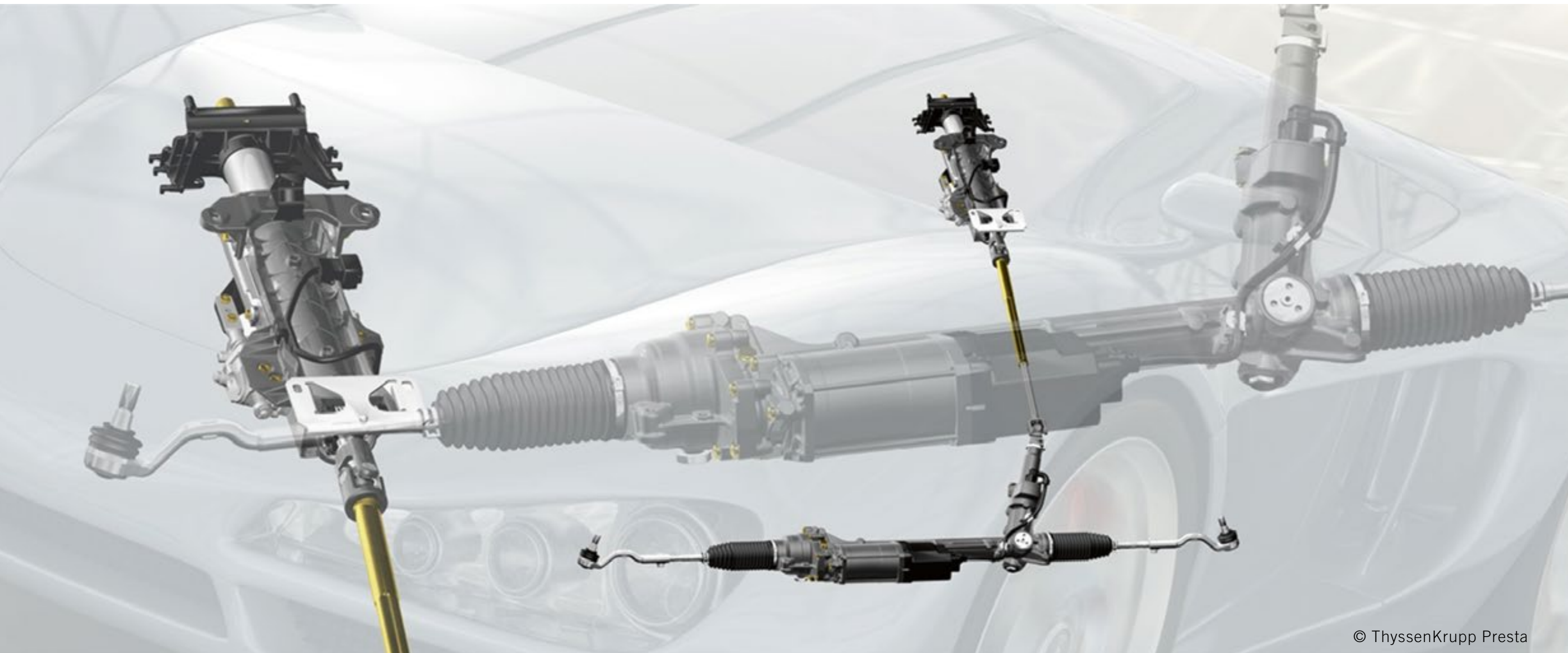

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Localising Defective Components with a Time-Reversal Approach

Traditional trial-and-error tests for identifying defective components in the steering system are inadequate in terms of the amount of time required and material costs. This article describes a new approach for the localisation, which is based on the time-reversal method. It could greatly improve standard processes, especially in terms of time efficiency.

INTRODUCTION

Acoustic performance is an indicator of comfort and quality in the automotive industry. Especially inside the vehicle, acoustic performance plays an important role. This performance is dominated by engine, wind and rolling noises. These noises are transmitted into the vehicle though different paths. One important transmission path is the steering system.

