# UNDERSTANDING SEISMIC SIGNATURES OF HEAVY MILITARY VEHICLES

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## 1 INTRODUCTION

Ground vibrations are traditionally studied in the fields of civil engineering and environmental acoustics[1,2]. More recently though, they have been investigated also for the purposes of remote detection and monitoring of heavy military vehicles[3-6]. In particular, the roles of generated ground vibration spectra (also termed as seismic signatures) have been studied experimentally in the framework of the so-called *Bochum Verification Project* (BVP) [3,4]. This project was one of the first academic investigations into this topic open for participation of scientists from several European countries, USA and Russia. Whilst acoustic monitoring of vehicles, which was investigated in the BVP as well, would allow detection at much greater distances than those typical for seismic methods, seismic monitoring has a greater potential to identify specific vehicle parameters and hence the types of vehicles.

It is envisaged that a typical application of the technology would be for peace-keeping forces – to monitor agreed limits concerning cease-fire lines and weapons free zones, disarmament treaties, etc. Currently it is typical for only major routes to be staffed by inspectors, with other areas regulated through spot-checks and patrols. This leaves vast off-road portions of land that provide ample opportunity for prohibited movements. Autonomous seismic sensors would provide covert monitoring, be independent of time-of-day or weather, and maximize coverage. A well-orchestrated network of sensors could provide gap-free monitoring, detecting suspicious activity and alerting a common control centre. This form of monitoring would prove less intrusive than a permanent human presence, and providing the systems are cost-effective, would demonstrate financial benefit.

This paper aims to explore some fundamental characteristics of ground vibration spectra that could be attributed to heavy vehicles traversing over flat terrain. Unlike works of other researchers, who employed either experimental techniques[3,4] or purely numerical approaches[5,6], the present paper adopts mainly analytical techniques in order to describe the dynamic motion of typical heavy vehicles and to determine the forces applied from vehicles to the ground surface. These forces are then used for derivation of analytical expressions for generated ground vibrations, predominantly Rayleigh surface waves, using Green's function method. The advantage of such an analytical approach is that it assists in better understanding of seismic signatures of heavy military vehicles and its dependence on different parameters.

Primarily, a simple Quarter Car Model (QCM) representation of a heavy vehicle is considered. For this representation, the dynamic forces applied from a vehicle to the ground are derived and then used for calculation of generated ground vibrations. The model simulates the effect of tyre or track geometrical irregularities (discontinuities) on generating ground vibrations. It is shown that the obtained ground vibration spectra contain spectral peaks associated with vehicle characteristic parameters and vehicle speed. The QCM is then replaced by the so-called Planar Ride Model (PRM) that takes into account both translation and rotation of a vehicle body. Some preliminary calculations of generated ground vibrations are carried out for the PRM case using a simplified assumption of vehicle tyres being absolutely rigid. The comparison of the calculated ground vibration spectra with the published experimental data shows their reasonably good agreement.

# 2 CALCULATION OF VEHICLE-INDUCED GROUND FORCES

Ground vibrations generated as a result of heavy vehicle motion over terrain can be attributed to the following dynamic forces:

- Forces exerted to the ground as a result of wheel motion over ground disturbances or track (tyre) periodic irregularities.
- Unbalanced forces due to engine and drive rotation that are transmitted to the vehicle body and then to the ground.

## 2.1 Ground Force Spectra for a Simplified Quarter Car Vehicle Model

A simple quarter car model (QCM) has been used to simulate the point contact forces exerted to the ground as a result of a vehicle body motion over surfaces characterised by the presence of geometrical irregularities (see Figure 1). For tracked vehicles moving over perfectly flat ground, these irregularities are due to the small gaps between track links. For wheeled vehicles, tyre treads can induce a similar effect. Several assumptions have been made to justify QCM as a valid vehicle simplification[7]:

1. A point contact patch assumption is deemed sufficient as typical wavelengths of generated Rayleigh waves are greater than the characteristic dimensions of a vehicle.
2. Total vehicle mass is distributed evenly to all the wheel stations at all times.
3. The road surface is rigid, as are the track links for tracked vehicle models.

For the QCM shown in Figure 1, the magnitude of the force $F_t$ exerted to the ground is equivalent to the force exerted by the compression of the tyre spring due to the vertical displacement of the wheel. Therefore, the solution for the dynamic response of the wheel $z_w(t)$ to an input from the road irregularity $z_r(t)$ is required to determine such ground forces.

