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THEORETICAL PREDICTION OF GROUND VIBRATIONS FROM HEAVY MILITARY VEHICLES

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ABSTRACT

The demand for reliable autonomous systems capable to detect and identify heavy military vehicles becomes an issue of paramount importance in the current complicated and delicate political climate. It is expected that such autonomous systems would alleviate some of the burden placed on UN peace keeping forces, who currently must patrol areas systematically to identify and monitor military activity. A promising method of detection and identification that influenced increasing levels of recent investment is the one using the information extracted from ground vibration spectra generated by heavy military vehicles, often termed as their seismic signatures. This paper presents the results of the theoretical investigation of ground vibrations generated by heavy military vehicles, such as tanks and armed personnel carriers. Initially, vehicle models of different degrees of complexity are considered - to identify the resulting dynamic forces applied to the ground. Then the obtained analytical expressions for vehicle dynamic forces are used for calculations of generated ground vibrations (primarily Rayleigh surface waves) using Green's function method. A comparison of the obtained theoretical results with published experimental data shows their good agreement.

INTRODUCTION

During the last two decades ground vibrations have been 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 (see e.g. [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]. Whilst acoustic monitoring of vehicles would allow detection at much greater distances than those typical for seismic methods, seismic monitoring has a far greater potential to identify specific vehicle parameters and hence the types of vehicles. A typical application of the technology would be for peace-keeping forces – to monitor agreed limits concerning cease-fire lines and weapons free zones, 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 fundamental characteristics of ground vibration spectra that could be attributed to heavy vehicles traversing over 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 calculation of generated ground vibrations, predominantly Rayleigh surface waves, using Green's function method.

Primarily, a Quarter Car Model (QCM) representation of a heavy vehicle is presented, which is then developed in into a more comprehensive Planar Ride Model (PRM). Both basic model types simulate the effect of tyre or track geometrical irregularities (discontinuities) on generating ground vibrations. In particular, at a fundamental frequency of excitation associated with vehicle speed and track or tyre periodicity. It is shown that the obtained ground vibration spectra contain spectral peaks associated with vehicle characteristic parameters and vehicle speed. The comparison of the calculated ground vibration spectra with the published experimental data shows their reasonably good agreement.

CALCULATION OF VEHICLE-INDUCED GROUND FORCES

Ground vibrations generated as a result of heavy vehicle motion could 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 transmited to the vehicle body and then to the ground.

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 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 to the dynamic response of the wheel to an input from the road irregularity is required to determine such ground forces.

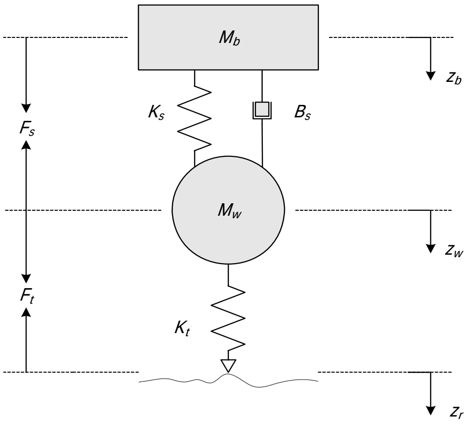

Figure 1. A quarter car vehicle model

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 (see e.g. [7]) that reduces QCM to a 1-DOF system by freezing the low-frequency ‘body bounce’ mode of vibration. Therefore, it is sufficient to analyse only the wheel hop response to the displacement input from surface discontinuities. Namely, the product of the wheel hop frequency response function (FRF) with the Fourier series representation of the input signal yields the Fourier representation of the ‘wheel hop’ displacement.

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].

