INVESTIGATION OF THE TIME DELAY OF ARRIVAL (TDOA) METHOD FOR DIAGNOSTIC PURPOSES ON MOTOR VEHICLES

A BEÉRKEZÉSI IDŐKÜLÖNBSÉGEK MÓDSZER (TDOA) DIAGNOSZTIKAI CÉLÚ ALKALMAZÁSA GÉPJÁRMŰVEKEN

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A gép mechanikai meghibásodásának kimutatására számos akusztikus és vibrációs módszer létezik. A gépjárműveknél azonban ez a fajta diagnosztika nem elterjedt. Ennek oka a belső égésű motor, a segédberendezések, a hajtáslánc, a gördülési zaj és az áramlás okozta zaj és rezgés okozta meglehetősen összetett zaj- és rezgésviselkedés működés közben. Ez a cikk a beérkezési időkülönbségek módszerével foglalkozik gépjárművek diagnosztikai céljára. Bemutatjuk a módszer főbb jellemzőit, és a módszert először egyetlen téglalap alakú acéllemezre, valamint személygépkocsi karosszériájára is alkalmazzuk impulzuskalapáccsal szimulált hibaforrásokkal végzett kísérletek során. Három lehetőséget mutatunk be az érzékelők közötti időkésések számításához: a keresztkorrelációs módszert, az általánosított keresztkorrelációs módszert és a küszöbátlépési módszert. Az időkésések alapján kiszámítjuk a szimulált hiba számított koordinátáját és összehasonlítjuk a tényleges értékkel. Következtetések vonunk le, és a jövőbeli munkára vonatkozó ötletek is bemutatásra kerülnek.

1. INTRODUCTION

Present day the vibroacoustic diagnostics is used widespread by the diagnostics of industrial machines. Performing vibration measurements on the machine the faulty part (e.g. roller bearings, gears etc) can be identified, resp. a possible replacement date of that part can be determined if several previous measurements data sets are existing.

On the other hand, the vibroacoustic diagnostics is not used on motor vehicles and very few literatures [1], [3] are existing which are handling that problem. The reason is quite simple: a motor vehicle is a very complex system containing sub-systems as the car body, the internal combustion engine, the powertrain (incl. clutch, gearbox, shafts, differential etc.) and the chassis. These components containing a lot of parts, and they also produce a wide spectrum excitation. Several excitations are existing at the same time, and the excitations coming from the components can interfere with each other, so the discrimination between the sources is nearly not possible.

This is leading us to the idea not to concentrate directly on the failure (which component has a failure, what type of failure), but we should concentrate on the localization of the failure in a vehicle-bound coordinate system. So, we do not say which component is defect, but we say where approx. the failure (coordinates) is. If we know the coordinates, we can simply isolate the defect part.

For that purpose, the so-called Time Delay of Arrival method will be adapted and investigated.

2. THE METHOD

The method itself is not new, its various versions have been used for a long time in many fields of science and technology. Seismology, where the epicentre of earthquakes is determined using this method, GPS-based navigation, acoustic emission testing of materials, military applications such as e.g. determining the position of the gunshot. In connection with these, many specialized literatures deal with the method and its use in these areas. In many areas, raising problems is relatively simple, since e.g. in the case of GPS signals, the propagation is normally not limited by anything between the transmitter (satellite) and the receiver, we work with a homogeneous medium in terms of wave propagation. The acoustic emission test is a more complex application because the wave propagation takes place in a solid medium, or the geometric structure of the examined objects (components, subassemblies) can be more complex.

Using this method in the case of vehicles, we face the problem that the car body has a complex structure and does not allow homogeneous wave propagation furthermore several types of waves can propagate. Our

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aim is therefore to examine the usability of the TDoA method in the case of car bodies.

3. THE TESTS

During the investigations our intention was to perform first tests on a simple structure, like a rectangular plate and after that, similar test on a more complex structure, like a car body. In this phase of the investigations artificial excitation was utilized. This means on the rectangular plate and on the car body the component failure was simulated by an impact hammer hit on defined positions of the plate, resp. on the car body. In addition, in both cases three accelerometers in defined positions were put on the structures. One of the accelerometers (CH1) was declared as reference point with the coordinates 0 cm; 0 cm; 0 cm. The sensor and the excitation positions were defined randomly. The dimensions of the rectangular plate were 500 x 460 x 1,5 mm (Length x Width x Thickness). The car that was used for the test was a Ford Focus Mk1.

