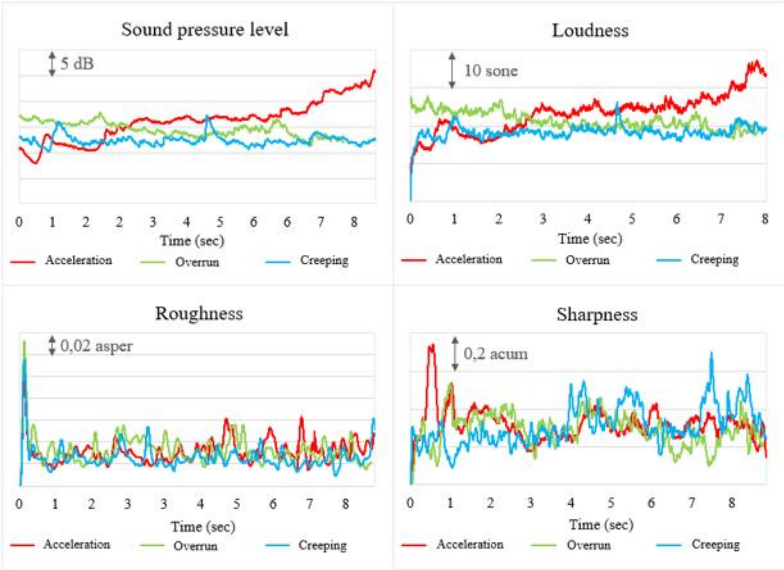


Figure 4.2.2. *Psychoacoustic characteristics and sound pressure level in three different vehicle operating states*

In conclusion, the noise problem can be successfully identified via acoustic analysis. The analysis of psychoacoustic parameters confirmed that the noise indeed acts as a disturbing effect in terms of sharpness, meaning the owner's claim proved to be justified. Although the noise problem is detectable, this research work did not fully achieve its goal, as critical structural information regarding the gearbox was unavailable. Such data would be necessary to identify the malfunctioning mechanical element causing the noise via frequency analysis or alternative methods.

4.3 KIA CEE'D REAR SHOCK ABSORBER NOISE ISSUE

A Kia Cee'd passenger car was investigated, which exhibited a rattling, knocking noise originating from the rear right section of the vehicle while driving. The fault was uncovered during subsequent repair; the issue was caused by the shock absorber mounting bolts becoming loose relative to the vehicle body. After tightening the bolts, the observed noise phenomenon disappeared. We were interested in evaluating the potential of vibroacoustic methods to reveal this type of noise problem, so simple measurements were performed while driving.

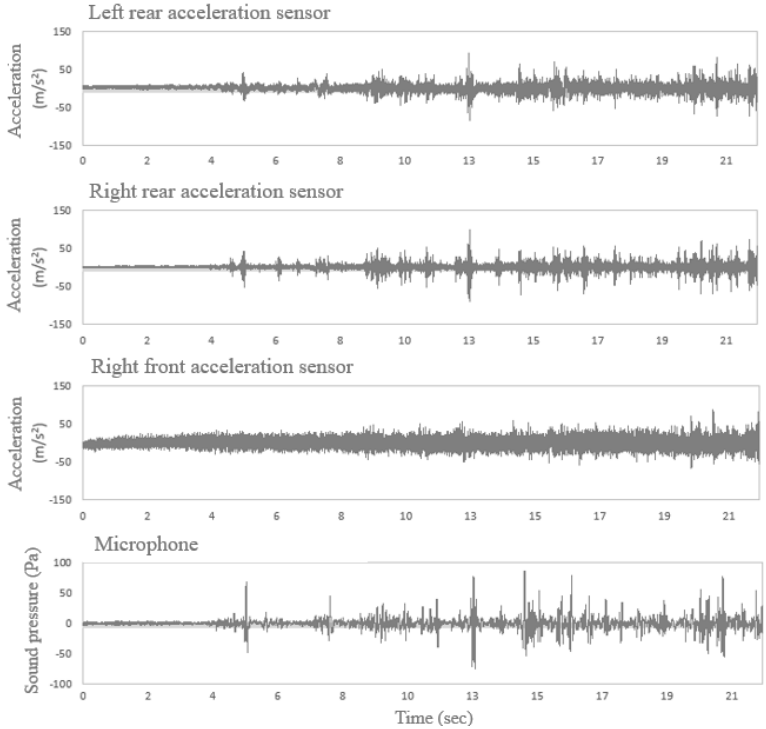


Figure 4.3.1. *Time signals recorded at each measurement point during the test*

Piezoelectric accelerometers with magnetic mounts were placed on the vehicle body at the height of the door handles on the right and left rear sections, as well as on the front right side. Furthermore, a microphone was placed at head height on the

passenger seat in the cabin. During the tests, the vehicle accelerated up to 50 km/h, driven at this constant speed, and finally decelerated to a standstill.

The rattling, knocking noise was caused by transient vibrations acting across a wide frequency range. These transients are averaged out in the standard spectrum and therefore cannot be displayed as discrete frequency components. For this type of malfunction, it is more appropriate to select analysis methods that display the time axis in some manner. An examination of the time domain is straightforward (Figure 4.3.1), where the amplitude peaks associated with the excitation are clearly distinguishable from the background noise.