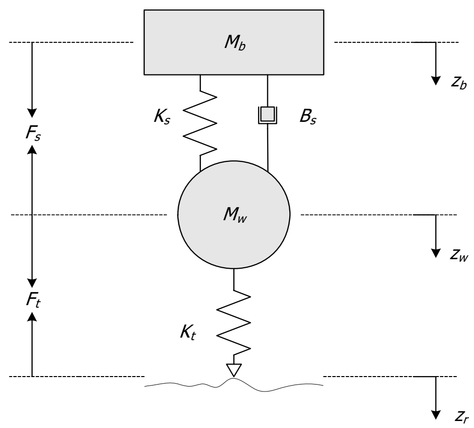


Figure 1. A quarter car vehicle model

As a 2-DOF system, QCM responds well at both ‘wheel hop’ and ‘body bounce’ natural frequencies. To simplify QCM even more, one can consider the ‘body still’ approximation[7] that reduces QCM to a 1-DOF system by freezing the low-frequency ‘body bounce’ mode of vibration (around 1-2 Hz). As a result, the problem is reduced to the analysis of only the wheel hop response to the displacement input from surface discontinuities that takes place at higher frequencies. This is usually sufficient for calculation of generated ground vibrations since they are generated more efficiently at higher frequencies.

In the time domain, the input into the quarter car model under consideration is the elevation changes $z_r(t)$ as a result of the wheel's passing over track linkages and treads for tracked and wheeled vehicles respectively. For simplicity, the variation in surface profile over which a wheel (modelled as a point contact) traverses can be estimated as a finite series of half sine wave pulses with a frequency $f_{tr}$ corresponding to the ratio of the vehicle forward velocity $V$ to the track pitch $a$: $f_{tr} = V/a$. By carrying out a simple Fourier Integration, this input signal can be represented in the frequency domain: $z_r(\omega)$. The corresponding expressions for $z_r(t)$ and $z_r(\omega)$ take the form

$$z_r(t) = \begin{cases} z_{r_{\max}} \sin(2\pi f_{tr} t) & \text{for } z_r(t) \geq 0 \\ 0 & \text{otherwise} \end{cases} \tag{1}$$

$$z_r(\omega) = \int_{-\infty}^{\infty} z_{tr}(t) e^{-i\omega t} dt \,. \tag{2}$$

To calculate the displacement of the wheel in the frequency domain $z_w(\omega)$, the well-known frequency response function (FRF) for the above-mentioned 1-DOF quarter car model $Z_w(\omega)$ can be applied to calculate the displacement of the wheel in the frequency domain: $z_w(\omega) = z_r(\omega)\, Z_w(\omega)$. Finally, to calculate the vertical force spectrum for a single axle applied to the ground $F_t(\omega)$ one can use the following expression[7]:

$$F_t(\omega) = K_t\left[\left(z_r(\omega) Z_w(\omega)\right) - z_r(\omega)\right], \tag{3}$$

where $K_t$ is the rubber tyre compliance.

The QCM model described above is valid for modelling a single axle wheel displacement. To establish the ground force spectra observed due to the effects of multiple axles, a simple superposition of all wheel hop displacement responses should be taken. Obviously, the wheel hop response at each axle differs only by a phase shift that corresponds to the distance of the additional wheel axle (characterised by the integer number $n$) from the front axle $E_{1n}$ divided by the vehicle forward speed $V$ (see Reference 7). The resulting expression for the vertical force $F_z^{mw}(\omega)$ applied to the ground from the entire vehicle then takes the form

$$F_z^{mw}(\omega) = F_z(\omega) \cdot \left(1 + \exp\left(i\omega \frac{E_{12}}{V}\right) + \exp\left(i\omega \frac{E_{13}}{V}\right) ... + \exp\left(i\omega \frac{E_{1N}}{V}\right)\right), \tag{4}$$

where $F_z(\omega)$ is the force spectrum for a single wheel axle defined by the expression (3), and $N$ is the number of axles in a vehicle.

## 2.2 Calculated Ground Force Spectra for the Test Vehicle Parameters

Let us now introduce the two main 'test vehicles', on which most of the theoretical calculations of this paper are based. These are the *Leopard* Main Battle Tank (MBT) and the *Transportpanzer* (Fuchs) Armoured Personnel Carrier (APC) – see Figure 2. For the former, a set of experimental results for generated ground vibration velocities is available as part of the published works following from the *Bochum Verification Project* **(**BVP) [3,4].