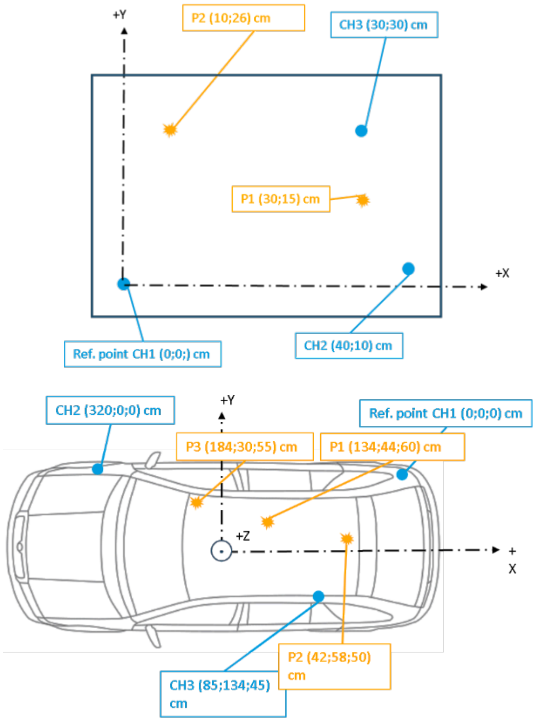

Figure 1. Measurement and excitation point positions (with coordinates) on the plate (left) and on the car body (right)

During the first tests the plate was hit by the impact hammer in the positions P1, P2 and the impulse responses were measured by the accelerometers (CH1 – CH3). The data acquisition was done by a B&K Photon+ 4 channel DAQ with different sampling frequencies. Started with 20 kHz sampling frequency, the values were increased by approx. 20 kHz steps until the capabilities of the DAQ board 192 kHz is reached.

Due to the different geometric distances between excitation point and response points the time delay of arrival could be measured in both cases. An example is shown in figure 2, where first few milliseconds of the 4 recorded time signals are represented. The blue signal represents the excitation, the force signal of the impact hammer. This signal arises as first, followed by the three accelerometer signals with certain time delays.

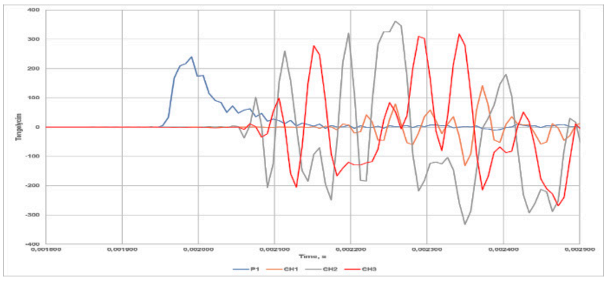

Figure 2. Time signal of excitation (blue) and responses (yellow, grey, red) recorded with 132 kHz sampling frequency on a rectangular steel plate

Our goal is to identify the time differences of arrival of the accelerometer signals, referenced on the reference accelerometer. Methods are present for that purpose, which were applied on the measurement raw data. For that purpose, a GNU/Octave code was written which could read the time signals and performs the necessary mathematical calculations [2] on the imported data.

First, the well-known cross-correlation method was implemented and tested. The Octave's (and Matlab's) built-in function Xcorr was used. During signal processing, the cross-correlation function Rxy(m) is used to describe the correlation of two different signals x(t) and y(t) at different time offsets τ between the two signals. The operation provides information about the similarity between two signals, it shows the extent to which one signal contains the other. The time shift of the two signals is ultimately obtained by finding the x coordinate of the maximum location of the cross-correlation function.

Second, the Generalized Cross Correlation (GCC) method was implemented. To do this, CH1, CH2 and CH3 signals are transformed into the frequency domain, then the complex spectrum of CH1 is multiplied by the complex conjugate spectrum of CH2, (and with CH3 respectively) which produces the so-called cross power spectrums. With the inverse FFT transformation of the crosspower spectrums the cross-correlation functions are obtained. By finding the maximum values of this functions, the time delays can be found like by the first method.

