ISSN : 1302-7050

Namık Kemal Üniversitesi

Tekirdağ Ziraat Fakültesi Dergisi

Journal of Tekirdag Agricultural Faculty

An International Journal of all Subjects of Agriculture

Cilt / *Volume:* **11** **Sayı** / *Number:* **1** **Yıl** / *Year:* **2014**

Sahibi / Owner

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Analysis of Relations of Towed Vehicles and Road Profile

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The qualities of the different road profiles highly influence the life span of the vehicles using them. The more uneven a stretch of road is, the greater the damaging effect. The aim of the research was to develop a comparative method that makes possible to compare the vibration generating effects of different road profiles. Using the comparative method a testing system was developed that is suitable to conduct accelerated fatigue tests that generate failures occurring under real working conditions.

Keywords: power spectral density, fatigue test, root mean square, vehicle damaging effects of road profiles

Introduction

In many cases fatigue tests of terrain vehicles resulted in malfunctions which were different from failures appearing in real terrain conditions. This can be due to the fact that the testing methods used so far have not been accurate enough in modeling the forces acting on vehicles under real conditions. In order to identify the damaging forces acting on terrain towed vehicles, first we need to develop a comparative method of general use. The use of this method opens up a possibility to develop a Fatigue Testing Method that is closer to real life forces.

During the research, a number of issues emerged, where the solution required carrying out series of measurements. One of these questions was how to compare the destructive effects of two different stochastic road profiles, and how to compare the extent of the damaging effects of two fatigue tests. According to the research objective I search answers to these questions.

Vehicle-Ground Relationship

The examination of the behavior of off-road vehicles, including towed vehicles belongs within the field of the theory of off-road vehicles. Of the four models of rolling wheel-track relations, the “deforming wheel on deforming surface” model was identified as the most effective approach for examining forces acting on off-road towed vehicles according to Kiss and Laib (1999).

Terrain towed vehicles are exposed to stochastically distributed forces. These forces derive from both the random motion of the towed vehicle and from the roughness of the terrain profile, as Gedeon (1993) and Abarbanel (1996) have formulated it.

Excited by the towing vehicle and by unforeseeable factors (G_x) resulting from terrain profile the vehicle starts vibrating, which results in forces damaging its structure. The question of the thus resulting vibration was studied by Nguyen (2011) during field tests. Thus, the vehicle damaging forces depend on the degree of excitation and the vehicle structure, that is, on the transfer function (H (f)). The extent of response function (G_y) measured on the vehicle depends the vehicle speed, weight, and the mechanical properties of the terrain profile. The vehicle-ground relationship is illustrated in the following figure 1, where the stochastic excitation of a linear oscillating system with a single degree of freedom and its transmission and response functions are shown.

In case of a vehicle and a road profile, the relationship is much more complex, since each

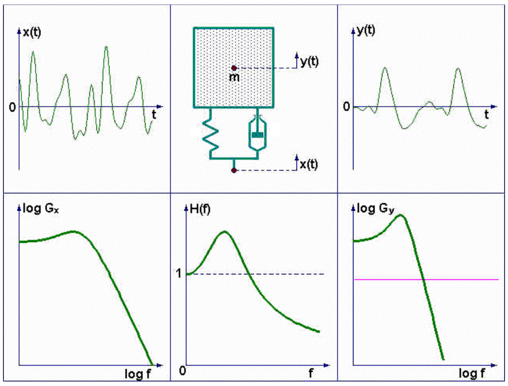

Figure 1: Excitation Of A Linear Oscillating System With A Single Degree Of Freedom

wheel of the vehicle gets a separate excitation from the ground, and in case of towed vehicles the towing vehicle is exciteuing the examined structure. So it is appropriate to handle the power spectral density function of the vehicle terrain profile and the transmission characteristics in a matrix. The response function ($\overline{\overline{G}}_{yy}(f)$) of the vehicle given to the spectral density function of the road profile ($\overline{\overline{G}}_{xx}(f)$) can be described by the following equation in matrix form:

$$\overline{\overline{G}}_{yy}(f)=\overline{\overline{H}}_{xy}(f)\overline{\overline{G}}_{xx}(f)\overline{\overline{H}}_{yx}^{T}(f) \qquad (1)$$

Where: $\overline{\overline{G}}_{yy}(f)$: is the power spectral density matrix of the excited oscillating system [m2s]; $\overline{\overline{H}}_{xy}(f)$: is the transmission frequency function matrix of the oscillating system [-]; $\overline{\overline{G}}_{xx}(f)$: is the power spectral density matrix of the terrain profile [m2s].

