Available online at www.sciencedirect.com
ScienceDirect
Journal of Terramechanics 63 (2016) 1–12
Journal of Terramechanics
www.elsevier.com/locate/jterra

Country road and field surface profiles acquisition, modelling and synthetic realisation for evaluating fatigue life of agricultural machinery

Dimitris S. Paraforos [a,*], Hans W. Griepentrog [a], Stavros G. Vougioukas [b]

[a] University of Hohenheim, Institute of Agricultural Engineering, Garbenstr. 9, D-70599 Stuttgart, Germany
[b] University of California, Davis, Department of Biological and Agricultural Engineering, One Shields Ave., Davis, CA 95616, USA

Received 30 March 2015; received in revised form 8 September 2015; accepted 10 October 2015
Available online 26 October 2015

Abstract

Fatigue life of agricultural machinery is strongly affected by the surfaces that these machines operate on. In the present paper a sensor-frame was developed to acquire road and field profiles in absolute geo-referenced coordinates. The sensor-frame was validated by measuring discrete trapezoidal bumps with known dimensions resulting in a root mean squared (RMS) error of 6–8 mm. Profiles were acquired from a country road and from a mowed grass field. Using the quarter-car vehicle model, the movement of an agricultural vehicle was simulated for various speeds. The resulted vertical loads were rainflow-counted and the accumulated fatigue pseudo damage was calculated using Palmgren–Miner linear rule. Based on the derived Power Spectrum Density (PSD), the profiles were classified according to ISO 8608 standard. Two methodologies were followed to model and create a number of synthetic realisations for each profile: Direct Spectrum Estimate (DSE) and ISO based modelling. Simulating the produced synthetic profiles with the quarter-car vehicle model, the corresponding pseudo damage was calculated. The accumulated damages from the DSE models were closer to the corresponding ones from the measured profiles. ISO based models could not model the profile irregularities, which proved to contribute the largest part of the accumulated fatigue damage.

Keywords: Fatigue life; Road and field profiles; Quarter-car vehicle model; Accumulated damage; ISO 8608; Synthetic profile realisation

1. Introduction

Structural durability of agricultural machinery is of growing importance due to recent trends in machine weight and cost reduction and requirements for increased safety and reliability. In the past, farmers would accept the extra weight and cost necessary for generous safety margins (Harral, 1990). Nowadays, they seek cost effective machines that are also light enough not to damage the soil structure via compaction, which is known to have hazardous consequences on crop production cycles (Fountas et al., 2013). The increased size and weight of modern high-capacity agricultural implements make this goal difficult to reach. Estimating the expected fatigue life of agricultural machinery at the design stage becomes necessary to avoid machine breakdowns and at the same time keep implement weight and cost at reasonable levels.

A standard method for fatigue analysis of material specimens under constant amplitude load is the so called *S–N* approach (Lee et al., 2012). However, agricultural machines are subjected to repeating loads that are not constant and vary according to diverse machine operating modes and associated operating surfaces. Fatigue life due to variable amplitude loading is often assessed by combining the

* Corresponding author. Tel.: +49 711 459 24553; fax: +49 711 459 24555.
E-mail address: d.paraforos@uni-hohenheim.de (D.S. Paraforos).

http://dx.doi.org/10.1016/j.jterra.2015.10.001
0022-4898/

Palmgren–Miner linear damage accumulation hypothesis (Palmgren, 1924; Miner, 1945) with the *S–N* curves (Johannesson and Speckert, 2013). This method expresses the total accumulated damage due to variable amplitude loading as a linear combination of the individual accumulated fatigue damages induced by individual stress amplitudes.

Recent experimental work (Paraforos et al., 2014) has shown that surface geometry affects the expected fatigue life of agricultural machinery. In addition, surface geometry information can help evaluate vibration behaviour and acoustics. The problem that arises is how to measure accurately the surface profiles that agricultural machines operate on. Having this information, the surface profiles can be also modelled and simulated. The equation of motion of a linear vehicle model (with linear geometry and linear springs and dampers representing tyre and suspension elements) can be used to calculate the vertical loads (Gillespie, 1992) towards predicting fatigue life of agricultural machinery when operating on surfaces with varying roughness.

