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RAILWAY SOUND SOURCE SEPARATION BY COMBINED SOUND PRESSURE AND SOUND VELOCITY MEASUREMENTS

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Abstract

A concept for sound source measurements is presented which is based on the combination of a pressure microphone with one or two velocity sensors. As the sensitivity of the velocity sensors depends on the cosine of the angle of sound incidence they can be used in the far field as directional microphones. This allows for a direct focusing on distinct regions of complex sound sources respectively a suppression of unwanted contributions. Alternatively sound source identification and separation can be done by establishing a system of sound propagation equations for each measurement signal. It is shown that this system of equations can be solved for up to six sound sources. With a suitable optimization strategy during signal analysis not only sound power but also the positions of the sources can be derived. Simulations though show that measurement uncertainties limit the number of sound sources that can successfully be separated. The method has been developed and tested for measuring train pass-bys. So far measurements have been performed at travelling speeds of 50 to 220 km/h. Further tests are planned at speeds around 300 km/h. Velocity sensors based on pressure gradients as well as recently developed sensors of the type Microflown have been used. The later are based on the measurement principle of a hot wire anemometer. As a consequence of the high miniaturisation a pressure sensor as well as three velocity sensors can be combined in a single probe.

INTRODUCTION

The primary sound source in railway noise is rolling noise. Rolling noise is caused by vibrations from wheels, rails and sleepers that are generated by the combined roughness of wheel and rail running surfaces. Common calculation models and measurement procedures restrain

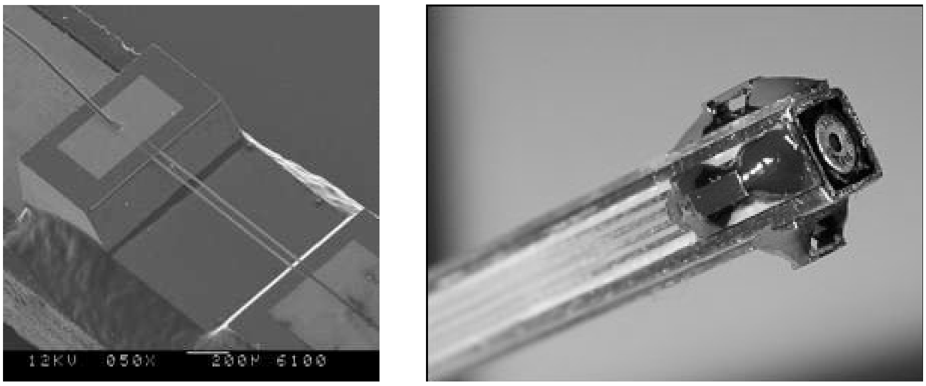

Figure 1: The left figure shows the core of the Microflown velocity sensor: Two platin-wires of 200 nm thickness that are attached to mounting plate of 1 mm length and 5 μm width. In the right figure a three dimensional probe type USP is depicted with three velocity sensors with a cartesian orientation and a 0.1" sound pressure microphone in the centre. For measuring purposes the sensors are covered by a protective cap. (figures from [3])

to describing and measuring this sound source [8], [10]. In order to achieve an increased accuracy, particularly with regard to action planning it is crucial not only to model rolling noise but also additional sound sources stemming from traction noise, fan noise or aerodynamic noise. The importance of these secondary sources varies from type of train and travelling speed and their sound power is generally inferior to rolling noise sources over a vast range of speeds. But as these sound sources are often located in the upper part of the vehicles their contributions can nevertheless become dominant in combination with barriers.

A measurement method that allows the detection of these secondary sources even when the overall sound exposure is dominated by rolling noise are microphone arrays. This measurement technique has been successfully applied to railway noise in several different variations [1], [2], [6], [7]. As a consequence of the great number of microphones involved and the elaborate data analysis the conduction of array measurements is though generally very expensive. These high costs in combination with the complexity of the method make an application on a regular broader basis seem unlikely. Therefore an alternative approach has been developed for the detection of spatially separated contributions of complex sound sources.