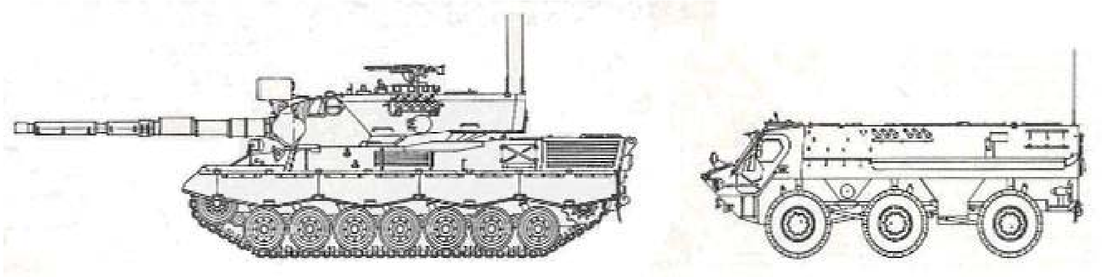

Figure 2. Leopard MBT and Transportpanzer (Fuchs) APC (right)

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	$Z_{tr_{\max}}$ / 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

Multi-axle force spectra

The QCM model 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. Subtracting the frequency representation of the input signal (due to the surface irregularity) from the wheel hop displacement response for each wheel station, one can derive an expression that need only be multiplied by the tyre compliance to produce the multi-axle force spectrum. Obviously, the wheel hop response at each axle differs only by a simple phase shift that corresponds to the distance of the wheel from the front axle divided by the vehicle forward speed.

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, 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.

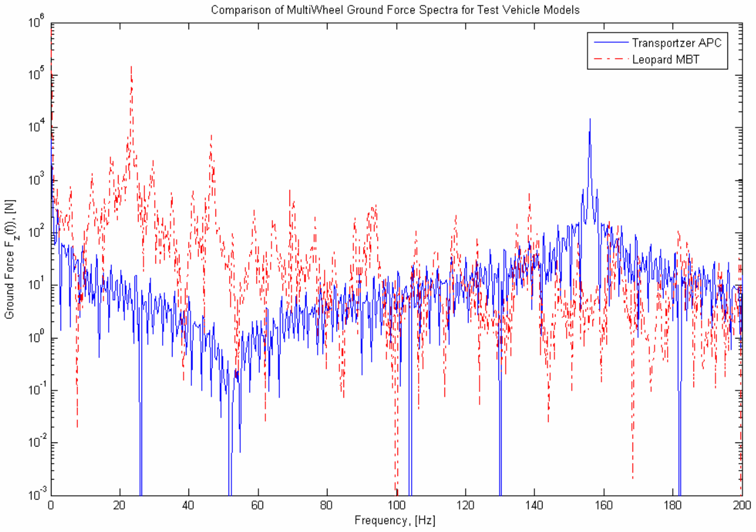

Figure 3. Ground force spectra for the test vehicles calculated using QCM

The results obtained for the parameters of the Transportpanzer APC (solid curve in Figure 3) show that the 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.

CALCULATION OF GENERATED GROUND VIBRATIONS

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 [7] for more detail). 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	ρ / kgm^{-3}	1800
Shear Modulus	μ / Nm^{-2}	4 x10^7
Loss Factor	γ	0.05
Poisson's Ratio	σ	0.25

Table 2 Ground material parameters used in calculations

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 2nd harmonic, with the theoretical results attenuating with frequency more rapidly than it is observed experimentally. A possible incorrect 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, showed little difference from the calculations shown in Figure 4. The only noticeable difference, as expected, was observed at very low frequencies.

