Localization of Vibration Sources along Railway Tracks

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Summary

Groundborne vibrations from railway traffic is an increasing problem in urbanized areas and measures are often needed to minimize their effects on the environment. An important question when dealing with railway problems is to identify the source(s) of vibrations emitted along the railway track. Once this information is available, it is often possible to mitigate the problem by improving stiffness of the railway track and/or to upgrade worn-out or damaged rail sections and turnouts.

This paper describes a method which makes it possible to determine the locations of track sections which are likely to emit strong ground vibrations. A purpose-built track-bound vehicle which can be vibrated continuously at different frequencies can identify track sections having unfavorable dynamic foundation conditions. A theoretical concept is presented which makes it possible to calculate the potential of energy emission from the vehicle along the track.

Further, an innovative method is presented which makes it possible to determine the location of vibration sources by measurement of ground vibrations from existing railway traffic. This information can be used to determine the location of track sections where remedial measures are needed. Results are presented which illustrate application of the concepts, which can also be applied to mitigate other types of vibration problems.

1 Introduction

Railway systems offer environmentally friendly and efficient transportation for freight and passenger traffic. However, in urban areas, railway traffic can have negative environmental consequences such as disturbance from ground vibrations. Commonly, negative effects are related to the living environment and human disturbance. However, vibrations can also affect structural elements of buildings or sensitive equipment (e.g. in hospitals, offices, factories or research institutions). The consequences of vibrations have increased also due to more economic

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structural design which makes structures more vibration sensitive. Further, general public awareness of environmental effects is increasing, which is reflected by more restrictive vibration standards and specifications.

In some cases it is possible to consider potentially negative effects at the design stage, for instance by incorporating vibration-reducing measures. However, prediction of ground vibrations caused by railway traffic and their effects on buildings and installations is often a complex problem. Therefore, vibration problems are often not considered at the design stage and only noticed once buildings have been constructed. At this stage it is more difficult to mitigate vibration problems. In order to apply remedial measures along railway tracks it is important to identify the location of the source(s) of vibrations.

This paper describes prediction of ground vibrations caused by railway traffic along tracks with variable conditions. A theoretical model is presented which makes it possible to identify track sections which have high potential vibration emission, using a purpose-built vibrating vehicle. In addition, vibrations generated by railway traffic can be used to accurately determine locations of vibrations sources along the track.

2 Location of Vibration Sources

Dynamic track stiffness and energy (vibration) emission can be investigated by a track-bound, instrumented vehicle with a large vibrator [1, 2]. The Swedish Transport Administration which, together with the Royal Institute of Technology in Stockholm, has a long history of research in train-induced vibrations (e.g. [3, 4]), has developed a vibrating train car, called Rolling Stiffness Measurement Vehicle (RSMV), see Fig. 1. Similar vehicles exist in several other countries.

Fig. 1. View inside of the RSMV, showing oscillating masses on either side

The RSMV is normally used for determining the condition of existing tracks and thereby directing maintenance actions. The vehicle can be vibrated at different frequencies (2 to 50 Hz) while driving at low speed (usually less than 10 km/h, up to 50 km/h). By measuring the induced dynamic force and acceleration it is possible to calculate vertical displacement (double-integration of acceleration) and dynamic stiffness of the track support. A sketch of the different components of the RSMV is shown in Fig. 2.

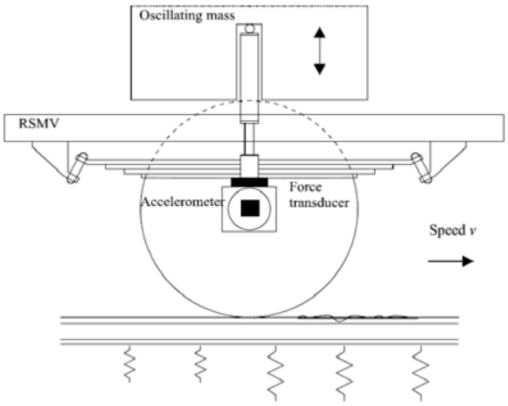

Fig. 2. Principal sketch of the RSMV measurement procedure, from [1]

From the calculated dynamic stiffness and phase angle, emitted energy from the vibrator to the track support and into the ground can be calculated by a new theoretical model, the calculation steps of which will be described in the following chapter. Thus, RSMV measurements make it possible to determine the location of potential sources of strong vibrations. High potential of vibration energy emission does not necessarily mean that strong ground vibrations will be generated by regular traffic at that location, as this also depends on other factors such as unevenness of the track, track changes, turnouts and the speed and dynamic characteristics of the train. If, however, such areas of high potential energy emission coincide with unevenness along the railway track (e.g. a turnout) or a sudden change in track stiffness, strong vibrations will be emitted and propagated to the surrounding soil.