Due to the complexity of the described relation it is appropriate to determine the calculations using computer simulations.

According to Márialigeti's study (1994) about terrain profiles it can be stated that in general in case of profiles registered in a sufficiently large number of samples, the values obtained are of stationary and ergodic characteristics, so they can be described as stochastic statistics process. Terrain profiles showing stochastic nature can be made comparable based on a power spectral density function (PSD) and the size and distribution of their micro-and macro barriers. About the application of PSD functions in engineering practice in the book of Bendre et al. (1980) can we find an adequate description.

The stochastic distribution of the terrain profiles can be characterized with the help of a power spectral density function (G (n) using random variables. The PSD functions are formally identical to the Fourier transform of the correlation which can be defined by the equation:

$$G(n)=\lim_{L\to\infty}\frac{1}{2L}\left(\int_{-L}^{L}\left(\left|\xi(x)e^{-jnx}\right|\right)dx\right)^{2} \qquad (2)$$

Where: L: sampling length [m]; $\xi(x)$: random variable of the road profile in vertical direction [m]

With the determination of the PSD function of the road profiles, the power spectral density of each wavelength value becomes comparable. However, this is not sufficient to compare the vibrations generating effect of two profiles of identical length. A new method had to be developed for the comparison of vehicles damaging effect of different road profiles, using the power density functions.

Material and Methods

To achieve the objective, the realization of the following tasks was required. The first step was to determine the mechanical and vibrational properties of the observed vehicle which makes the system, or in other terms, the transfer function determinable. After that with a series of measurements the extent of the devastating impact of the different stochastic and built obstacle systems could be determined, which is described by the response function of the structure given as a reaction to the excitation.

Measurement of the terrain's effects was carried out on a single axle, semi suspended structure, i.e. the header trailer. The trailer without overrun brakes, built to transport headers is mostly used on agricultural dirt tracks under normal operational conditions. A particular feature of the structure is that it contains no separate shock absorbers apart from its rubber tyres. The load of the trailer for the measurements was a purpose-built dummy header (Figure 2.) which - in terms of its mass and center of gravity - is equivalent to an 8 row corn header. Thanks to the construction of the structure, it is also suitable for modeling various load conditions by loading or unloading concrete blocks used as auxiliary weights.

Figure 2. SHERPA BG3 type trailer and CONSPEED 8 row DUMMY header

Acceleration sensors were placed on the trailer at the locations indicated in Figure 3. to measure the dynamic effects it is subjected to. The instruments sensed the vibrations of the trailer via piezoelectric means and forwarded the signals detected to the measurement data collection unit.

The measurement sequence is made up of four distinct phases. Measurement of the trailer's ability to overcome terrain obstructions, the coordinates of the trailer's centre of gravity and its vibrational characteristics took place in the first phase. The vehicle's own frequency as well as the spring characteristics of the tyres were also determined.

The second series of measurements focused on obtaining measurement data in realistic operational scenarios on five different types of roads. The first towing measurement sequence took place on a good quality paved road, followed by a bad quality paved road selected for this purpose. The other towing measurements were taken on three agricultural dirt tracks of varying soil types. Separate measurements were taken on sandy, clay-based and coarse gravel roads. The road profile was also recorded for every road section tested.

In the third phase of the measurements the two different accelerated fatigue tests were compared. One of the test methods was fatigue testing on the roller test bench (Figure 4.), and the other was the circular test track.

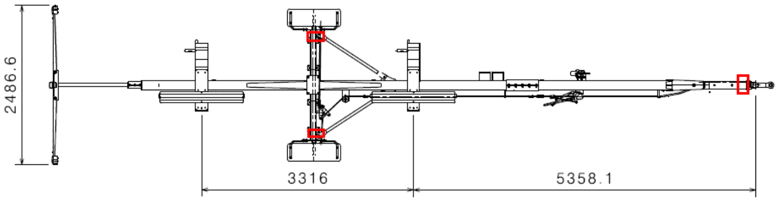

Figure 3: Single axle header trailer acceleration sensor measurement points

Figure 4. Measurement on a roller test bench

In the fourth phase of the measurement series, combinations of artificial obstacles were tested. The aim of this sequence of measurements was to test the effects of the various artificial terrain obstacles.

Measurement Devices

Upon measuring the vibration acceleration of the vehicle towed on terrain, PCB Piezotronics triaxial MEMS DC 200 mv/g 10 g acceleration sensors were used. Data were then collected using a Höttinger Spider 8 type data collection unit. The road profiles were registered using levelling devices functioning by the principle of communicating vessels, with the help of which the profile data were collected in increments of 100 mm. The soil's mechanical parameters were determined using a Farnell penetrometer and a GEONOR H60 hand-held shear vane tester.