MEASUREMENT SENSORS

The basic idea of the measurement method is to combine sound pressure microphones with sensors with a strong directivity in order to suppress signals from distinct parts of the vehicle. Directional microphones as cardioid microphones or microphones with a figure of eight polar pattern, which are commonly used in audio applications, show frequency dependent directivity patterns that are not precise enough for emission measurements. A higher accuracy is

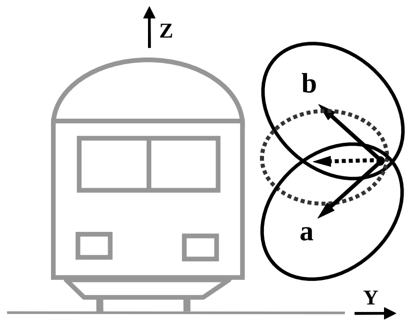

*Figure 2: Sketch of the measurement setup with two velocity sensors. The continuously drawn arrows show the orientation of the velocity sensors **a** and **b**. The dotted arrow indicates the orientation of the virtual sensor resulting from the multiplication of the signals **a** and **b**.*

provided by two types of sound velocity probes.

- A measurement principle that is known for several decades and is successfully applied for sound intensity and sound power measurements deduces sound velocity from the sound pressure gradient between two microphones (see for example [4]).
- Only available for a few years are probes of the type Microflown. They represent a further development of mass flow sensors and consist of two heated wires. Sound velocity is directly deduced from the temperature difference between the wires, measured by the resistance. As can be seen in figure 1 the sensors can be highly minimized which allows to combine three velocity sensors and a sound pressure microphone in a single probe. The sensors offer a broad field of application in the far as well as the near field and are for example successfully utilized in the automobile industry (for further details see [3]).

The velocity probes measure the projection of the sound velocity vector onto the orientation of the sensor, resulting in a cosine directivity pattern.

MEASUREMENT AND ANALYSIS CONCEPT

The measurement concept is based on the combined gathering of signals from a pressure microphone and either one or two velocity sensors. The following explanations concentrate on the case with two velocity sensors.
For measuring purposes the probe has to be placed in a way that the two velocity sensors point at the lowest and at the highest possible source position in the vehicle profile as indicated in figure 2. While sensor a is insensitive to contributions from the roof section, sensor b suppresses signals from the rail-wheel-area.
The measurement position can be optimized according to the properties of the sources and does not necessarily feature angles of 45 degrees of the velocity sensors as shown in figure

2. An optimized position for the identification of sources in the roof section was found at a height of 3.5 m above track level and a distance of 3.25 m from the centre of the track. Using this measurement position the two velocity have to be tilted downwards by 10 degrees relative to the orientation in figure 2 to still yield a maximum suppression of the rail-wheel-area.
From the three basic signals six level quantities can be derived: one sound pressure level, two sound intensity levels and three sound velocity levels. While two velocity levels result from squaring the signals, the third is calculated by their multiplication. This virtual sensor has a directivity pattern of a quadrupole which features its highest sensitivity 45 degrees rotated regarding the orientation of the velocity sensors, as indicated in figure 2.
Disregarding sound propagation effects as air absorption and ground effect, equations 1 to 3 give an analytical solution of the integration for the pass-by of a point source for sound pressure square, sound intensity and the product of two sound velocities. As a consequence of the small measuring distances and sensor positions high above ground the influence of these sound propagation effects is small and a neglecting therefore seems admissible. As indicated by the factor 2π it is assumed that sound is radiated in a half sphere. In the equations the velocity signals are labelled with a and b. The equations are though valid for any combination of velocity signals. The integration should ideally be done from the middle of one coach to the middle of the succeeding one under the condition that at least two coaches of the same type are operated consecutively (see [5]).

$$\int p^2(t)\,dt = \frac{W\cdot\rho c}{2\pi}\int\frac{1}{r^2(t)}\,dt = \frac{W\cdot\rho c}{\pi\cdot u\cdot d}\,\arctan\left(\frac{uT}{2d}\right) \tag{1}$$

$$\int p(t)\,v_a(t)\,dt = \frac{W}{2\pi}\int\frac{\cos(\theta_a(t))}{r^2(t)}\,dt =$$
$$\frac{W}{2\pi}\left[\Delta h\cdot\cos(\gamma)+\Delta v\cdot\sin(\gamma)\right]\left[\frac{T\left(1+\frac{(uT)^2}{4d^2}\right)}{\left[d^2+(\frac{uT}{2})^2)\right]^{1.5}}\right] \tag{2}$$

$$\int v_a(t)\,v_b(t)\,dt = \frac{W}{2\pi\cdot\rho c}\int\frac{\cos(\theta_a(t))\cos(\theta_b(t))}{r^2(t)}\,dt =$$
$$\frac{W}{4\pi\cdot\rho c}\left[\Delta h\cdot\cos(\gamma_a)+\Delta v\cdot\sin(\gamma_a)\right]\left[\Delta h\cdot\cos(\gamma_b)+\Delta v\cdot\sin(\gamma_b)\right]\cdot$$
$$\left[\frac{T}{d^2\left[d^2+\left(\frac{uT}{2}\right)^2\right]}+\frac{2\arctan\left(\frac{uT}{2d}\right)}{d^3u}\right] \tag{3}$$