Since the excitation is independent of the engine speed in a direct sense, analysing the frequency components does not yield useful diagnostic information. Given that it is a broadband excitation, we can only infer the location of the fault from the sensor positions. Fundamentally, transient excitation events associated with 'knocking' are better observed as a function of time. The typical shape of the time signal in such cases is characterized by regularly or randomly repeating peaks above the baseline noise level. This pattern is clearly observable in the signals from the microphone and the rear accelerometers. The energy of the impacts is essentially stored across the entire frequency range captured by the sensors, depending on the attenuation of the transmission paths. Based on the sensor positions, the location of the fault can be isolated to the rear part of the vehicle. More detailed localization requires personal presence, since we are only able to determine the direction of the sound based on human hearing in the absence of a binaural microphone. The results obtained do not provide definitive proof that the fault is specifically the loosening of the shock absorber bolt. Similar to the VW Touran noise problem - which is a fault of a similar nature with a similar spectral distribution - the presence of the malfunction can be established based on the analyses, but the root cause of the fault cannot be uncovered.

4.4 FORD FOCUS GEARBOX FAULT – TOOTH BREAKAGE

Vibroacoustic measurements were performed on a first-generation Ford Focus (model year 1998) passenger vehicle. A single tooth was removed from the output gear of the gearbox final drive, thereby artificially inducing a potential tooth breakage defect. The objective of the measurements was the vibration-based diagnostic analysis of the gearbox malfunction.

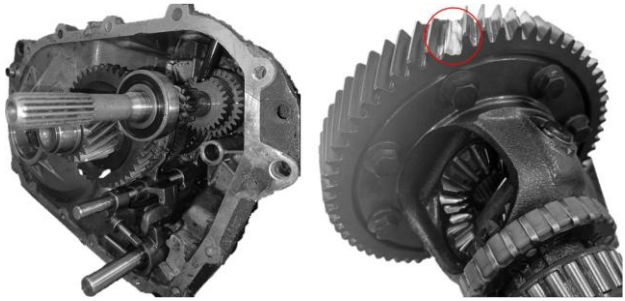


Figure 4.4.1. *Ford Focus 5-speed manual gearbox and the machined tooth from the final drive output gear*

The induced malfunction was not perceptible to the human ear. Measurements were performed in second and third gears at constant and variable speeds. The testing location was a low-traffic public road. The public road tests—due to compliance with speed limits—fundamentally constrained the possibilities and conditions of the measurements. During run-up tests, the vehicle was operated in second gear within an engine speed range of 1200 – 5000 rpm. The constant-speed tests were conducted at engine speeds of 2000 rpm and 3000 rpm in second gear, and at 2000 rpm in third gear.

The evaluation covers the analysis of spectra and spectrograms obtained via Fourier transform. The objective was to find a clear indication of the fault within the vibration data. To evaluate the results, it is necessary to know the internal architecture of the gearbox. Knowing the input engine speed and the gear ratios, the meshing frequencies of the shafts and gears were calculated, considering second and third gears, as well as the final drive output gear.

The gearbox was disassembled and reassembled multiple times at different locations. The spectrogram of the run-up test reveals that certain resonance frequencies appear only in the faulty condition (e.g., between 2200 – 2400 Hz), while other resonance frequencies almost entirely disappear (e.g., between 1200 – 1400 Hz).

Regarding the rearrangement of resonance frequencies, the hypothesis is that variations in the positions of shafts, bearings, and the housing cover during assembly operations, as well as modifications in individual component interfaces, caused a shift in the system's overall stiffness. Thus, during assembly operations, it could not be guaranteed that we did not introduce deviations from the original state that were independent of the artificial fault. In the signals recorded via the microphone channel and the sensor placed on the front right side of the body, primarily fundamental frequencies originating from the engine appear; the topological frequencies of the gearbox cannot be recognized. Low frequencies entering the passenger compartment are mostly below 1500 Hz, and even lower frequencies excite the body elements. Therefore, problems related to the gearbox can only be detected from the signal of the sensor fitted directly onto the transmission housing.

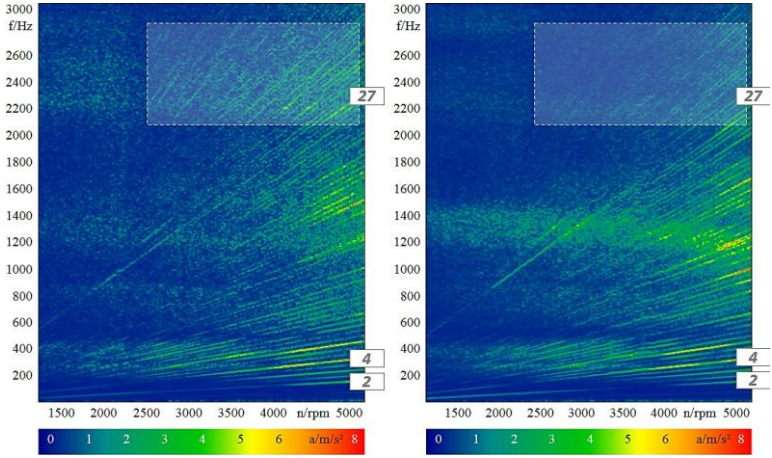


Figure 4.4.2. *FFT vs. RPM diagram (spectrogram) of run-up test, 0–3000 Hz (left: tooth breakage, right: normal)*

In the large volume of publications dealing with the vibration testing of gear damage found in the literature, vibration spectra are typically investigated under laboratory conditions, generally for a single gear pair. In contrast, during the vibration analysis of a tooth breakage problem in a complete vehicle gearbox in its installed state under real operating conditions, the theoretical fault spectrum cannot be recognized. There is no trace of the frequencies or sideband modulations characteristic of a faulty gear in either the vibration or acoustic spectra; the appearing frequencies do not point to the induced problem. The good and degraded states cannot be sharply separated based

on the test results, because the tests performed in different gear ratios do not provide a consistent evaluation of the vehicle's behaviour. Furthermore, the rotational speed of the final drive output gear at an engine speed of 2000 rpm is considered low: 255 rpm in second gear, and 384 rpm in third gear. As is well known, the amplitude of vibration acceleration increases proportionally with rotational speed. High-energy vibrations originating from the engine crankshaft, which largely dominate the vehicle's vibration characteristics, suppress the low-speed gear harmonics and prevent their visualization in the spectra.