The steering system begins at the wishbones and ends at the steering wheel. It consists of two track rods, a steering gear, an intermediate shaft and a steering column. These components are characterised by bearings, gear units, sliding tubes and fixed joints. Through material wear as well as through material defects and/or production errors, the acoustic performance in the vehicle inte-

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rior can be strongly influenced by a defect in the steering system (e.g. squeak and rattle noises). Localisation of a defective component is usually performed by trial-and-error tests. However, these tests are inadequate due to the amount of time they require and material costs, especially during installation conditions. For this reason, time-reversal source detection is implemented in order to localise defective components in the steering system.

PROCESS OF TIME-REVERSAL SOURCE DETECTION

The time-reversal method was proposed in the 1980s [1, 2]. The main fields of application were in the bio-medical and military sectors. The method is based on the invariance of the equation of motion due to time reversal. However, the change in variable translating time reversal leads to a different behaviour for the damping term. Indeed, that term changes its sign after reversal, thus reflecting the fact that the energy previously lost cannot be recreated, equation 1.

Consequently, if reversed final conditions are applied, the vibration, by going back in time, describes the motions that ended in the final conditions. Thus, for point sources 'S_1' the created reversed waves '$R_{(A,B)}$' go back towards point source 'R_1', giving rise to focalisation, **FIGURE 1**. Focalisation means that a high vibration level following the wave converges at a specific position and time. The process of focalisation depends on structural parameters, such as damping and complexity. These parameters define the accuracy of this localisation method. Theoretically, the reversed final conditions must be reproduced at all points of a vibrating system. However, the boundary conditions play the role of virtual sources. That is why, for complex structures in particular, only one transmitter is sufficient [3].

The transient sources localisation method is based on focalisation detection applied to signals created by the time-reversal process at several areas.

$\tau = t$	$\tau = -t$
$M \frac{\partial^2 x}{\partial t^2} + \lambda \frac{\partial x}{\partial t} + Kx = 0$	$M \frac{\partial^2 x}{\partial t^2} - \lambda \frac{\partial x}{\partial t} + Kx = 0$

EQUATION 1 of motion by reversing the time

For practical reasons, signals are re-emitted virtually through a transfer function. This means that the localization process requires a 'learning step', in which a frequency transfer function database is acquired. This database defines the transfer function between sensors and areas of interest (learning areas). The second step is called the 'monitoring step', in which a signal is acquired during the operation condition. Finally, that signal goes back to start from the sensor position towards the learning areas. The virtual time-reversal process and focalisation make it possible to detect sources of vibration. Focalisation detection leads to an indicator value for every learning area. This indicator value is normalised through all areas in order to obtain a clearer and comparable result. The normalised indicator amplitude gives the probability of source localisation in a specific area. A representative output of a test with multiple signals in specific areas is shown in **FIGURE 2**.

TEST SPECIMENS

In the present case, the time-reversal approach is used to localise a very unpleasant defect in the steering system: a bearing defect on an intermediate shaft. An intermediate shaft is located between the steering gear and the steering column. This part is necessary to transmit the torque and the direction of rotation from the steering column to the steering gear and further to the front wheels. An intermediate shaft also transports feedback from the wheels to the driver about the driving conditions (road condition, driving performance, etc.). Normally, an intermediate shaft consists of two universal joints (rotational axes) and a sliding joint (translational axe), **FIGURE 3**. A defect in a universal joint (bearing) can lead to squeak and rattle noise. It can also lead to unpleasant vibration on the steering wheel. There is currently no efficient test procedure (with regard to time and material) for localising squeak and rattle noise in steering systems (all implemented components) under installation conditions. For that reason, the time-reversal approach will be tested.

METHODOLOGY

To verify and to test the applicability of the time-reversal localisation method for detecting defects on intermediate shafts, three different test conditions were implemented. First, the intermediate shaft was suspended on elastic ropes in an acoustic chamber, thus imposing free-free conditions. In this condition, up to four structure-borne sound sensors were installed for the 'learning step'. The positions of these sensors were randomly chosen. The learning signal was created by a shaker and/or an impact hammer on the areas of potential noise sources. These areas were the rotational axes of the two bearings. The 'learning steps' were used to generate the frequency response functions from each area of noise to the sensor positions. During the 'monitoring step', random impacts were