Equations 1 to 3 can be combined to a system of equations that can theoretically be solved for up to six separate sound sources. If less sources shall be separated the remaining measurement signals can be used to test the found solution. By simulating the measured signals with the resulting sound sources a comparison with the measurement is possible.
This strategy can be used not only to find the sound power of the sources but to optimize the source positions as well. By calculating all possible combinations of source positions the

solution can be found that fits best the measured data. As not only the sound power but also the source position is unknown the number of free variables is doubled and therefore the maximum number of sources that can be separated is reduced to three.

$$\int p^2(t)\, dt = \sum_{n=1}^{N} \frac{W_n \cdot \rho c}{2\pi} \int \frac{1}{r_n^2(t)}\, dt \tag{4}$$

$$\int p(t)\; v_a(t)\, dt = \sum_{n=1}^{N} \frac{W_n}{2\pi} \int \frac{\cos(\theta_{an}(t))}{r_n^2(t)}\, dt \tag{5}$$

$$\int v_a(t)\; v_b(t)\, dt = \sum_{n=1}^{N} \frac{W_n}{2\pi \cdot \rho c} \int \frac{\cos(\theta_{an}(t))\cos(\theta_{bn}(t))}{r_n^2(t)}\, dt \tag{6}$$

In numerical tests with differing source positions and sound powers the behaviour of the algorithms in the presence of measurement uncertainties has been studied. It was shown that uncertainties primarily affect the positioning of the sources. The results indicate also that the variance of sound power increases the more sources are separated. It is therefore recommended to restrain the number of sources to three with known source positions and to two if the positions have to be optimized as well. For test series with variations of the positioning of the probe by $\pm$ 0.1 m, the orientation of the probe by $\pm$ 1 degree and the measured level by $\pm$ 1 dB, the difference between true and calculated source powers was less than 0.1 dB and the standard deviations were below 1 dB for both sources.

MEASUREMENT RESULTS

The measurement method has been tested on several occasions already but further analysis and testing is planned. Two measurement results shall be presented in order to show the abilities of the method and the type of results that can be gathered.

Identification of a loudspeaker on a freight train

A loudspeaker was placed on a freight train, that passed the measurement section 14 times with speeds of 50, 80 and 100 km/h. The loudspeaker was operated by a radio signal transmitted from the measurement position with pink noise of different level. The loudspeaker signal was varied over a range of 20 dB. In combination with the different rolling noise levels as a consequence of train speeds of 50, 80 and 100 km/h a wide data set of ratios between primary and secondary source level was acquired. The emission levels of the loudspeaker were designated and compared to reference values. The reference values were derived from standstill loudspeaker measurements using the same measurement geometry.
The deviation between the measurement and the reference values was used to assess the accuracy of the measurement procedure. An analysis of the measurement results showed a generally high accordance of the overall level as well as the measured spectra. The average deviation between the measured A-weighted loudspeaker signal and the reference value accounted

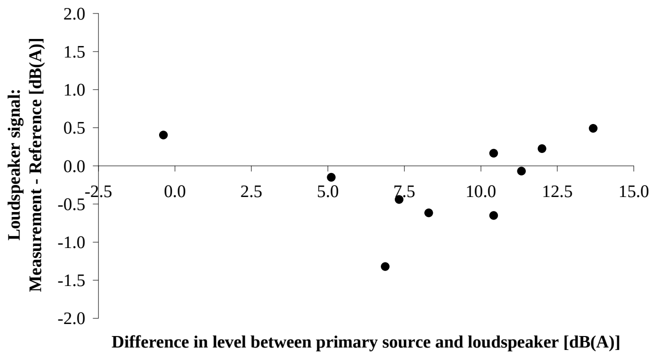

Figure 3: Result of the loudspeaker experiment. The deviation between the reference value of the loudspeaker signal and the measurement result are compared to the relation between primary and secondary source strength.