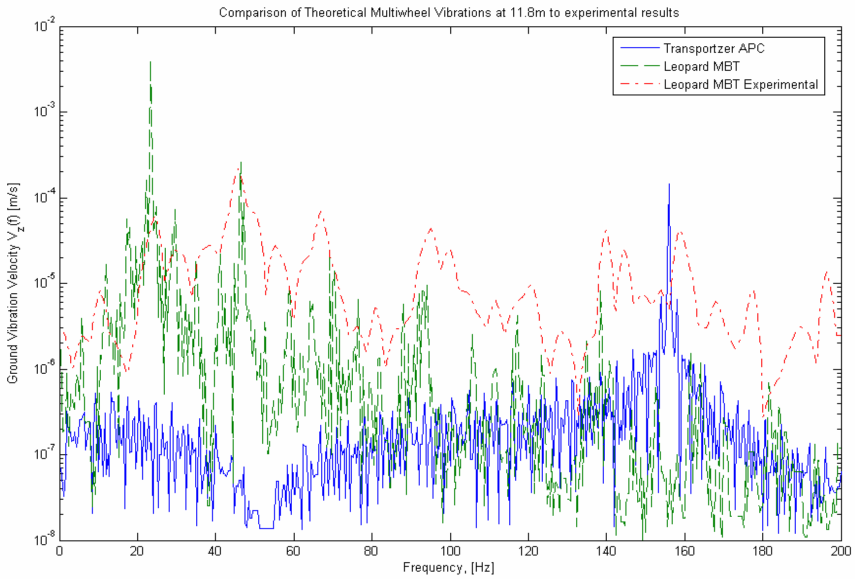

Figure 4 Ground vibration velocity spectra for the test vehicles calculated using QCM

Note that it was mentioned in [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 inefficient radiation of Rayleigh waves at low frequencies.

Results calculated using the planar ride model

The Planar Ride Model (PRM) of a vehicle has been used in this work to simulate the relative vertical displacement and rotation of the vehicle body, namely the 'bounce' and 'pitch' degrees of freedom. As before, the vehicle was modelled by a series of wheel suspension units that could respond to the track/tread displacement input. The dynamic analysis of this 2-DOF model and calculation of the dynamic forces applied to the ground have been carried out using Lagrange's equations. The results of the calculations of ground vibration spectra are shown in Figure 5 for the Leopard MBT and for the Transportpanzer APC. Also shown are the experimental results obtained for the Leopard MBT [3,4].

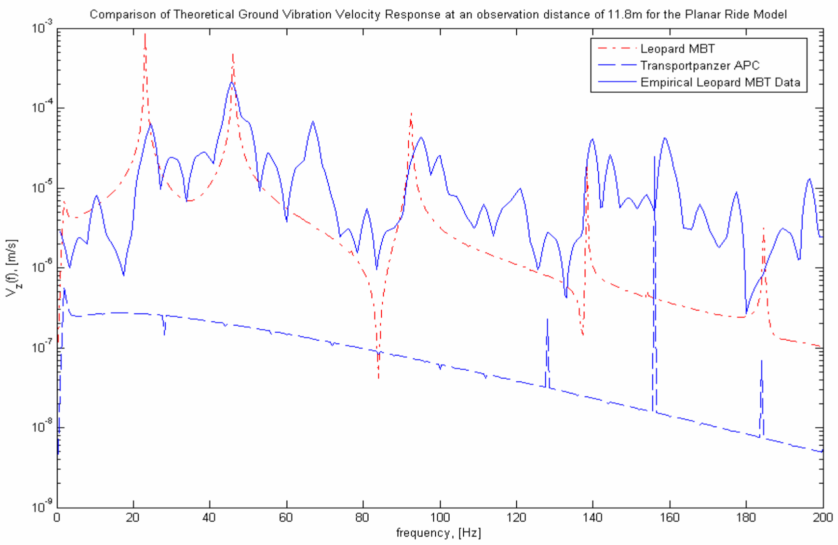

Figure 5. Ground vibration velocity spectra for the test vehicles calculated using PRM

As one can see from Figure 5, calculation of vehicle-induced ground vibration spectra using PRM results in even better agreement with the experiment. The observed differences could be attributed to various additional generation mechanisms that have not been taken into account in this work, in particular to acousto-seismic coupling [8], effects of engine vibrations due to rotation imbalance, variations in ground parameters, ground topography, etc. Further research is needed to explore the effects of these mechanisms on generated ground vibration spectra.

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.

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