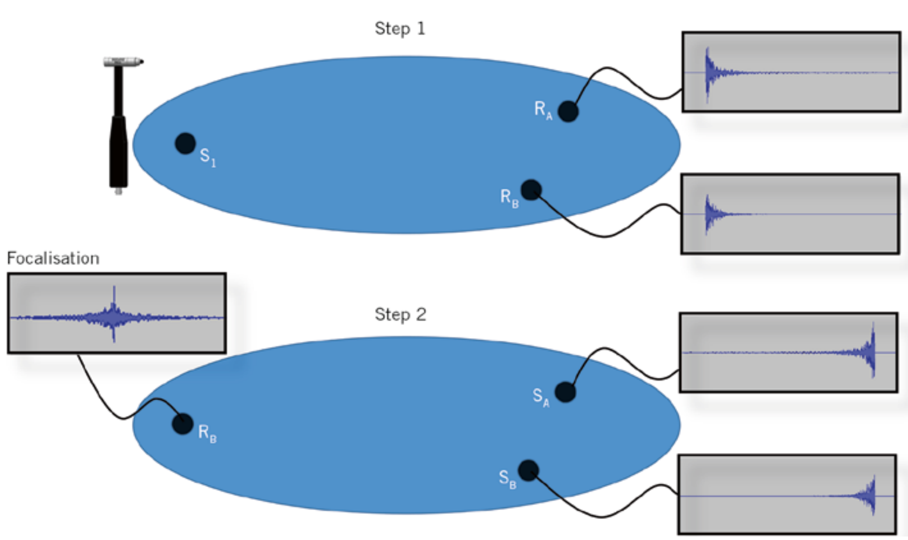

FIGURE 1 Time-reversal process (© ThyssenKrupp Presta)

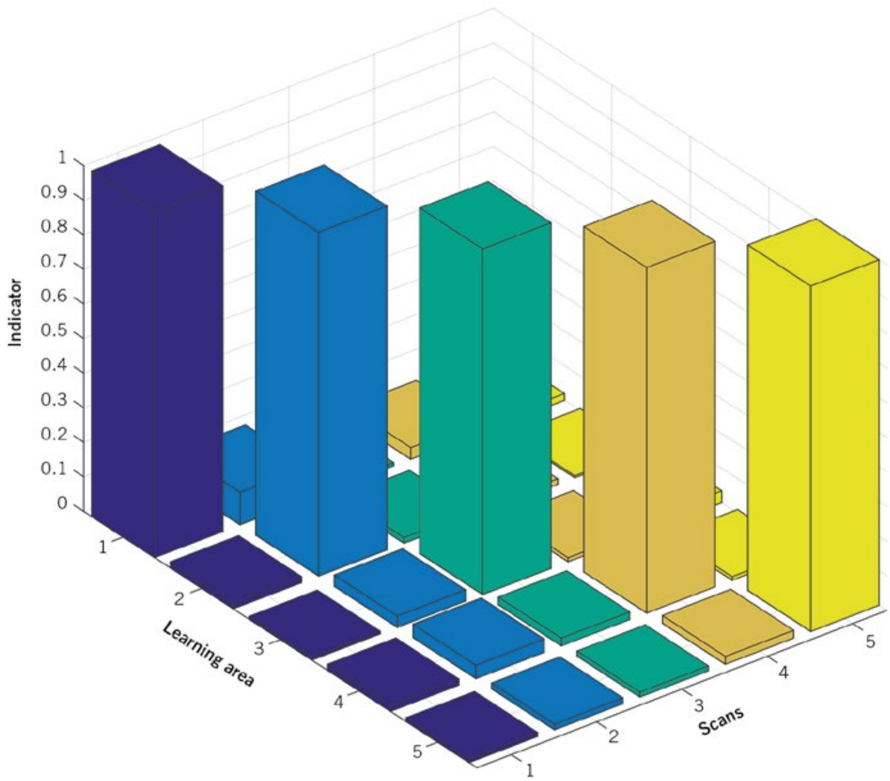

FIGURE 2 Focalisation indicator for multiple scans (© ThyssenKrupp Presta)

implemented on the different axes of the bearings. These signals were recorded and used for the virtual time-reversal process. Finally, the indicator value was calculated for each random impact in order to test the localisation function.