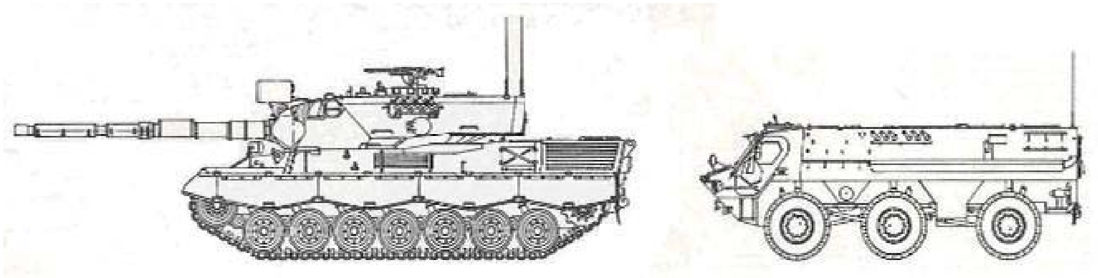

Figure 2. Leopard MBT and Transportpanzer (Fuchs) APC (right)

The parameters of the test vehicles that have been used in calculations of the present work are shown in Table 1.

| Quarter Car Model Parameters | Symbol / Unit | Leopard I MBT | Transportpanzer I (Fuchs) APC |
|---|---|---|---|
| Total Vehicle Mass | $M_v$ / $kg$ | 40000 | 17000 |
| Quarter Car Body Mass | $M_b$ / $kg$ | 2857.14 | 2833.34 |
| Mass of Wheel | $M_w$ / $kg$ | 317.46 | 314.81 |
| Number of wheels | $N_w$ | 14 | 6 |
| Suspension Spring Stiffness | $K_s$ / $Nm^{-1}$ | 4.44 x10$^5$ | 4.41 x10$^5$ |
| Tyre Compliance | $K_t$ / $Nm^{-1}$ | 1.27 x10$^6$ | 1.26 x10$^6$ |
| Suspension Damping | $B_s$ / $Nsm^{-1}$ | 1.27 x10$^4$ | 1.26 x10$^4$ |
| Vehicle Forward Velocity | $V$ / $ms^{-1}$ | 3.9 | 3.9 |
| Track/Tread Pitch | $a$ / $m$ | 0.169 | 0.025 |
| Magnitude of Discontinuity | $z_{r_{\max}}$ / $m$ | 0.04 | 0.005 |
| Vehicle Mass Moment of Inertia | $I_y$ / $kgm^2$ | 50 x10$^3$ | 20 x10$^3$ |
| Height of vehicle Centre of Mass | $h_{cm}$ / $m$ | 1.2 | 1.0 |
| Wheelbases | $E_{12}$ / $m$ | 0.665 | 1.75 |
| | $E_{23}$ / $m$ | 0.665 | 2.05 |
| | $E_{34}$ / $m$ | 0.665 | |
| | $E_{45}$ / $m$ | 0.665 | |
| | $E_{56}$ / $m$ | 0.665 | |
| | $E_{67}$ / $m$ | 0.665 | |

Table 1. Test vehicle parameters

Figure 3 illustrates the resulting multi-axle ground force spectra calculated for the Leopard MBT (with 7 axles) and for the Transportpanzer APC (with 3 axles) using the simplified QCM. As expected, for the Leopard MBT (dash-dotted curve in Figure 3) the most significant force peaks are at the main frequency of excitation $f_{tr} = V/a$, i.e. at 23 Hz - this corresponds to the forward speed of the vehicle divided by the track pitch. Noticeable force amplitudes are observed also at integer multiples of this fundamental frequency (harmonics). Note that the effect of multiple axles produces little increase in the average force spectra magnitudes in comparison with the single-axle model. However, it makes the spectra more irregular, with the kind of amplitude modulation defined by the distances between axles.