The vibration accelerations registered during towing were evaluated using the DIAdem programme. The Origin programme was used for the further analysis of the data and the evaluation of the parametric equations. The determination of the power spectral density (PSD) of the road profiles was carried out using the ProVAL programme. The ADAMS programme was used to create the dynamic model of the trailer and to simulate the movements.

Results

The method, developed for the comparison of vehicle damaging effects of stochastic road profiles, can be determined with the use of power spectral density functions based on profile data of micro obstacles. In Figure 5. the power spectral density is presented, based on the values of different types of road profiles.

Pursuant to the use of power spectral density (PSD), with the help of a so called space-time conversion, the vehicle exciting frequency spectrum of the road profile can be defined. By the determination of the area under the PSD function curve (TG), the frequency excitation effect of road profiles, in case of road profiles of the same length value, should be comparable. Using this method, the frequency excitation effects of road profiles can be clearly characterized and grouped. Figure 6. shows the previously presented PSD curves.

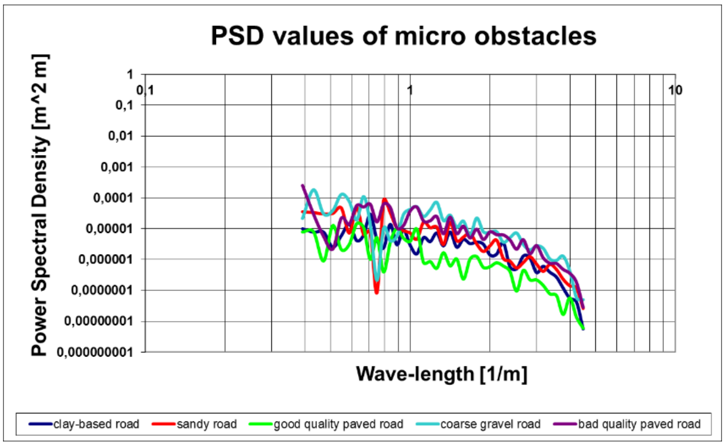

Figure 5. PSD curve of the micro obstacle system of off-road road types

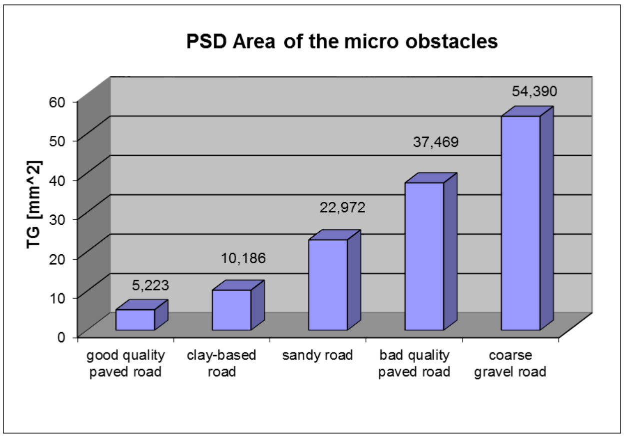

Figure 6. Areas of the PSD curve of the micro obstacle system of off-road road types

The figure clearly shows that good quality asphalt road has the least, while the gravel pebble road the greatest vehicle disruptive effect.

Our results, based on the profile data, are proved and checked by a series of measurements on a towed test vehicle. On the tested road profiles and at different towing speeds, We registered the vibrations of the passing test vehicle, which values are proportional to the vehicle devastating effect. Based on the root mean square values of the acceleration values, we have ranked the different types of road which are demonstrated in Figure 7.

Comparing the two diagrams it is clearly shown that in both cases, independently of the towing speed, the same road type sequence has emerged. This means that the method used for the comparative analysis of terrain profiles is suitable.

Determining the transfer function of the towed vehicle

The response function of a towed vehicle for excitation depends on the vibrational behavior of the vehicle. The dynamic model of a vehicle includes the weight, centre of gravity, the number and kind of flexibility and shock-absorbing elements of the structure. To determine these values measurements were required. To determine the characteristic angular frequency and the parameters that influence it, the tire spring characteristics of the vehicle had to be examined at different tire pressures. After that the damped period of oscillation of the structure had to be measured on the basis of different loads and different spring characteristic settings. In Figure 8. characteristic angular frequency features are shown characteristic for the test vehicle in case of different axle loads and spring characteristics.