Secondly, the intermediate shafts were fixed on a test bench in an acoustic chamber. The intermediate shaft was connected on each side with a different fixture. Fixtures were combined with a shaker to apply different torques to the test objects. The excitation frequency of the shaker was constant at approximately 15 Hz. The second fixture holds the intermediate shaft in a stable position. During the 'learning step', the shaker was not in operation. The implemented structure-borne sound sensors were located as in the previous test. Afterwards, impacts were generated on the potential noise sources to generate the frequency response functions. Afterwards, the 'monitoring step' was performed. In this step, the shaker was operating and the accelerations were recorded on the sensor positions. The virtual time-reversal approach was used to calculate the indicator value. For these investigations, different intermediate shafts were analysed. The main focus was on an intermediate shaft with damage in only one bearing and an intermediate shaft without any damage. To investigate the influence of the test conditions, the fixtures could be attached on both sides of the intermediate shafts.

Finally, the test objects were implemented on a steering system in a test vehicle. During the 'learning step', two structure-borne sound sensors were integrated into the intermediate shaft. Due to difficult access, the sensors were placed in close proximity to the bearings on the intermediate shaft. The frequency response functions were calculated from impacts on the potential noise sources. Afterwards, the 'monitoring step' was performed by running the vehicle on a test track. The test track was characterised by a surface of cobblestones. The sensor signals of the acceleration sensors were used for the analysis using the time-reversal approach. This test was repeated several times to reduce measurement error.

RESULTS

The first investigation on a suspended intermediate shaft was necessary in order to examine the requirement conditions for the subsequent investigations. Examples of the test results are shown in **FIGURE 4**. During this test, impacts were generated on four different areas on the intermediate shafts. The normalised indicator value gives a clear overview of the location of the impacts. During further tests, the number of structure-borne sound sensors was reduced from four to two, but the indicator values clearly show the correct location of impacts. Furthermore, the reduction from four to two learning areas is sufficient to localise damage in bearings. With a reduction in the number of sensors and learning areas, efficiency with regard to the amount of time required and material consumption was improved.

During the second part, the test objects loaded with a torque were put on a test bench. Different intermediate shafts were analysed. In particular, an intermediate shaft with prepared bearing damage showed clear results with the time-

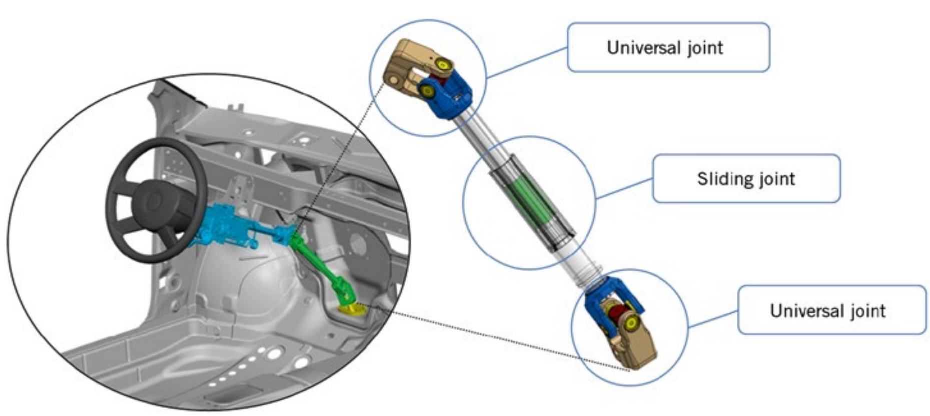

FIGURE 3 Components of a steering system (© ThyssenKrupp Presta)

reversal approach. Based on the reversed time signal, the indicator value shows the location of impacts caused by bearing damage. A representative result of the reversed time signal is shown in **FIGURE 5**. The virtual time-reversal signal was calculated and categorised according to focalisations. In order to validate the results, the intermediate shaft in the fixtures was mounted in the opposite way. The new measurements show that the damage was again on the right side of the damaged bearing. This means that the test fixture has no fundamental influence on the test results. Furthermore, during the test with a damage-free intermediate shaft, the outcome of the indicator value is comparable on each of the learning areas. Thus, no illusory damage is indicated by the time-reversal method.