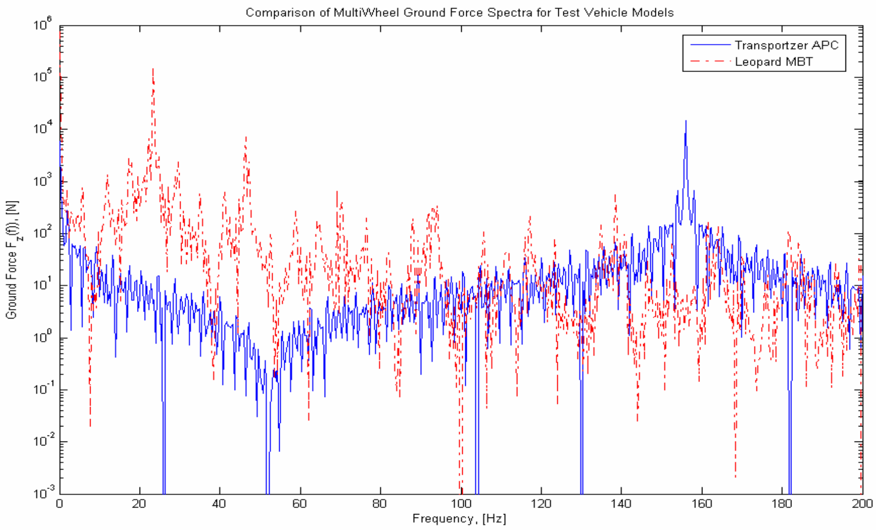


Figure 3. Ground force spectra for the test vehicles calculated using QCM

The results obtained for the parameters of the Transportpanzer APC (solid curve in Figure 3) show that amplitudes of the ground forces in this case are generally significantly smaller than those for the tank, approximately 10% of the maximum tank force amplitude was observed. The frequency of the main force peak in this case is around 156Hz – this corresponds to the forward speed of the vehicle divided by the distance between the tyre tread elements.

# 3. CALCULATION OF GENERATED GROUND VIBRATIONS

## 3.1 General Information

To calculate ground vibration spectra generated by the vehicle-induced ground forces one can use Green's function method, taking into account only generated Rayleigh surface waves as they carry most of the radiated elastic energy (see Reference 7 for more detail). The vertical component of generated ground vibration velocity in the frequency domain $v_z(\omega)$ is given by the expression[7]

$$v_z(\omega) = \left(\frac{2\pi}{k_R \cdot r}\right)^{\frac{1}{2}} \frac{(-i\omega) k_R k_S \nu_s \nu_l}{2\pi\mu F'(k_R)} F_z^{mw}(\omega) \cdot e^{-k_R \gamma \cdot r} \cdot e^{ik_R r - 3\pi/4} \tag{5}$$

In this expression, the vertically applied point force and observation distance from the source are represented by $F_z^{mw}(\omega)$ and $r$ respectively. The remaining parameters, which are not explained here for brevity, describe material properties of the ground and how the generated Rayleigh waves depend on frequency[7].

As our intention was to compare the results of the calculations with the experimental data obtained for the Leopard MBT in the course of *BVP,* the selection of ground material constants had to be as consistent as possible with the ground parameters on the site of that experiment. The predominant soil type on the site of the experiment was sand silt, and thus the material parameters shown in Table 2 attempt to replicate this as closely as possible.

| Material Parameter | Symbol/Unit | Value |
|---|---|---|
| Soil Mass Density | $\rho / kgm^{-3}$ | 1800 |
| Shear Modulus | $\mu / Nm^{-2}$ | 4 x10$^7$ |
| Loss Factor | $\gamma$ | 0.05 |
| Poisson's Ratio | $\sigma$ | 0.25 |

Table 2 Ground material parameters used in calculations

## 3.2 Results Calculated Using the Quarter Car Model

The calculated ground particle velocity spectra generated by the ground forces determined using the simple QCM are shown in Figure 4. In the same figure, the experimental spectra observed for the Leopard MBT [3,4] are shown as well. One can see that theoretical and experimental spectra agree fairly well from the magnitude of the 2$^{nd}$ harmonic, with the theoretical results attenuating with frequency more rapidly than it is observed experimentally. A possible incorrect representation of the track profile and of the attenuation coefficient assigned to the model could attribute to the divergence of these data plots. Note that the magnitude corresponding to the fundamental frequency (23Hz) is essentially lower in the experimental data. There is also a clear difference between the spectrum generated by the APC wheeled vehicle and the one created by the tracked vehicle (MBT). Calculations carried out using full QCM, i.e. taking into account body bounce (not presented here for brevity), showed little difference from the calculations shown in Figure 4. The only noticeable difference, as expected, was observed at very low frequencies.