4.5 FORD FOCUS MISFIRE ISSUE

One of the most common problems in internal combustion engines is an aged spark plug, which causes weak ignition or a misfire, and can disturb the uniform rotation of the crankshaft. Existing diagnostic strategies include measuring cylinder pressure or crankshaft rotational speed fluctuations. The misfire was artificially induced by disconnecting the ignition coil. Vibroacoustic measurements were performed on the first-generation Ford Focus passenger car introduced in the previous section. During the measurements, a key requirement was the extremely simple installation of sensors onto the vehicle without any disassembly. For this purpose, a single-axis accelerometer was mounted on the front right side of the body, another was attached to a connecting bolt head between the engine block and the transmission housing, and a condenser microphone was placed on the front passenger seat.

Measurements were repeated multiple times at idle speed, and at constant engine speeds of 2000 rpm and 3000 rpm. Furthermore, noise and vibration were measured in transient acceleration mode (run-up) from 1500 rpm to 5000 rpm. It can be stated that the consequences of the induced misfire are detectable in the acoustic signal. From the order spectrum, it can be established that in the event of a misfire, the vibration level of the first order of the engine crankshaft and its subharmonics increases. Analysis performed on the spectra shows that a family of subharmonic modulations linked to the crankshaft frequency appears above 1000 Hz. Excitation by the firing frequency appears dominantly within the cabin and on the body panels.

Precise localization of the problem is impossible, as the vibration diagnostic investigation does not reveal which specific cylinder is misfiring. Statistical metrics of the time signal can separate the good and degraded states; however, they do not indicate the nature, cause, or position of the malfunction. From the obtained acoustic pattern, the crankshaft can be identified as the source of the anomalous vibration. Since this is an

artificially created fault, however, we know that the crankshaft is not a defective component; rather, we detect torque fluctuation as a vibration source, which is a symptom of the misfire.

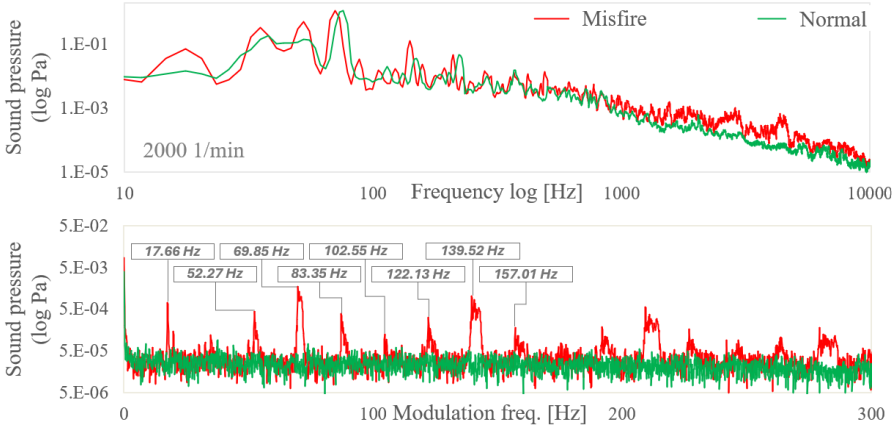


Figure 4.5.1. *Comparison of amplitude and modulation spectra corresponding to a rotational speed of 2000 rpm*

Acknowledging this, the conclusion is that it is impossible to fully localize the fault or determine its root cause using vibration diagnostics alone. Any malfunction leading to non-uniform rotation of the crankshaft will display a very similar spectral pattern; therefore, a misfire cannot be uniquely determined as the exclusive cause of the fault.

4.6 MAZDA CX-5 STARTER MOTOR ISSUE

Malfunctions can occur for numerous reasons within the complex system of a starter motor. In our case, the malfunction was accompanied by a noise that was similar in nature to the normal condition, but slightly louder and longer in duration. After complete replacement of the starter motor, the anomalous noise ceased. Although the starting mechanism is well understood, the nature of the acoustic phenomenon was nevertheless difficult to characterize. During the analysis, we restricted our focus to the acoustic signal from a microphone placed above the engine.

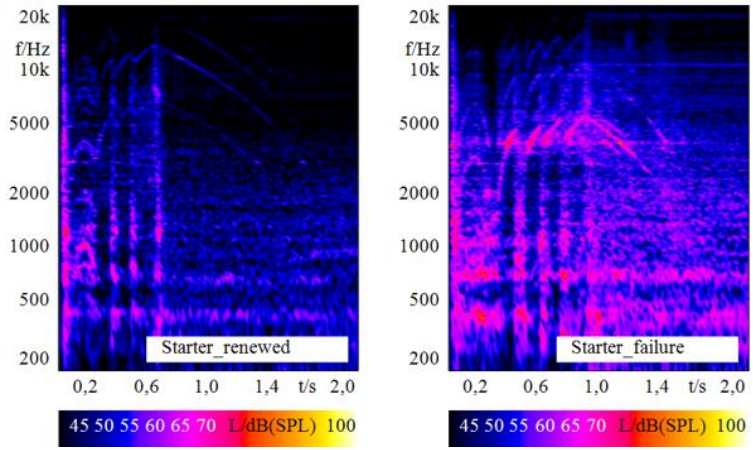


Figure 4.6.1. *Fourier spectrogram comparison*

The moment of engine startup is linked to the final transient event, after which the starter motor speed drops abruptly. In the faulty state, based on the shape of the order, it can be stated that the drop in rotational speed during torque transfer is greater. An impact-like phenomenon is naturally visible between individual drops in speed, the origin of which remains unknown. Viewed as a function of the frequency domain, it can also be stated regarding the orders that in the faulty condition, the starter motor is inherently unable to reach as high a rotational speed as during normal operation. Presumably, insufficiency in torque transfer causes the problem; therefore, the internal combustion engine was less capable of reaching the rotational speed required for its own starting.