Compared to test bench investigations, tests in operating conditions have different specifications. Firstly, unwanted noise can come from other elements. Theoretically, the focalisation process allows the signal level from the learning area to be increased, which consequently overrides the unwanted noise. Secondly, the boundary conditions were modified in operating conditions. In both tests, the

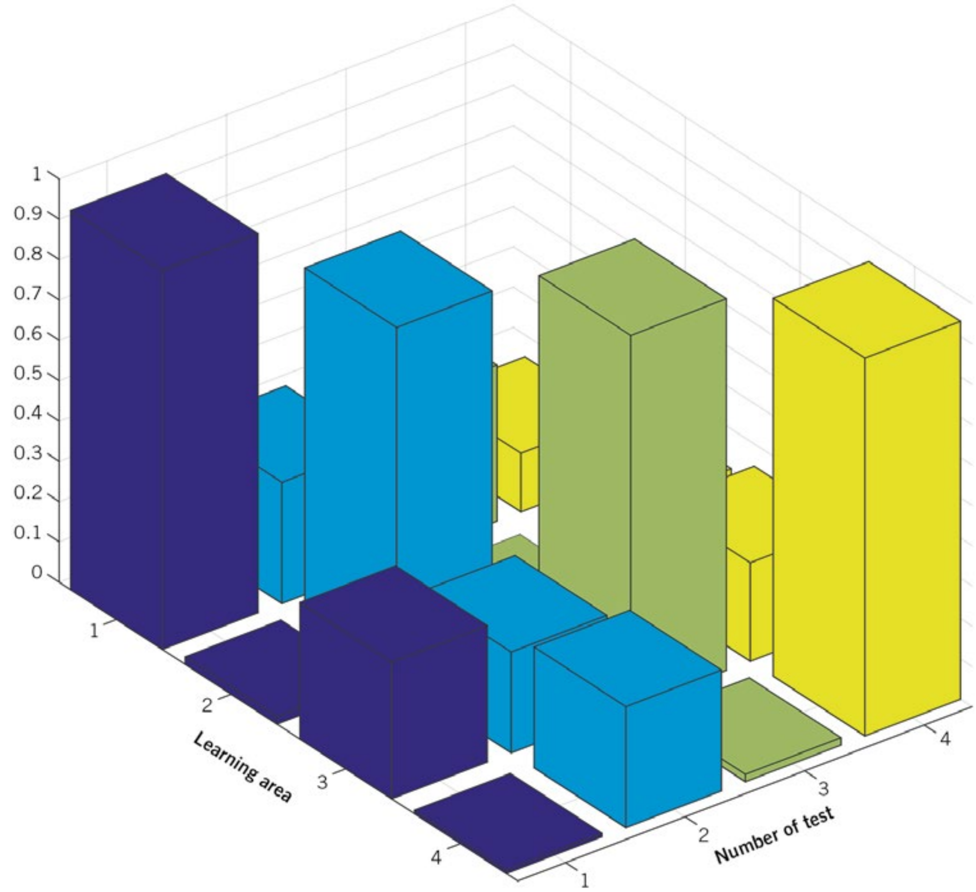

FIGURE 4 Localisation indicator for “suspension” test (© ThyssenKrupp Presta)