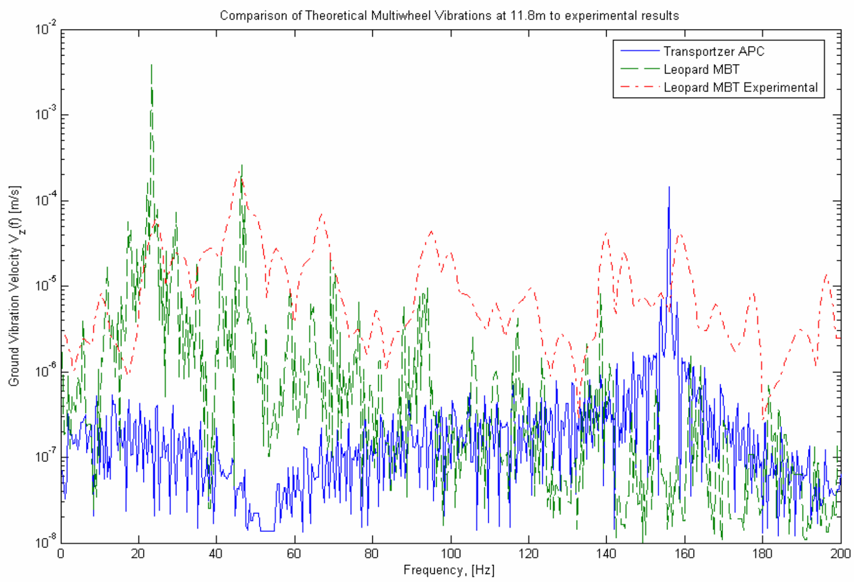


Figure 4 Ground vibration velocity spectra for the test vehicles calculated using QCM

Note that it was mentioned in Reference 3 that for tracked vehicles at low speeds, the second multiple of the fundamental frequency was the strongest on passing the sensors, as depicted by the experimental results of Figure 4. For higher speeds, the fundamental frequency would produce the dominant response. The reason for this could be the above-mentioned inefficient radiation of Rayleigh waves at low frequencies.

## 3.3 Preliminary Results Calculated Using the Planar Ride Model

The Planar Ride Model (PRM) of a vehicle has been used in the present work to undertake a preliminary study of the effects of both vertical displacement and rotation of the vehicle body, i.e. the effects of 'bounce' and 'pitch' degrees of freedom. As before, the vehicle was assumed to contain a series of wheel suspension units that could respond to the track/tread displacement input. However, to simplify the problem associated with the additional degree of freedom due to the tyre compliance, all wheels were assumed to be rigid in this preliminary investigation (see Figure 5).

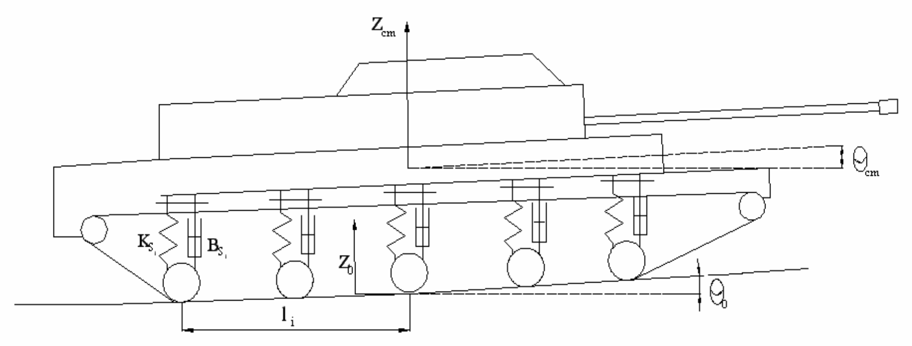


Figure 5. Planar Ride Model with rigid wheels

The dynamic analysis of the resulting 2-DOF model and calculation of the dynamic forces applied to the ground have been carried out using Lagrange's equations. These equations have been solved in the time domain with the subsequent numerical calculations of the frequency spectra using FFT algorithm. The results of the preliminary calculations of generated ground vibration spectra are shown in Figure 6 for the Leopard MBT and for the Transportpanzer APC. Also shown are the experimental results obtained for the Leopard MBT [3,4]. For simplicity, contributions of only one wheel-axle have been taken into account in both cases – the central axle for the Leopard MBT and the front axle for the Transportpanzer APC.