The above findings necessitate a reference baseline measurement against which the spectral images can be compared. The precise cause of the fault cannot be

determined using the applied analyses, but the joint time-frequency analysis allows for inferences regarding the mechanical behaviour of the starter motor. We also know that after replacing the starter motor, the unusual phenomenon disappeared; thus, the battery or the fuel supply system is not the source of the problem. After the internal combustion engine started, the starter motor disengaged without issue; therefore, a mechanical failure of the Bendix drive mechanism can also be ruled out. From the nature of the starting sound (it does not grind or scrape) and from the fact that the starter motor remained functional, it can be established that the malfunction was not severe, but rather of an incipient nature. Judging from the behaviour of the orders and the variation of the transients, the fault phenomenon could stem from minor friction or binding. Insufficiency in torque transfer can be caused by several factors. A contact fault, contamination, burning, or corrosion of the bypass ignition terminal or contact disc can make it difficult to draw the voltage from the battery required to provide the necessary torque. Other possible causes include deformation or internal damage to the rollers of the freewheel mechanism, dried-out bearings, a bent armature, or a fault in the field coil windings. Due to the complete replacement of the starter motor, we were unable to identify the specific failed element inside it, meaning that we unfortunately cannot uniquely assign a root cause of the fault to the spectral distribution.

4.7 VW GOLF DIFFERENTIAL NOISE ISSUE

The investigated vehicle was a VW Golf 1.5 TSI. During operation, while cornering at speeds above approximately 60 km/h, the owner heard an unusual noise in the passenger cabin that was perceived as disturbing by the occupants.

A general arrangement was chosen for the accelerometers, based on which we saw an opportunity to manage the challenges arising from the developing complex noise and vibration state. Three single-axis sensors were positioned via magnetic attachment on the body surface on the front right, rear right, and rear left sides of the vehicle at a height of 0.8 m from the ground level. The locations for the measurements were roads 2519 and 2505, during which the vehicle covered a total of 42 km. When selecting the measurement locations and road sections, a key criterion was that the curves found there could be traversed at a sustained speed above 60 km/h in 5th gear.

The briefly experienced acoustic phenomenon is audible between seconds 5.6 and 6 of the measurement. It can be seen from the markings of the wave packets determining the noise phenomenon that these are slightly offset relative to one another. This implies that the vibration originating from the target excitation reached the sensor above the

front right axle sooner than the other two. Thus, the machine element causing the noise is in the front right section of the vehicle.

Using the reciprocal of the excitation time differences of the front right sensor, it can be calculated that the frequency of this transient excitation is approximately 8 – 10 Hz. Based on the investigations carried out, objectionable noise can be detected via vibration measurement. The problem cannot be considered permanent or systematic, as the noise was heard a total of 3 times out of 14 measurements. This suggests that factors external to the vehicle structure also contribute to the generation of the disturbing acoustic effect, such as a loss of traction during cornering on roads of a specific quality.

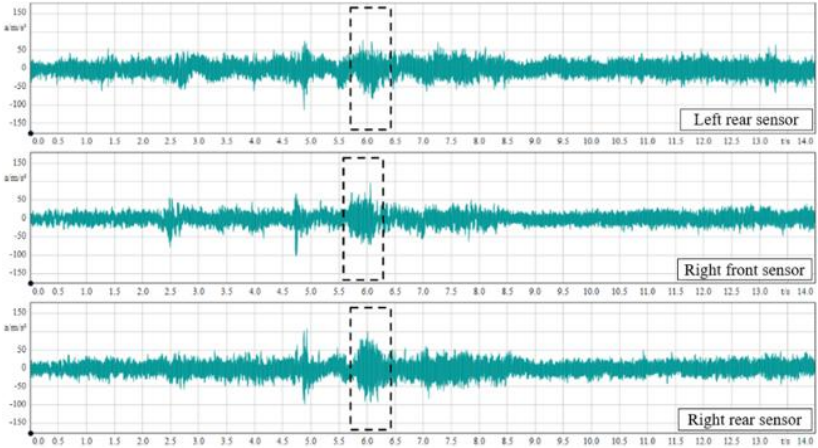


Figure 4.7.1. *Raw vibration signals recorded by each sensor during the measurement (0 - 14 sec)*

In the measurement data, we were able to identify the characteristic frequency of the XDS system's operation (8-12 Hz); thus, the XDS can be considered the source of the disturbance. However, the noise phenomenon cannot be considered a malfunction, as it results from the normal, corrective operation of the XDS system. It must be stated that a full diagnostic interpretation would not have been possible purely through vibration measurement without knowledge of the vehicle system's operating principles and supplementary tests. In the first instance, based on the analysis of the Campbell diagram and time signals, we were able to determine the approximate location of the noise source and identify the nature of the noise. Subsequently, through targeted investigation of the 10 Hz excitation modulation frequency, we were able to prove our hypothesis regarding the XDS electronic differential lock system.

4.8 SUMMARY OF DIAGNOSTIC MEASUREMENT RESULTS

Vibroacoustic methods do not always allow for the full localization of a malfunction within a vehicle's powertrain system. The difference between normal and anomalous behaviour can be detected via vibration and acoustic measurements; thus, the two states are well-differentiated from each other. Nevertheless, in most cases, a deep analysis and disclosure of the fault source require supplementary tests as well as a priori knowledge.