Ground vibration measurements from regular train traffic can also be used to locate the actual sources of vibrations. By installing photocells at different track sections, it is possible to determine the location of the train in the time history record which can be linked to the time history of the vibration signal.

Based on information obtained by these two methods, it is possible to identify track sections where strong ground vibrations are emitted and mitigation measures may be implemented, for example adjustment of tracks, modification of rail support, upgrading worn-out turnouts or ground improvement measures at locations showing strong vibration emission.

3 Energy Emission

The RSMV can be operated at specific frequencies, measuring acceleration and applied force. Normally, the purpose of such measurements is to determine the condition of the track by calculating displacement and dynamic stiffness. Dynamic track stiffness is normally presented along with phase angle between force and displacement, see Fig. 3, and is considered a measure of the static condition of the ballast. These quantities are, however, also related to dynamic properties of the rail, ballast and subgrade and, based on the below theoretical model, they can be used to locate sources of high potential vibration emission.

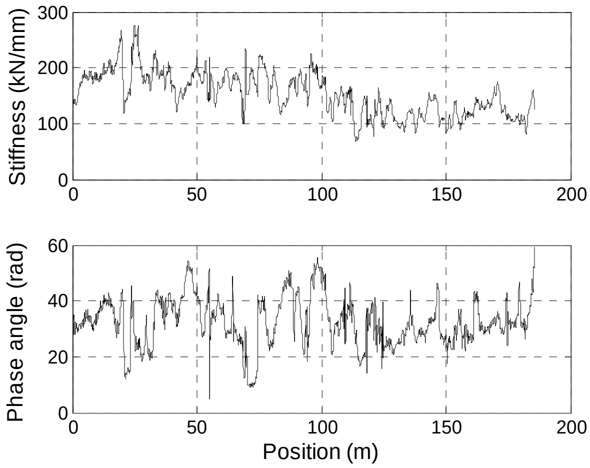

Fig. 3. Example of dynamic stiffness and phase angle as determined by the RSMV at 8 Hz

3.1 Dynamic Model

One of the most commonly used concepts for modeling train-induced vibrations is a moving point load on a Bernoulli-Euler-beam on a Kelvin material (BEK-model, Fig. 4, e.g. [5]). In case of the RSMV, the speed is very slow (normally less than 10 km/h) compared to the critical speed (greater than 200 km/h, e.g. [6, 7]). The model can therefore be analyzed with zero point load velocity.

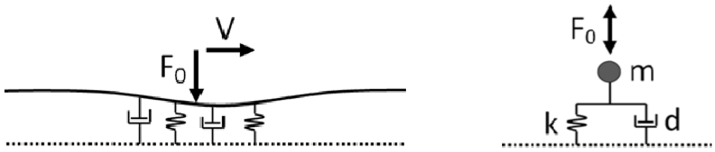

Fig. 4. BEK-model (left) and SDOF model (right)

A BEK-model with zero velocity yields very similar results to the simpler mass-spring-damper SDOF model, shown in Fig. 4. Such a model, having a sinusoidal force with amplitude F_0, mass m, spring stiffness k and a damper with impedance d, is therefore used to analyze the RSMV results. The complex dynamic stiffness, $K(\omega)$, can by described by

$$\mathrm{Re}(K(\omega)) = k - m\omega^2, \mathrm{Im}(K(\omega)) = -d\omega . \quad (3.1)$$

Derivation of Eq. (3.1) can be found in various texts on acoustics or vibration analysis, e.g. [8].

3.2 Dissipated Energy

The RSMV measures particle acceleration and force amplitude. Acceleration is integrated twice to obtain particle displacement from which dynamic stiffness is calculated. Measurements are commonly presented in stiffness amplitude, K_0, and phase angle, ϕ. The following relationship is obtained from Eq. (3.1)

$$d \cdot \omega = K_0 \cdot \sin(\phi) . \quad (3.2)$$

Of the three elements in the model (Fig. 4), only the damper dissipates energy. Fig. 5 shows the force/displacement diagram of the damper. The relationship is elliptic, moving in a negative (clockwise) direction with increasing t.