As one can see from Figure 6, calculation of generated ground vibration spectra for the Leopard MBT using the above-mentioned simplified PRM leads to a rather good agreement with the band-averaged experimental values. However, many individual resonant peaks visible in the experiment are not reproduced in the calculated spectra. This was expected as in the simplified PRM under consideration, in contrast to QCM case, the contributions of multiple wheel-axles and their interference have been ignored. This discrepancy will be resolved in our future more detailed calculations.

Note that the observed differences between the obtained theoretical results and the observed experimental values for both QCM and PRM cases could be attributed also to inaccuracy in modelling the track profile and to various additional generation mechanisms that have not been taken into account in this work. These additional mechanisms are acousto-seismic coupling[8], effects of engine vibrations due to rotation imbalance, variations in ground elastic parameters and mass density, ground topography, etc. Further research is needed to explore the effects of these mechanisms on generated ground vibration spectra.

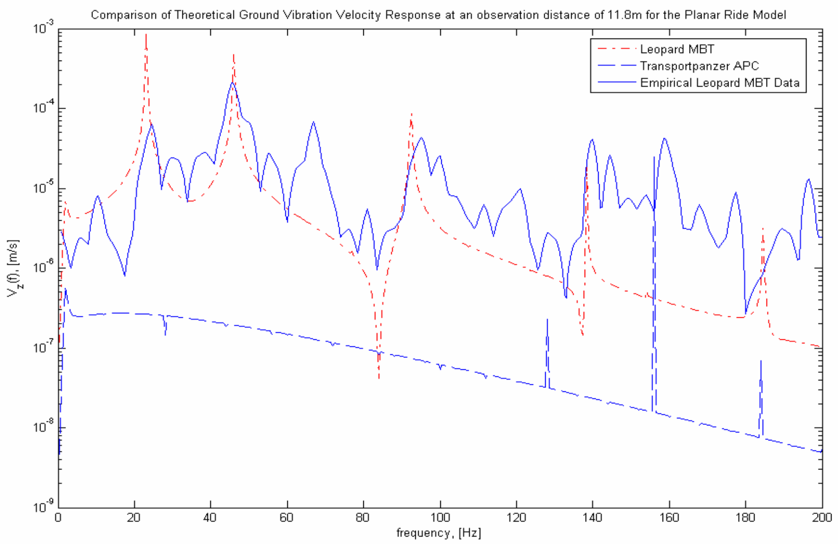


Figure 6. Ground vibration velocity spectra for the test vehicles calculated using PRM

# 4 CONCLUSIONS

The results of this work show that analytical techniques based on quarter car and planar ride vehicle models as well as on Green's function method are capable of producing ground vibration spectra generated by heavy military vehicles that are in reasonably good agreement with the published experimental results. The established relationships between vehicle parameters and some characteristic features of ground vibration spectra could be used for more reliable vehicle detection and identification.

# 5 REFERENCES

1. Transportation noise: Reference book (ed. P. Nelson), Butterworths, London (1987).
2. Noise and vibration from high-speed trains (ed. V.V. Krylov), Thomas Telford, London (2001).
3. J. Altmann, S. Linev and A. Weiss, Acoustic-seismic detection and classification of military vehicles – Developing tools for disarmament and peace-keeping, Applied Acoustics, 63, 1085-1107 (2002).
4. J. Altmann, Acoustic and seismic signals of heavy military vehicles for co-operative verification, Journal of Sound and Vibration, 273, 713-740 (2004).
5. T.S. Anderson, M.L. Moran, S.A. Ketcham and J. Lacombe, Tracked vehicle simulations and seismic wavefield synthesis in seismic sensor systems, Computing in Science and Engineering, November/December, 22-28 (2004).
6. S.A. Ketcham, M.L. Moran, J. Lacombe, R.J. Greenfeld and T.S. Anderson, Seismic source model for moving vehicles, IEEE Transactions on Geosciences and Remote Sensing 43, 248-256 (2005).
7. V.V. Krylov, Generation of ground elastic waves by road vehicles, Journal of Computational Acoustics, 9, 919-933 (2001).
8. J.M. Sabatier, H.E. Bass, L.N. Bolen and K. Attenborough, Acoustically induced seismic waves, Journal of the Acoustical Society of America, 80, 646-649 (1986).