The frequency characteristics of the noise or vibration influence the effectiveness of finding the faulty component, since in the case of broadband excitation, there is no fundamental frequency component originating from structural features that could be used to identify individual machine elements. Frequency analyses require knowledge of the mechanical architecture of the structures and their operating conditions. The success of root cause analysis can also depend on the choice of appropriate measurement positions.

Another difficulty is that due to the subjective perception of sounds, characterizing noise phenomena is a complex task and their evaluation is not unique; consequently, in many cases, it cannot be asserted with full certainty whether the perceived noise is generated by a malfunction or corresponds to normal operation. For this reason, it is advisable to consider a baseline reference measurement when evaluating measurement results.

Under certain technical problems, the malfunction emits detectable noise only under specific conditions and during specific operating states. This is advantageous from a diagnostic perspective on one hand, as it can narrow down the suspected malfunctioning component, but it can complicate the preparation of measurement plans on the other. Beyond the complex vibration conditions prevailing in the vehicle engine compartment, the interaction between the tires and the road, as well as wind noise, generates broadband vibrations that complicate the extraction of desired signals during diagnostics.

The vibration characteristics of the investigated passenger vehicles are determined to a decisive degree by the most dominant vibration source, namely the internal combustion engine. High-energy vibrations originating from the engine crankshaft suppress the gear harmonics operating at lower speeds—such as those of the gearbox final drive—preventing their visualization in the spectra. This means that the generally applied measurement arrangement has a limitation regarding the subsystems that can be

investigated with an adequate signal-to-noise ratio due to excitations occurring from multiple sources in the vehicle.

When creating artificially induced faults, we observed that conflicting, inconsistent, or non-unidirectional results were obtained between individual tests. The reason for this is highly likely the incorrect and inconsistent assembly methods applied under workshop conditions. Thus, during mechanical interventions, it is crucial to perform assemblies and modifications with sufficient precision to ensure that the mechanical state—and thereby the vibration state—of the tested equipment does not change significantly. During the complex and highly synchronized operation of the vehicle, the spectral distributions generated by malfunctions can vary widely. Nonetheless, the exact same acoustic pattern can belong to multiple malfunctions. For example, the acoustic pattern observed during a misfire result from the non-uniform rotation of the crankshaft; however, this effect can be induced by other damage as well. This implies that multiple fault causes can share an identical spectral distribution. It follows that the result of an FFT spectrum analysis does not point directly to the root cause (the faulty component) but rather allows us to observe the consequence (symptom) of the malfunction.

5. TDOA ANALYSIS

The concept behind experimenting with the Time Difference of Arrival (TDoA) method is to focus not directly on the malfunctioning component and the type of malfunction, but rather on the geometric position of the fault. Thus, the goal is not to precisely determine the faulty component through its gear meshing frequency, for instance, but to determine the geometric position of the malfunction within a certain distance inside a vehicle-fixed coordinate system. Knowing the coordinates, we can easily identify the component causing the anomalous excitation.

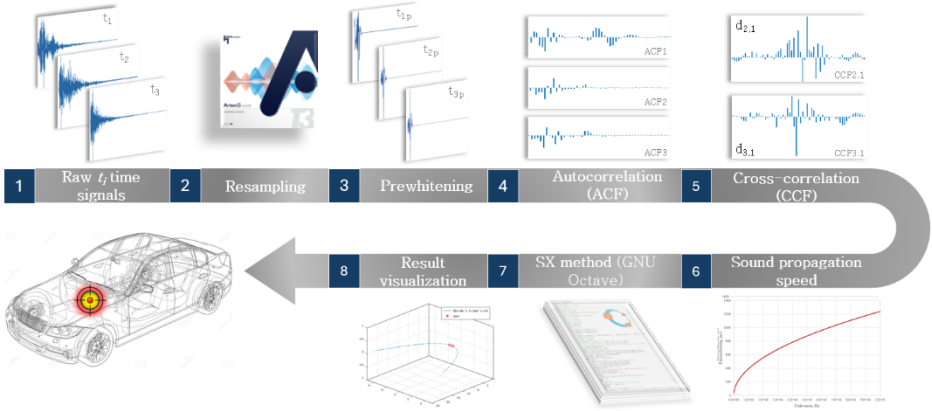


Figure 5.1. *Routine of the TDoA source localization method*

During the adaptation of the source localization procedure to vibration signals, we developed the process steps necessary for successful impulse source determination. Vibration signals (t_i) must be measured synchronously on at least three different channels. Subsequently, due to the correct order of magnitude of the time delay and to remove disruptive high-frequency components, the raw time signals must be resampled in the 1 – 10 kHz range. The cross-correlation function of a very high-frequency signal is fine and rapidly oscillating, making the peaks difficult to identify. Performing 'prewhitening' is an indispensable step before computing the cross-correlation. Highly dominant frequency components (e.g., rotational harmonics, structural resonances) are frequent in the vibration signals of mechanical systems. Due to the predominance of dominant frequencies, the cross-correlation becomes distorted and does not reflect the true time-delay information. Prewhitening flattens the spectrum of the signal and noise, ensuring that the cross-correlation is not sensitive to just one or two frequencies.

In addition to the time delay, the phase velocity of the bending wave propagating through the body elements must be determined as an input parameter. This is performed using the relation valid for the phase velocity of a bending wave, which depends on the geometry, material properties, and frequency. To compute the velocity, the frequency used for resampling is taken as a baseline. To facilitate calculations, a program code was prepared in GNU Octave. This code enables reading the prewhitened time signal and generating the time delays via cross-correlation. Subsequently, the SX method directly computes the source coordinates as a function of the required input data (propagation velocity of the sound wave, positions of the sensors, time delay). The visualization of the quadratic equation to be solved is a parabola, whose zero crossings contain the x and y coordinates of the source.