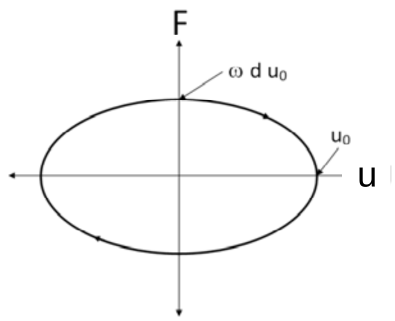

Fig. 5. Force/displacement relationship for the damper

Since the displacement amplitude is u_0 and the force amplitude is $\omega d u_0$, the area of the ellipse, and thus the dissipated energy per cycle, is

$$E = \pi \cdot d \cdot \omega \cdot u_0^{\;2} , \quad (3.3)$$

and using Eq. (3.2),

$$E = \pi \cdot K_0 \cdot \sin(\phi) \cdot u_0^{\;2} . \quad (3.4)$$

The physical stiffness, $K_0(\omega)=F_0(\omega)/u_0(\omega)$, together with Eq. (3.4) yields

$$E = \pi \cdot \frac{F_0^{\;2}}{K_0} \cdot \sin(\phi) \cdot \quad (3.5)$$

The power, i.e. dissipated energy per unit time, then becomes

$$P = E \cdot f = \frac{\omega}{2} \cdot \frac{F_0^{\ 2}}{K_0} \cdot \sin(\phi), \qquad (3.6a)$$

or,

$$P = \frac{1}{2} \cdot F_0 \cdot v_0 \cdot \sin(\phi), \qquad (3.6b)$$

where v_0 is the particle velocity (integrated from acceleration) measured on the RSMV. The emitted power can be calculated from Eq. (3.6a), using the information shown in Fig. 3. Assuming that the dynamic force and frequency are constant, the potentially emitted energy increases with increasing phase angel and decreasing dynamic stiffness. Eq. (3.6b) presents emitted power in terms of measured quantities and shows that only force, particle velocity and phase angle are governing for vibration emission.

3.3 Emitted Power

The energy from the RSMV vibrator that is emitted into the ground can be calculated at every location using Eq. (3.6). Since subgrade response, and thus emitted power, varies with frequency, investigations are carried out at different frequencies. An example is shown in Fig. 6, where the RSMV has been driven along the same track four times, operating at four different frequencies (5-8 Hz). Darker color indicates track sections of higher energy emission. The ballasted track in the example is underlain by 4-7 m of fill, followed by a thin peat layer (less than 1 m), 5-10 m of clay and 1-4 m of granular soils (glacial till) on bedrock.

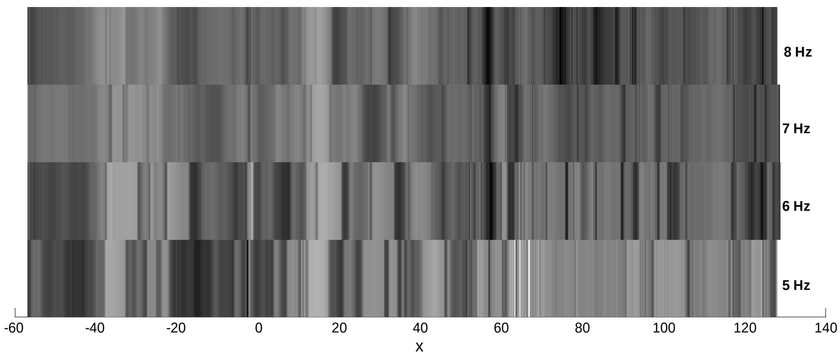

Fig. 6. Power emission from the RSMV for different frequencies. Darker color implies higher emission

High energy emission from the RSMV does not necessarily mean that large vibrations are generated when regular trains pass that location. It is merely a quantification of *potential* vibration generation. If there is no unevenness in the track, an impulse is not generated. If, however, a sudden change in stiffness occurs or there is, for instance, a turnout or damaged rail, the generated impulse will easily propagate into the subgrade and the surrounding soil.

4 Train-Induced Ground Vibration Measurement

While the RSMV can determine potential vibration sources, ground vibration measurements from regular traffic can be used to locate vibration sources which are generated by trains. With the use of at least two photocells installed in different positions along the railway track, the train velocity and its position at any given time can be determined. By identifying measured vibration peaks and determining the train position when peaks occur, a relationship between train location and high vibrations is obtained.

4.1 Measurement Procedure

For obtaining useful results it is crucial that ground vibration measurements are carried out with high accuracy, using either accelerometers or geophones. Particle velocity is normally used in regard to human perception of vibrations and, therefore, acceleration signals are integrated to velocity. It is also easier to determine peaks in velocity records than acceleration records. Note that high pass filters may be required in order to eliminate drift.