The third method that was implemented in Octave is based on the finding of the first threshold crossing. If the signal starts to rise it crosses a pre-defined threshold level (figure 3).

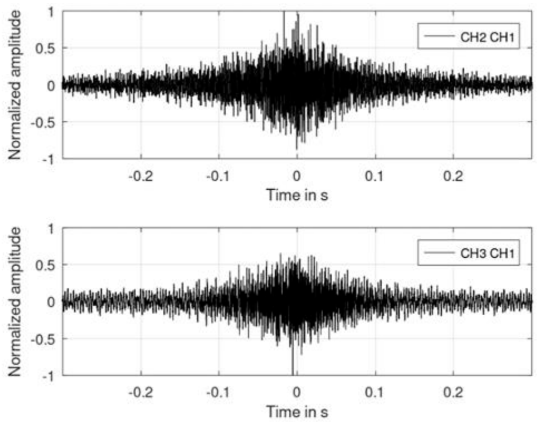

Figure 3. The cross-correlation function in case of the plate for the 1st excitation point (P1)

The time coordinate of the first threshold crossing gives the signal arrival time. Based on the arrival times the arrival time differences between the reference sensor and all other sensors can be calculated. The finding of the threshold crossing is widely used e.g. in the Acoustic Emission (AE) testing. After the tests with the rectangular plate were done the measurement and the analysis were repeated also on the car body. In this case although only by 20 kHz sampling frequency.

4. RESULTS OF THE SOURCE LOCALIZATION

First, we show the time delay (TD) results with the three investigated methods on the simple rectangular plate for excitation point 1 (P1). The TD results are shown Table 1.

Method	TD [s] CH1 to CH2	TD [s] CH1 to CH3
Cross-Corr.	*0,0169922*	*0,0183105*
Generalized C-C.	*0,0060058*	*0,0056640*
Threshold crossing	*0,000145*	*0,000137*

Table 1. Time delay (TD) results of the three methods on the rectangular plate for excitation point 1 (P1).

We can see on the table that the TD results have deviation between the methods. Performing the source localization calculations only for the threshold crossing method, we obtain 23 cm on the x axis and 13 cm on the y axis related to figure 1. The actual position of the excitation point is 30 cm, resp. 15 cm. Compared the result with the actual excitation point coordinates we can state that the experimental determined results could deliver the excitation point coordinates within a sufficient accuracy. The coordinate calculation results are not shown here since the TD values are one or two decimals larger, so they would deliver source coordinate values in the range of several dozen meters, which is not allowable. Next, in Table 2 the TD coordinates results on the car body will be shown, but now without the Cross-correlation method.

Method	TD [s] CH1 to CH2	TD [s] CH1 to CH3
Generalized C-C.	*0,00097656*	*0,0098419*
Threshold crossing	*0,0009613*	*0,0015259*

Table 2. Time delay (TD) results of the two methods on the car body for excitation point 3 (P3)

The TD results are closer to each other in case of the car body. The coordinates of the excitation point's x coordinates are 1,62 m for the GCC method and 1,79 m for the threshold method. The actual value is 1,84 m. The coordinates of the excitation point's y coordinates are 5,2 m for the GCC method and 0,46 m for the threshold method. The actual value is 0,3 m. Although the GCC method estimates the x coordinate quite well, the y coordinate is significantly larger than it should be. However, the threshold method estimates booth coordinates very well.

5. WAVE PROPAGATION IN COMPLEX STRUCTURES

The wave propagation in solid structures can be more complex as in fluids (e.g. gases and liquids). In fluids only longitudinal(pressure) waves are propagating. The propagation speed (speed of sound) in this case are cl = 340 m/s for air, resp. cl = 1440 m/s for water. In steel the propagation speed is cl = 5900 m/s.