5.1 INFLUENCE OF TDOA TEST PARAMETERS ON RESULTS

The investigation of factors influencing the results produced by the TDoA source localization method relates to analysing parameters affecting measurement accuracy. The objective of this section is to understand what can influence the quantities forming the input to the algorithm, and how these affect the measurement results. The section is primarily based on web sources [34]–[37], according to which the reliability of the method is mostly influenced by the multipath propagation of the utilized signals.

a. Wave propagation in complex structures. In plate-like components—such as the investigated vehicle body panels—the propagation velocity is strongly frequency-dependent. The frequency dependence of the sound propagation velocity is termed dispersion. The phase velocity of waves generated in plate-like components can be calculated as follows [38]:

$$c_B = \sqrt{\omega} \cdot \sqrt[4]{\frac{B}{\rho h}} \cdot \tag{1}$$

where

$$B = \frac{h^3}{12} \cdot \frac{E}{1 - \nu^2} \tag{2}$$

is the bending stiffness.

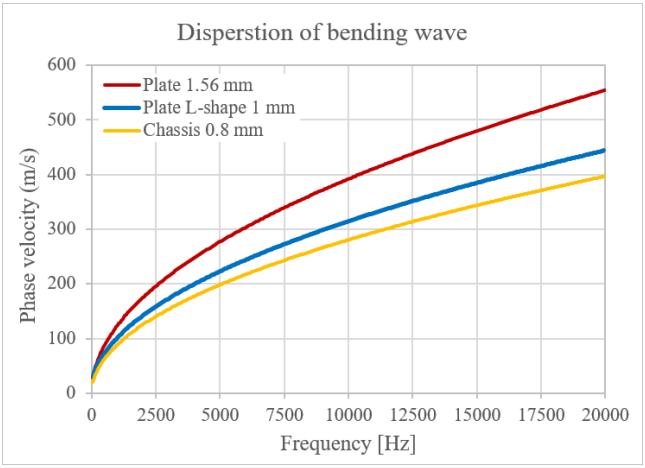


Figure 5.1.1. *Frequency dependence of bending wave propagation velocity for the plate and body elements used in the investigations*

Performing the calculations with parameters $h = 1.56$ és 0.8 mm; $E = 210 \cdot 10^3$ MPa; $\nu = 0.3$; $\rho = 7850$ kg/m^3 yields the frequency-dependent curves for propagation velocity shown in Figure 5.1.1.

b. Importance of sampling frequency. We know that excitation below 2000 Hz is dominant in body elements, whether its source is the engine or an artificial impulse. A sampling frequency of 4096 Hz means that a data point is sampled every 1/4096 Hz, i.e., $2.4 \cdot 10^{-4}$ seconds. A 4096 Hz bending wave traveling at a propagation velocity of 178 m/s covers 4.3 cm during this time, which represents the maximum spatial resolution achievable with this sampling frequency. By doubling the sampling rate—noting that the wave propagation velocity then becomes 251 m/s due to dispersion—the spatial resolution can be improved to 3.1 cm.

c. Geometric condition. If the source lies within the convex polygon bounded by the sensors, the expected localization accuracy will be high. If the emitter is behind one of the sensors, even if close to it, the uncertainty of the method increases drastically. Another constraint is that sensors cannot be positioned such that they fall on a straight line with the source. The practical applicability of the method on complex structures is

hindered by the requirement of a direct Line of Sight (LOS) between the sensors and the excitation.

d. Influence of reflection and background noise. If the direct Line of Sight (LOS) condition is not met, the vibration wave can only reach the sensors via reflection, traveling along multiple paths simultaneously. Each reflection can be considered an additional noise source, appearing as further peaks in the time signal, thereby complicating the determination of precise time delays. Reflection also occurs when the sound wave reaches the boundary of a different medium. The velocity of sound varies across different media; thus, homogeneous wave propagation - at a constant velocity within a given medium - cannot take place.

e. Modulated signals. In order to determine the relative displacement of the recorded time signals—that is, their arrival time differences at the sensors—the signal must not possess a random structure. Vibration sources also emit random white noise, whose structure does not allow for the determination of time delays required for the procedure. Repeating patterns present in the signal correspond to multiple similar time instants, making it difficult to determine the exact time offset between sensors during correlation calculation. The presented prewhitening method offers a remedy for the internal dependencies of the time signal; however, it is unable to bypass periodicity within the signal.

5.2 TDOA TESTING ON FLAT STEEL PLATE

During the investigations, our initial objective was to perform tests on a simple structure, such as a rectangular plate. The utilization of the simplified two-dimensional (2D) model was deemed important to uncover the influencing factors and capabilities of the procedure. In this stage of the investigations, artificial excitation was applied; impacts were delivered to the rectangular plate using an impulse hammer alternately at points P1 and P2. The dimensions of the rectangular plate are: 50 x 46 x 0.15 cm (length x width x thickness). During testing, the plate was positioned on foam pads attached to its four corners. The coordinate of the impulse delivered at position P1 (X30; Y15) can be determined via the source localization method with a deviation of 0.5 cm in the X-direction and 0.6 cm in the Y-direction.

However, the coordinates for the P2 (X10; Y26) impulse location are entirely inaccurate. The explanation for this lies in the geometric requirement imposed on the measurement, according to which the source of excitation must lie within the geometric

triangle described by the receiver sensors. If this condition is not met, determining the location of the source is impossible.