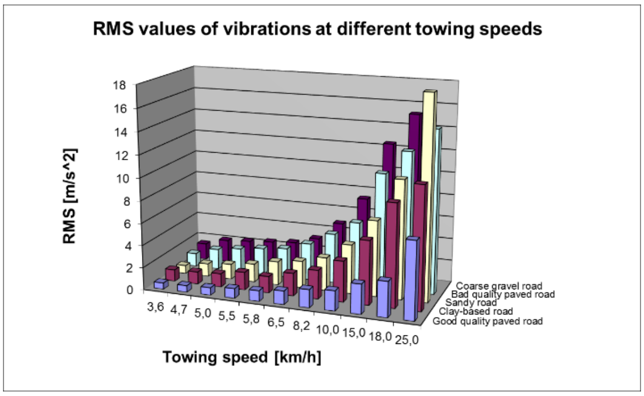

Figure 7. RMS values of the vibrations of off-road road types at different towing speeds.

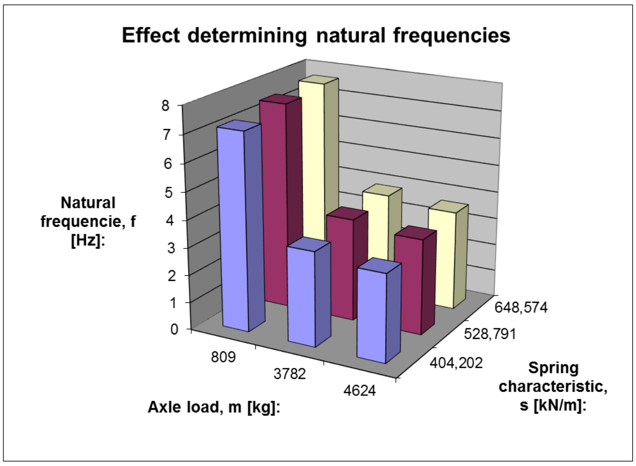

Figure 8. A comparison of the effects on the natural frequencies of the towed vehicle

Using the dynamics characteristics and the geometry data of the towed vehicle the dynamic computer model of the test vehicle was made. As a result of the motion simulation with the model, the transmission factor characteristic of the structure could be determined, for different excitation frequencies. Based on the resulting transmission factor values, characteristic angular frequency, characteristics of the structure was determined. A typical transfer function of the towed vehicle is shown in Figure 9.

Methods for measuring destructive effects

Based on vibration amplitude values measured on vehicles, a method has been developed for comparing the destructive effects of artificial (deterministic) and off-road (stochastic) road types. With the use of this method, the vibration excitation effect of various types of road can be compared based on the root mean square value (RMS) of vibrations registered on the test vehicle. The method can be applied under one condition, that is, by measuring the excitation effect; values of all profiles must be recorded with the same test vehicle.

Figure 10. clearly shows how the RMS values of the vertical vibrations measured on the vehicle vary in case of different road types due to the increasing towing speed of the vehicle.

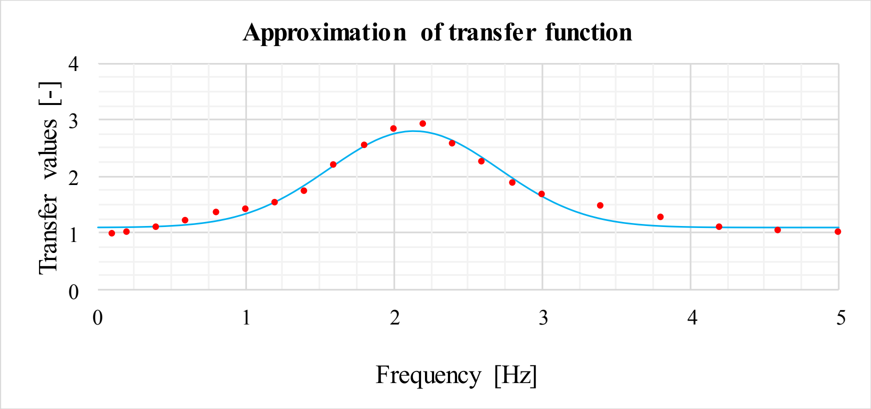

Figure 9. Transfer function between the profile excitation and the center of gravity of the towed vehicle.