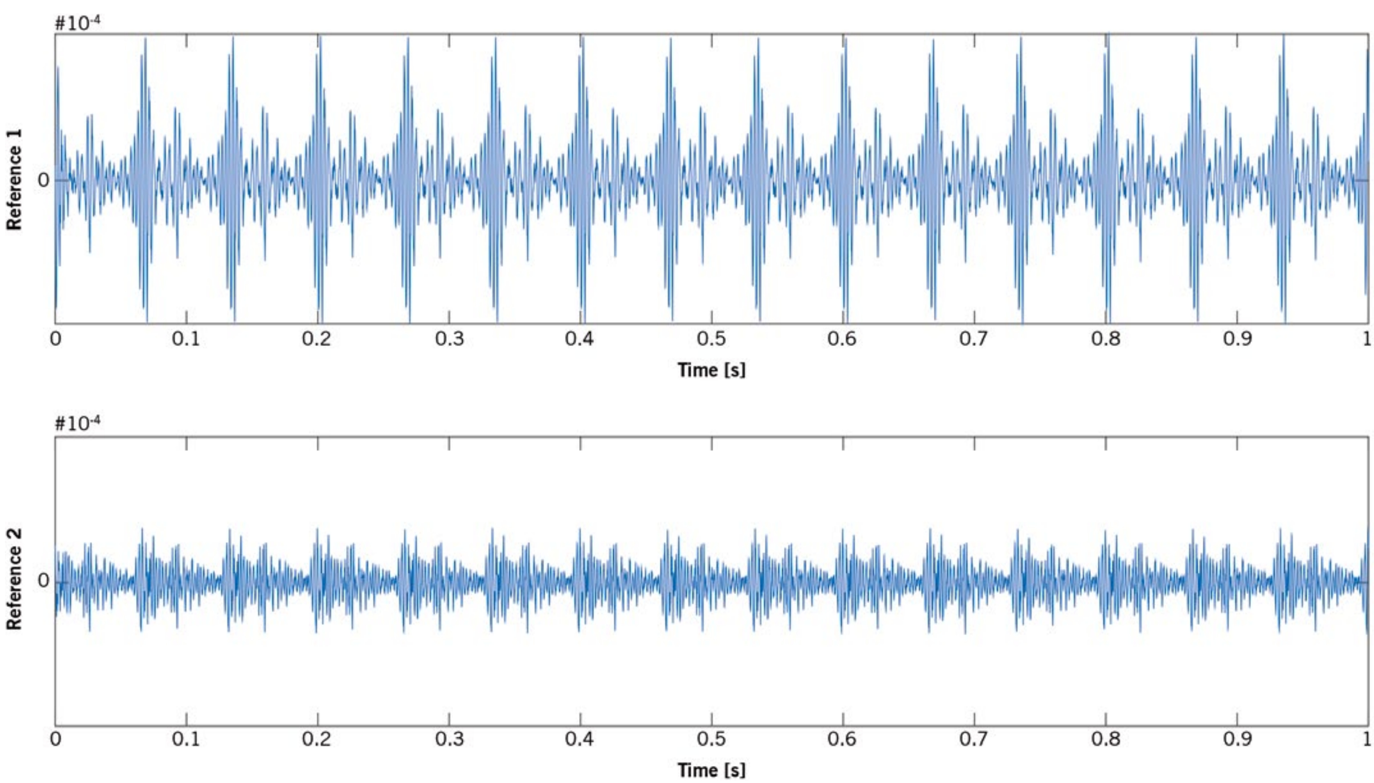

FIGURE 5 Calculated time-reversed signal to detect focalisation on a test bench (reference 1: indicator for a defect; reference 2: indicator for no defect) (© ThyssenKrupp Presta)