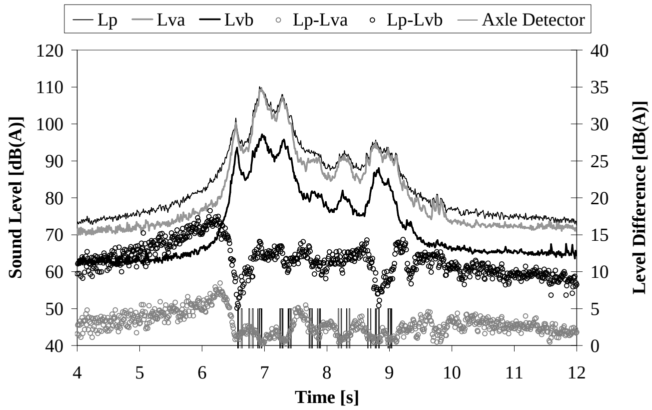

*Figure 4: Sound pressure and sound velocity level of a train pass-by at 200 km/h with the locomotive Re 460 at the end. Velocity sensor **a** was aiming at the wheel-rail-contact, sensor **b** was oriented towards the pantograph.*

for -0.2 dB(A). As can be seen in figure 3 the deviations are clearly below 1 dB(A) with the exception of one measurement with a level difference of -1.3 dB(A). On the ordinate of figure 3 the difference in level between primary and secondary source is depicted. The accuracy of the method does not seem to be substantially influenced by the level difference to the primary source as emission levels of secondary sources with up to 15 dB(A) lower levels could still be determined in good accordance.
The measurements were performed with an intensity probe type G.R.A.S. 50AI. Further details about the measurements can be found in [9].

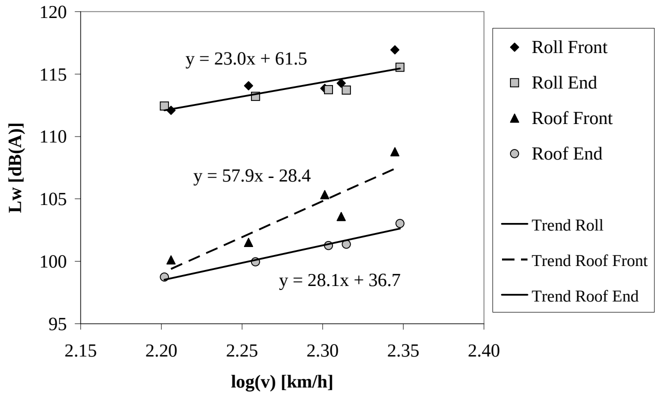

Figure 5: Sound source separation for the locomotive Re 460 depicted in function of the logarithm of the train speed.

Sound source separation on a locomotive Re 460 travelling with speeds around 200 km/h

A test train consisting of a locomotive type Re 460, three coaches EW IV and a locomotive type ES64U4 were measured at speeds between 160 and 220 km/h. Five pass-bys were recorded with the Re 460 in front and five with the Re 460 at the end. A three-dimensional Microflown probe type USP was used. As an example figure 4 shows measured sound pressure levels and sound velocity levels. The difference between sound pressure and sound velocity can be interpreted as a pointer towards the centre of gravity of sound emission. The difference between sound pressure and the velocity sensor a, which was oriented towards the rail-wheel-section, amounts to zero when the entire sound power is radiated from that area. On the other hand a reduction in level difference between sound pressure and sensor b is a hint for secondary sources in the roof section, as can be seen at the beginning and at the end of the train at the positions of the connected pantographs.
Figure 5 shows the resulting sound power of the first half of the locomotive Re 460 in function of the travelling speed, separated for a rolling noise source and an additional source in the roof section, presumably caused by aerodynamic noise. As can be seen rolling noise is independent of the position of the vehicle. Aerodynamic noise though is stronger when the locomotive is conducted in front and it also shows a higher dependence of the train speed.

CONCLUSIONS

First results prove that the measurement principle is working and that even sources with significantly differing sound power can be separated with good accuracy. Further tests concerning the potential and the restrictions of the measurement method are though still necessary.
Compared to array measurements the measurement procedure has some advantages: The method is less laborious and therefore less costly and the achievable differences in source

level that still can be separated also seem to be higher. Negative aspects are though that under practical conditions, including measurement uncertainties, a separation of more than two sources is rather unlikely with unknown source positions and that the localisation of the sources is subjected to greater uncertainties.
When designing an actual measurement geometry as well as in the process of data analysis it is helpful to be able to rely on general information from array measurements of comparable situations. Therefore the measurement concept should be seen as an addition to array measurements rather than a replacement.

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