Transducers should be placed in a hole in the ground and backfilled with material, preferably dry sand. For accurate ground vibration measurements, sensors should not be mounted on stiff road surfaces or attached to foundations of buildings. To be able to distinguish peaks in vibration data and thus to locate vibration sources, measuring points need to be located in the close vicinity to the railways track, approximately within a distance of 20 m.

4.2 Determining Peaks

The train engine, which is usually heavier than the following cars, is a more distinct and stronger cause of vibrations. In addition, it is easier to determine the location of the engine than individual cars. Therefore, locating vibration sources is preferably carried out using recordings of vibrations caused by the engine. These are easily indentified since they are the first to arrive at a measuring point and generally have a larger amplitude. Once the engine has passed the measuring point, vibrations are emitted from different train sections (cars), arriving simultaneously from different directions, making the analysis more uncertain.

Fig. 7 shows a typical time history of vibration velocity (vertical component) measured approximately 12 m from the railway track. The train consists of one engine, followed by nine cars and a second engine at the back. One can clearly distinguish the engines and individual cars in the vibration record. In this example, only the peaks around t = 20 s were used for analysis.

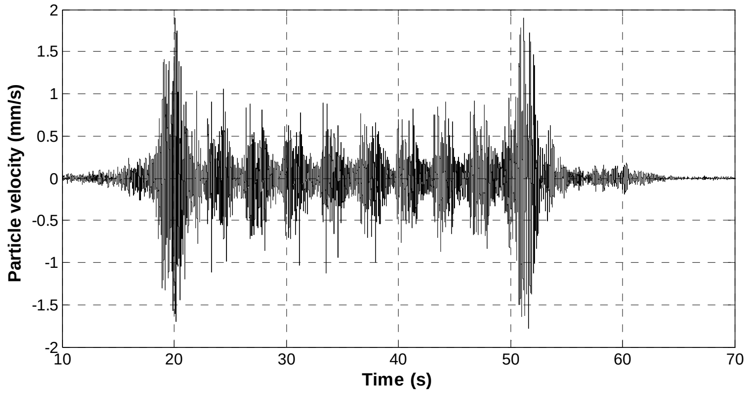

Fig. 7. Vertical vibration time history from a train recorded in the vicinity of the track

Fig. 8 shows the location of the engine and the corresponding peak particle velocity (PPV) when high peaks occur in the ground vibration measurements. Obvious vibration sources are located at x = - 33 m and x = 45 m.

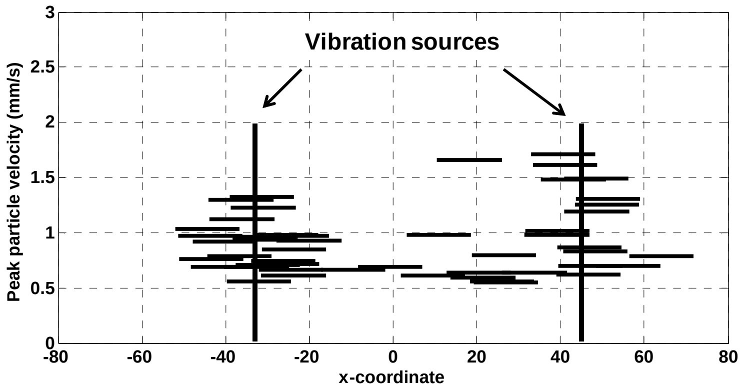

Fig. 8. Location of vibration sources determined by ground vibration monitoring

5 Conclusions

Two methods have been presented to identify vibration sources along railway tracks. The first method uses a purpose-build track-bound measurement vehicle (RSMV), equipped with a vibrator. The vehicle moves with a low speed, vibrating with a prescribed frequency. The measured dynamic force and acceleration can be used to determine the dynamic track stiffness and phase angle between force and displacement. A theoretical model is presented, from which the power emitted into the subgrade is calculated by a simple relationship. The potential of vibration emission increases with increasing phase angle and decreasing dynamic stiffness.

Measurements can be used to identify track sections with high potential of vibration emission.

The source of vibration emission from operating trains can be determined by measuring ground vibrations. The position of the train at any point in the vibration time records can be determined by installing photocells. High vibrations peaks in the records are determined by inspection of time histories, indicating track locations where high ground vibrations are generated.

Acknowledgements

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