In solid flexible structures every type of waves can propagate; longitudinal (pressure), transversal (shear, bending, Rayleigh, Love). The propagation speed is different for the wave types. For shear waves the propagation speed is given by the following formula:

$$c_T = \sqrt{\frac{G}{\rho}}\ where\ G = \frac{E}{2(1+\nu)} \qquad (1)$$

G is the shear modulus; E is the Young's modulus and ν is the Poisson-number. For steel the propagation speed given by the formula is $c_t = 3200$ m/s. On the other hand, the actual speed of propagation in plate-like components, such as the investigated bodywork elements, is strongly frequency-dependent. That frequency dependence is called dispersion. The propagation speed (phase speed) for plate-like components can be calculated as follows:

$$c_b = \sqrt[4]{\frac{B}{\rho h}\omega^2} \; where \; B = \frac{h^3}{12}\cdot\frac{E}{1-\nu^2} \qquad (2)$$

B is the bending stiffness, h is the thickness of the plate, ρ is the density of the plate's material and ω is the circular frequency [4]. Performing the above calculation for bending waves with the parameters h = 1,5 mm, E = 210000 Mpa, ν = 0,3, rho = 7850 kg/m^3, for the propagation speed the following frequency dependent curve can be obtained as shown in figure 3.

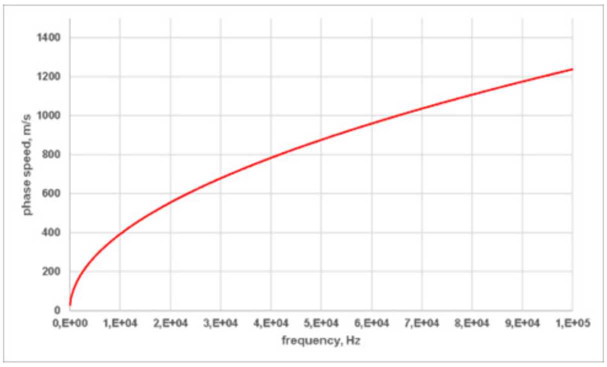

Figure 3. Dispersion curve of the bending wave propagation

Since the analysis shown in this paper were taken by the sampling frequency of 132 kHz (on the plate), acc. to the diagram in figure 3 an approximate propagation speed of 500 - 600 m/s could be considered. Also, similar speed range can be considered for the propagation in the plates in the car body.

The impulse responses shown in figure 2 are a good proof for the existence of dispersion. If there was no dispersion, the responses should have a similar shape and length as the excitation signal. But the responses have clearly different shapes and length, the response signals stretching over the time axis.

6. SIGNIFICANCE OF SAMPLING FREQUENCY

Sampling rate is a key factor in determining spatial resolution thus this also must be investigated along the source localisation. The sampling rate is the number of I/Q data pairs collected per second. This is, by definition, the temporal resolution: the temporal distance of the sample data points. The time distance between two samples is multiplied by the wave propagation speed to obtain the spatial resolution. Thus, the spatial resolution is directly proportional to the temporal resolution. Assume that the sampling frequency is fs = 20 kHz. The temporal distance between the samples is thus 50 µs. Multiplying this by the real wave propagation speed (500 m/s), the spatial resolution is 0,025 m (2,5 cm). Doubling the sampling frequency (40 kHz) results the half resolution (1,25 cm).

In our case a higher accuracy than 10 cm is not necessary, so for our purposes a sampling rate of 20 kHz is more than enough. A significantly higher sampling rate (in MHz range) makes only sense in cases where radio waves are propagating with the speed of light. There the radio waves can propagate high distances in a very short time (between two samples) if also we do not have very high sampling rate the accuracy of the source localisation will be unsatisfactory (in several hundred m to km range!).

7. SUMMARY

As shown in previous chapters the method, especially with the threshold crossing method, can find the location of an artificial excitation point (the proposed defect or failure) with an accuracy which is suitable for a failure detection on motor vehicles. The method used until now is quite simple, does not require special measurement technique.

Nevertheless, further investigations must be performed, since the other noise and vibration sources (e.g. internal combustion engine, gearbox, rolling noise etc.) on an operating motor vehicle can mask the signal. The time coordinate where the failure signal starts to rise, resp. the threshold crossing point cannot be found, only with large effort, using additional methods or algorithms such as e.g. pre-whiten the signal. Our next investigation aims this, we perform similar measurements on the rectangular plate excited with white noise by an electrodynamic shaker, respectively on an operating motor vehicle. In addition, we apply a filtering, pre-whitening algorithm on the raw time signals, to get suitable signals for the correlation calculations.

7. REFERNECES

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