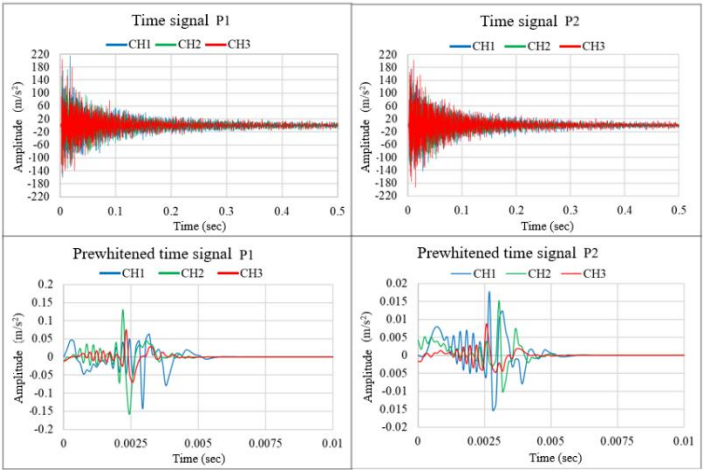


Figure 5.2.1. *Raw time signals and prewhitened vibration signals of CH1, CH2, CH3 impulse responses (blue, green, red) to excitation at points P1 and P2*

Thus, on a simplified model, the TDoA method can specify the origin of an artificial, single-source impulse-like excitation within an acceptable error margin in our chosen coordinate system, provided proper conditioning of the vibration signal is performed.

5.3 TDOA TESTING ON A BENT STEEL PLATE

As a continuation of the investigations, an L-shaped plate bent at 90° with a 60-40% structural proportion was developed (see Figure 5.3.1). The bending radius is 2 mm (R). The geometric dimensions of the plate are as follows: width W = 60 cm, height L = 100 cm, thickness h = 1 mm. The material of the plate is steel. The objective of the test was to verify the applicability of the TDoA method for a 3D structure and to validate the performance of the modified algorithm.

A relatively large deviation of 5 cm is observed in the X-direction, whereas the result in the Y-direction is acceptable, hovering around 2.5 cm. Thus, compared to the flat plate model, a larger deviation was experienced when determining the P2 source coordinates. The applied corrected calculation method shows an improvement of approximately 60% in the calculated coordinate values relative to the original relations.

We must take into account that the coordinate correction used due to violating the symmetry condition stems from the assumed position of the wave refraction (T) point; in reality, however, the exact path of the wave between the impact point and the sensors is unknow.

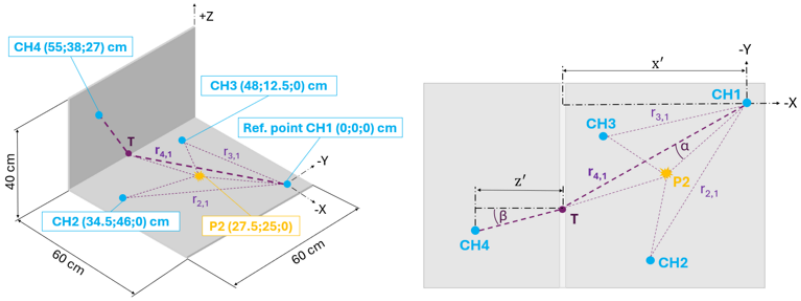


Figure 5.3.1. *Coordinates of measurement and excitation points on the bent steel plate and the unfolded view of the plate*

With increasing complexity of the mechanical model, physical wave propagation problems within solid bodies appear that are not typical in the method's original field of application. To address this, we further developed the currently applied SX method. The modification of the mathematical framework accounts for the differing propagation characteristics of distinct wave types, albeit via introducing a symmetry condition that complicates practical applicability.

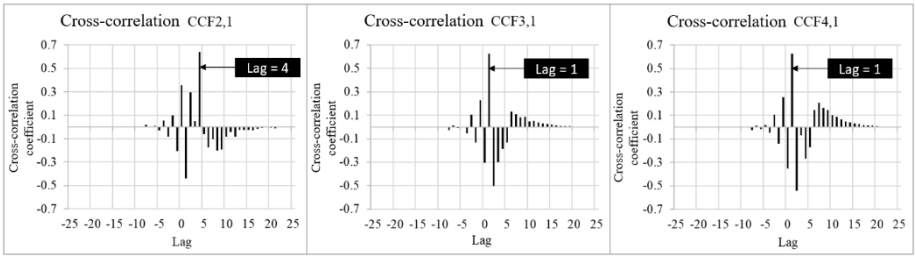


Figure 5.3.2. *Cross-correlation functions generated from measurement points (CH1…CH4) during excitation at position P2 on the L-shaped plate*

Ultimately, even a minor increase in the complexity of the investigated mechanical model leads to an increasing inaccuracy in the results of our developed TDoA-based source localization routine, and deviation that cannot be eliminated by the method in its current form.

5.4 TDOA TESTING ON A FORD FOCUS VEHICLE BODY

During the vehicle body investigation, TDoA measurements were performed across the entire vehicle as well as specifically on the hood. Analogous to the plate measurement, the body elements were excited at points P1, P2, P3, P4, and P5 using an impulse hammer. The raw time signal and force curve were recorded using the accelerometers (CH1, CH2, CH3). Resampling of the signal was performed at 4096 Hz in this case.