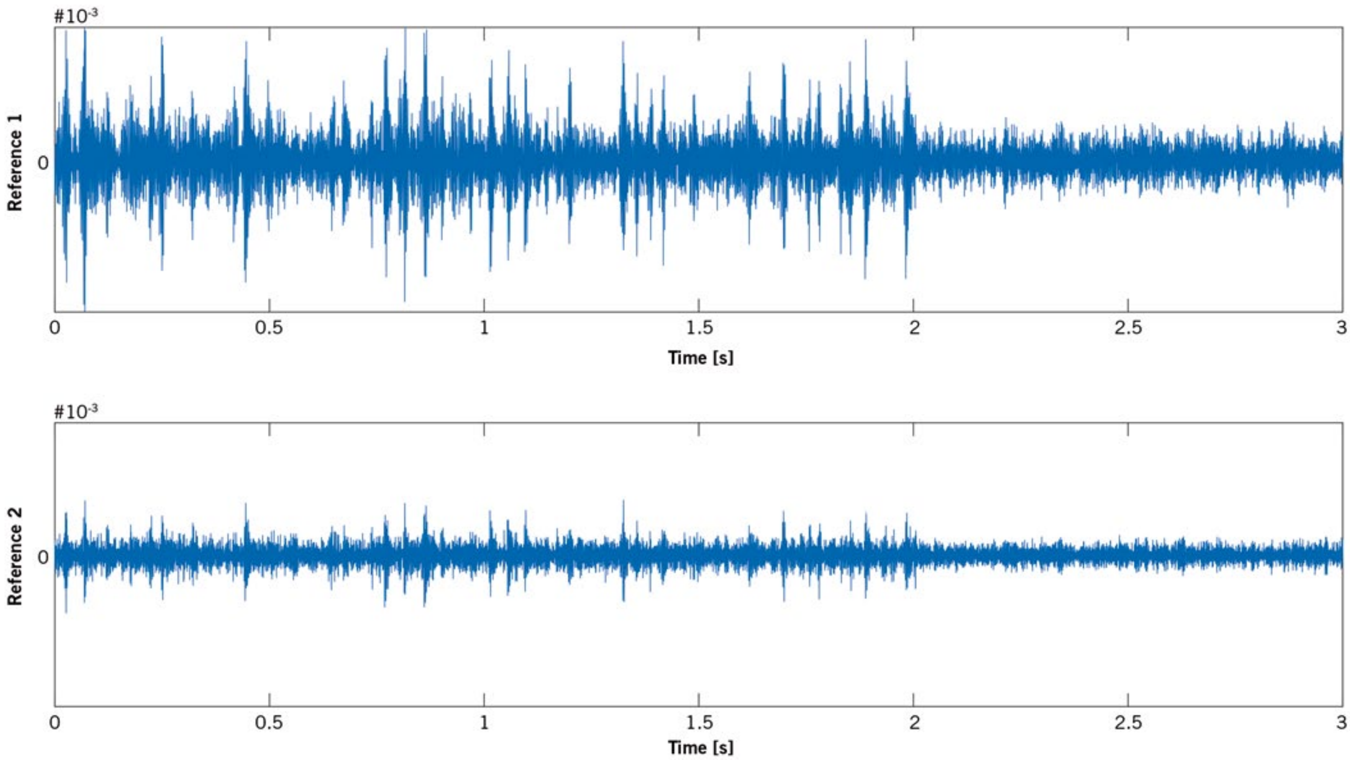

FIGURE 6 Calculated time-reversed signal to detect focalisation on a test track (reference 1: indicator for a defect; reference 2: indicator for no defect) (© ThyssenKrupp Presta)

outcomes of the virtual time-reversal signal and the normalised indicator show consistent results. Localisations of defective areas are shown in **FIGURE 6**. Moreover, the focalisation signal shows several focalisation peaks, which corresponds to the number of cobblestones on the test track. In conclusion: squeaks and rattles generated by the defective articulation component were correctly detected and localised with time-reversal source detection.

SUMMARY AND OUTLOOK

Acoustic performance in a vehicle interior can be strongly influenced by a defect in the steering system (e.g. squeak and rattle noise). At the moment, localisation of the defective component is usually performed by trial-and-error tests. However, these tests are inadequate in terms of the amount of time required and material costs.

As shown, the new approach, which is based on the time-reversal method, could greatly improve standard processes, especially in terms of time efficiency. The implementation was separated into three parts. Firstly, intermediate shafts were tested in a suspended condition. Several impacts could be clearly localised using the time-reversal approach. Secondly, the intermediate shafts were placed on a test bench to generate squeak and rattle noises by stimulation with a shaker. The defective area was localised and several focalisations produced by squeak and rattle shocks were observed. Intermediate shafts with no damage do not show focalisations in a specific learning area. Finally, an intermediate shaft was installed in a vehicle to investigate squeaks and rattles in operating conditions. The results were similar to the previous ones on the test bench. The localisation process clearly indicates the defective area and shows several focalisations resulting from squeaks and rattles.

In the next step, the learning areas for the time-reversal approach will be enlarged. Noise processing areas on a steering gear and a steering column will be integrated into the described measurement surroundings. These integrations will help to facilitate localisation and provide more precise measurement of noise sources in a system as complex as the steering system. In addition, a further reduction in the implemented structure-borne sound sensors will help to reduce the time required for this test.

This report has highlighted the application of the time-reversal approach to the detection of noise in the steering system. The door has now been opened for using the time-reversal approach to tackle other acoustic challenges.

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