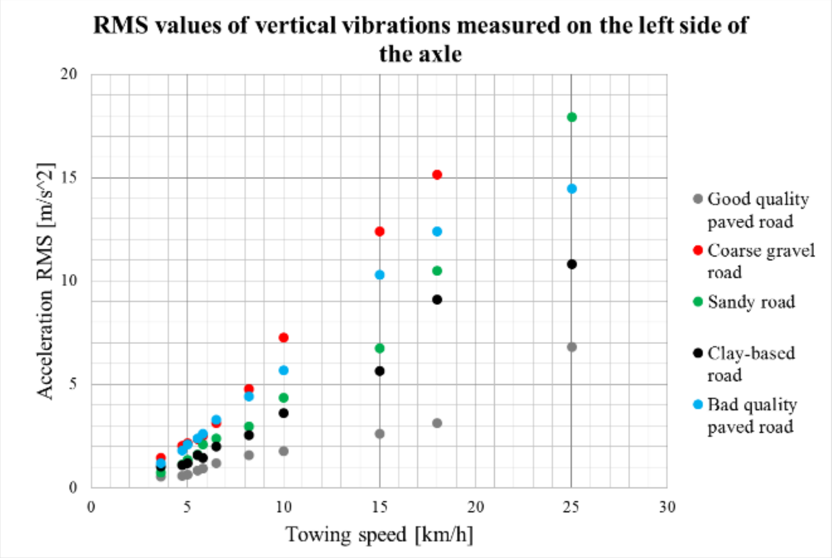

Figure 10. RMS values of vertical vibrations measured on the left side of the axle.

Vibration values resulting from terrain profiles had to be examined in the frequency amplitude range as well. Using the FFT (Fast Fourier Transformation), the response function of the system can be determined. The spectral analysis of the values measured on a pebble-gravel road is shown in Figure 11.

Based on the chart it can be stated that the curves belonging to different towing speeds envelop each other and in spite of the increasing amplitude, the characteristic frequency ranges of the system are not changed. It suggests that the destructive effects of road profiles on vehicles can primarily be compared on the basis of vibration amplitudes, more accurately on their RMS values.

Development of fatigue test methods of vehicles

Based on our knowledge of the comparative method of terrain profiles, a procedure was created, applicable for fatigue tests which ensures that the tested structures are, in all cases, loaded according to the appropriate load collective appropriate for the vehicles. In the case of the methods previously used for the validation of vehicles the vehicle damaging effect caused by the excitatory effect due to the same terrain obstacles. During the tests, the excitation of the road profile is the same in all cases, but the loads on the vehicles are different due to the transmission factors specific to the vehicle structure. In that unfavorable case when the natural frequency range of the vehicle is close to that of the standardized frequency of excitation, the structure is to bear much larger loads then the one fatigued on a road profile, having its own natural frequency in a different range. The developed fatigue test method, which is based on vibration values measured under the actual operating conditions (Figure 12.), is suitable to overcome this problem. The substance of the method is that an obstacle system must be built that causes similar vibration results as those measured under actual field conditions. With that provision, extreme vibrations caused by excitations near the natural frequencies can be avoided.

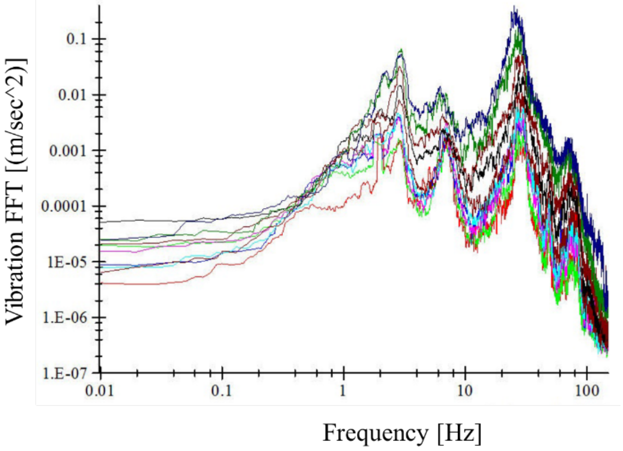

Figure 11. FFT analysis of the vertical vibrations measured on the left side of the axle on a pebble-gravel road by varying towing speeds.

Figure 12. Obstacle Calibration Measurement in Törökszentmiklós, at the site of CLAAS Hungaria Kft.

Conclusion

In summary, we was conducting several series of measurements during this research, where the results contain solution for both in the Theory of Off-Road Vehicles and for the validation of vehicles. A general method was developed for the comparability of stochastic road profiles based on the destructive effects of a micro obstacle system for vehicles. In addition, a new method has been introduced to compare the vehicle excitation effect of artificial terrain obstacle systems. Finally, the development of an examination procedure for fatigue test of vehicles has been implemented.

Based on the developed methods, in practice, more reliable, more adequate fatigue test systems can be created based on the loads under normal operating conditions. As a result, the examined structures will be more precisely dimensionable due to the corresponding load levels. Based on fatigue tests according to the new procedure, less off-road vehicles are expected to be produced that are under-or over-dimensioned due to improper validation procedures.

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