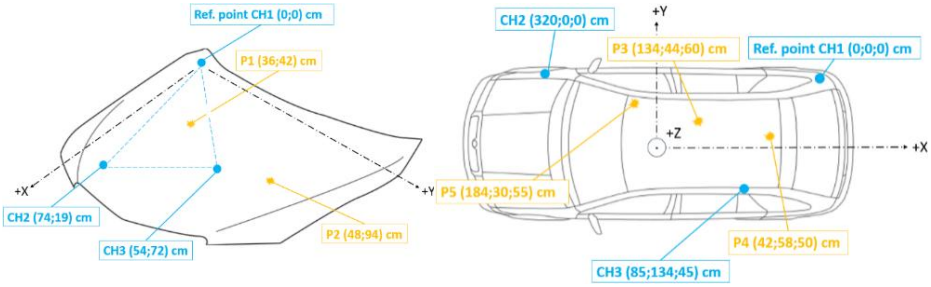


Figure 5.4.1. *Coordinates of measurement and excitation points on the hood and the complete vehicle body*

In the experiment conducted on the hood, we also applied an excitation point falling outside the geometric triangle bounded by the accelerometers positioned on the object. Consequently, determining the position of the P2 excitation point was not possible in this case either. Nevertheless, provided that the geometric condition is met, the source determination can be highly accurate. The X-direction position of point P1 was determined with an accuracy of 1 cm, and its Y-direction position with an accuracy of 0.8 cm.

Large deviations manifest in the coordinates relative to the real excitation position. An X-coordinate of 1.6 – 1.7 meters is obtained in all cases, and the Y-coordinate also specifies the position of the excitation points with high inaccuracy. The magnitude of the deviations is highly variable; the error cannot be said to be systematic.

The time delay value cannot be uniquely derived from the cross-correlation functions because the cross-correlation coefficient possesses multiple local maxima. The sensors were positioned on different body panels; thus, signal propagation did not take place continuously within a single component. Consequently, homogeneous wave propagation between the excitation points and the accelerometers was impossible. Vibration waves propagating across system boundaries - i.e., between components -

reached the sensors via multiple paths. Along the propagation paths (e.g., through spot welds or bonded joints across door hinges), components with differing attenuation characteristics presumably prevented homogeneous wave propagation at a constant velocity.

5.5 SUMMARY OF EXPERIMENTAL TDOA RESULTS

The theoretical foundation for adapting the source localization procedure to vibration signals was developed, and its functionality was demonstrated on a simplified mechanical model, namely a flat metal plate. Increasing the complexity of the mechanical model introduces phenomena and problems that were not relevant in the method's original domain of application, primarily linked to the characteristics of physical wave propagation within solid bodies. To manage these effects, the currently applied SX method was further developed. It allows for considering the differing propagation characteristics of distinct wave types, while simultaneously necessitating the introduction of a condition that significantly limits practical applicability. As a result, it was found that even a minor increase in the complexity of the investigated mechanical model leads to a degradation in the accuracy of our developed TDoA-based source localization procedure, a deviation that cannot be fully corrected in the method's current form. One of the main challenges of the localization procedure is to remain capable of proper positioning in Non-Line-of-Sight (NLOS) environments.

In its current state, the TDoA source localization method possesses numerous possibilities for further development. During signal preparation, the correct selection and appropriate tuning of the smoothing procedure depending on the signal type, as well as the parameterization of the ARIMA model, require further investigation. The quality of the residual signal conditioned via the prewhitening method significantly influences the correctness of the cross-correlation. For three-dimensional applications, a four-sensor measurement layout is required, and the algorithm had to be modified accordingly; however, extended experiments using four sensors did not yield more accurate results either. During the extension of the TDoA procedure to the field of vibration diagnostics, the possibility of measuring with microphones was raised. The advantage is that the dispersion of the vibration wave would not occur in an air medium. The disadvantage is that in many cases, the source of the audible noise phenomenon caused by malfunctions does not coincide with the physical location of the faulty component.

6. NEW SCIENTIFIC FINDINGS - THESIS

T1. Based on the investigations performed, I concluded that the time-domain, frequency-domain, and joint time-frequency-domain methods used in machine diagnostics are only of limited suitability for identifying mechanical faults occurring in a vehicle drivetrain and determining their location without dismantling the vehicle structure. Based on the conducted investigations, I conclude that it is more advantageous to apply a diagnostic method that does not identify a faulty component through the recognition of excitation fundamental frequencies (e.g., gear meshing frequency), but instead directly determines the location of the excitation generated by the fault within a vehicle-fixed coordinate system.

T2. Through real-world measurements performed on vehicles, I established that the metrics used in psychoacoustics, when reference measurements are available, are suitable for identifying an audible noise phenomenon occurring in a vehicle as a fault, even without determining its location or cause.

T3. Through measurements carried out on real test specimens and vehicle body structures, I demonstrated that the Time Difference of Arrival (TDoA) method may be suitable for determining the origin of mechanical waves generated by faults, even in complex structures, thereby enabling localization of the fault with adequate accuracy. Through measurements and the processing of measured vibration acceleration signals, I determined that, when applying the TDoA method to vehicles, preprocessing of the measured signals prior to analysis - specifically, signal “whitening” - is necessary. Furthermore, the algorithm requires further development so that it can handle anomalies arising during wave propagation within the vehicle body (e.g., reflections).

T4. Through measurements performed on a test specimen, I verified that the currently used source localization routine based on the SX method requires further development when certain structural and geometric configurations influence the propagation characteristics of vibration waves. I presented a modified algorithm capable of compensating, to a limited extent, for the localization errors of the method in the presence of specific geometric configurations. However, the modified mathematical framework requires the introduction of a symmetry condition, which limits its practical applicability.

7. LIST OF PUBLICATIONS RELATED TO THE RESEARCH TOPIC

[1] Kriston J. Balázs, Dr. Jálics Károly: **Meghibásodások lokalizálása vibro-akusztikus módszerekkel gépészeti szerkezetek esetén** - Localization of Failures with Vibro-Acoustical Methods in Case of Mechanical Structures, GÉP (0016-8572): 72 1-2 pp 31-35 (2021).

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[4] Kriston József Balázs, Jálics Károly: **Gépjármű sebességváltó meghibásodásának rezgésjeleken alapuló vizsgálata**, GÉP 73: 3-4 pp. 56-59., 4 p.(2022).

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