The problem of measuring road profiles occupied researchers many decades ago. All available techniques towards this aim in the 50s were reviewed in Yoder and Hampton (1958). Inertial profilometers that utilised an accelerometer, which measured the vertical response of the vehicle travelling on the road, was introduced in Spangler and Kelly, 1964. A detailed report on how to measure and interpret road profiles describing also a static method for obtaining off-road surface profiles was presented in Sayers and Karamihas (1998). Artificial neural networks have also been incorporated in order to reconstruct road profiles from measured vehicle accelerations (Ngwangwa et al., 2014). Latest surface acquisitions researches involve also three-dimensional (3-D) measuring technologies (Becker and Els, 2014).

Reporting of road surface profiles is standardised by ISO standard 8608 (Organization for Standardization, 1995) that uses Fourier analysis to calculate the Power Spectral Density (PSD) function of the surface vertical displacement. According to ISO 8608 the road profiles are modelled as Gaussian stochastic processes and can be classified in eight roughness levels. An early application of Gaussian models was presented in Dodds and Robson (1973). A recent review regarding the statistical properties of surfaces and the various modelling methods was performed in Ma et al. (2013). Furthermore, stochastic models of parallel road tracks have also been examined (Bogsjö, 2007). Although stochastic mathematical models that follow a normal distribution are commonly used, measured profiles may not accurately be described by a stationary Gaussian model (Bogsjö and Rychlik, 2009) and irregularities should be added to the stochastic model. As described in Chaika et al. (2004), in certain occasions, the off-road surfaces are neither Gaussian nor stationary. Thus, the ISO method to characterise the PSD can be deficient.

Limited research has been conducted on measuring and modelling road profiles for the agricultural sector where tractors and implements are usually operating on a very rough terrain. An early research on measuring and modelling agricultural-related surfaces was performed in Wendeborn (1965) where optical methods were used for measuring the surface unevenness. Measurement and mathematical analysis of field surfaces for agricultural machinery was presented in Laib (1977) based on acceleration measurements. A research on modelling rough terrains that are very important for agricultural engineering was conducted in Becker and Els (2014). A profiling technique which utilises stereography to obtain 3-D measurements of rough terrains was presented in Botha and Schalk Els (2015).

Vehicle accelerations from inertial profilometers have been widely used to reconstruct road profiles. Nevertheless, reaching from measured vehicle accelerations to surface geometry can be influenced by the tyres and the utilised vehicle (Ammon, 1992). Although several methodologies have been introduced that reduce the error caused by the vehicle suspension system, new technologies offer the possibility to develop measuring systems that are independent from the vehicle which is carrying the required sensors.

With the aim to assess agricultural machinery fatigue life this paper describes the development of a sensor-frame for measuring the road and field profiles in absolute geo-referenced coordinates. A simple vehicle model can be used to simulate the dynamics of an agricultural vehicle traversing these profiles. Subsequently, the resulted vertical loads are rainflow-counted and the accumulated fatigue pseudo damage is calculated using Palmgren–Miner linear rule. Based on their PSD, the profiles can be classified according to ISO 8608 standard. In many cases only the PSD of the profile is provided and not the actual measured profile. It should be examined if it is possible to create profile realisations from the provided PSD, which cause an accumulated fatigue damage to an agricultural vehicle almost equal to the one calculated from the actual road and field profiles.

2. Materials and methods

2.1. Instrumentation

A sensing system was developed to measure road and field surface profiles. All necessary sensors were attached on a metal frame, which was mounted on the rear three-point hitch of a tractor and was supported also by two wheels, which rolled on the surface (Fig. 1). The size and weight of the two wheels were chosen appropriately to prevent soil compaction while maintaining contact with the surface. Towards this goal, springs were added that pushed the wheels towards the ground. The width and diameter of the wheels were 180 mm and 350 mm, respectively. The positions of the laser pointers and the wheels