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Research Paper

Fatigue life assessment of a four-rotor swather based on rainflow cycle counting

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Assessing the fatigue life of agricultural machinery is a challenging task, especially when the machine assumes different configurations in various operating modes. In such cases, assessing fatigue life requires the recording of loads at high stress points on the machine chassis during every possible mode of operation. In this paper strain data were recorded at critical, high-stress points of a four-rotor swather, along with acceleration data on the main axle. All data were georeferenced using a global navigation satellite system (GNSS). Measurements were performed while the machine was transported on asphalt and along unmade roads that are typically used by farmers. Additionally, data were acquired during swathing operations in grass fields with different conditions and speeds. For each experiment performed the rainflow cycle counting method was used to extract load cycles from stress data, and the Palmgren-Miner method was used to determine the fatigue damage from each individual cycle, as well as the total accumulated fatigue damage. The results indicated the ability of the system to identify and quantify the damage that was accumulated in every operation mode of the swather. The transition between these operating modes, e.g. lifting the rotors for headland turning, proved to have a high impact on machine fatigue life. Fatigue damage under working conditions in grass fields was also increased by surface irregularities.

1. Introduction

The ability to assess the structural durability of machinery is of growing importance given the increasing – and often conflicting – demands of weight reduction and safe and reliable products (Berger et al., 2002). This is especially true for the agricultural engineering sector. In order to compensate for the variability of farm structures which results in different operation profiles, manufacturers have been developing advanced tractors and implements of ever increasing power, capacity and size, which in some cases (e.g. for swathers) can reach up to 19 m working width. Factors such as higher operating speeds and heavier machine weights affect the durability of agricultural machines, with high economic loss in the case of

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Nomenclature

b	fatigue strength exponent
D	accumulated fatigue damage
D_i	accumulated fatigue damage of a specific stress amplitude
E	modulus of elasticity, Pa
ε	measured strain, mm mm^{-1}
k	number of load levels
N_f	number of cycles to failure
$N_{i,f}$	number of cycles to failure at a specified stress amplitude
n	number of cycles at a specific stress amplitude
n_i	number of applied stress cycles for the i th load level
S_a	stress amplitude that caused failure at N_f, Pa
S'_f	fatigue strength coefficient, Pa
S_m	mean stress, Pa
S_σ	calculated stress, Pa

a machine breakdown. In the past, farmers would accept the extra weight or extra cost resulting from the generous safety margins that were placed on machines to avoid failures (Harral, 1990). However, today's farmers seek high-capacity cost effective machines that are also light enough to prevent the damage of soil structure (soil compaction), which can have hazardous consequences for the crop production cycle (Fountas et al., 2013) and requires increased energy inputs for its alleviation (Håkansson & Reeder, 1994). Hence, assessment of fatigue life is necessary to avoid failure while keeping the weight and cost reasonable.

Throughout their working lives, agricultural machines are subjected to repeating loads that vary according to their different operating modes and associated operating surfaces. At points subjected to high stresses, plastic deformation can gradually develop and cause permanent damage. In order for fatigue life to be assessed, strain data from such high-stress critical points on stressed machine components must be obtained or estimated.

A standard method for fatigue analysis of material specimens under constant amplitude load is the so called S–N approach (Lee, Barkey, & Kang, 2012). In this approach the stress amplitude S_a, as well as the number of load cycles N_f until failure are recorded. Fatigue life due to variable amplitude loading is often assessed by combining the Palmgren-Miner linear damage accumulation method (Miner, 1945; Palmgren, 1924) with the S–N curves (Johannesson & Speckert, 2013). This method expresses the total accumulated damage due to variable amplitude loading as a linear combination of the individual accumulated fatigue damages of individual stress amplitudes.

The Palmgren-Miner method requires a cycle counting algorithm to estimate the equivalent load cycles of varying stress amplitudes. Several cycle counting techniques for variable amplitude loading and fatigue analysis have been introduced in the literature (ASTM., 2005). The most commonly used is the rainflow cycle method, which was developed by Matsuishi and Endo (1968). Their algorithm draws on intuition by relating stress reversal cycles to the streams of rainwater flowing down the roof of a pagoda. Dowling (1971) investigated the validity of this method and concluded that it leads to better fatigue life predictions; other methods can result in notable differences between predicted and measured fatigue life.

Many variations of the initial rainflow counting algorithm have appeared in the literature. Anthes (1997) presented a modified algorithm that considered the load sequence – not just the superposition – while translating load data into damaging events. A rainflow counting method that is suitable for on-line counting was introduced by Dressler, Hack, and Krüger (1997), as in certain situations it is preferable to store rainflow data directly rather than storing the load time series data. In the present paper the off-line rainflow cycle counting algorithm proposed by Rychlik (1987) was used because it is more suitable for statistical and mathematical analysis.

One of the first important studies in fatigue load analysis of agricultural implements was performed by Kloth and Stroppel (1936), who determined the operational load of a binding mower. Koike and Tanaka (1976) measured the strains at different locations on the rear axle housing of a tractor, in order to predict fatigue strength. A review of tractor-related cumulative damage is presented by Renius (1977); examples of fatigue analysis of tractor components are also described. The fatigue life of tractor transmission components has also been investigated (Kim, Ryu, & Kim, 2001). In a more recent study related to tractor structural tests, Mattetti, Molari, and Sedoni (2012) collected and analysed strain data from an 80 kW tractor.

The existing literature has focused on the fatigue analysis of tractors and their components, and very limited research has been conducted on predicting the fatigue life of agricultural implements. The fatigue life of a rotary cultivator was investigated by Chisholm and Harral (1989) using rainflow counting of strain data. Palmer and Glasbey (1990) built an apparatus for collecting load histories of a tine working in soil, in order to estimate the corresponding fatigue life. Fatigue life of rotary tiller blades has also been investigated (Gao, Wang, Wang, & Chai, 2011), while Abo Al-kheer et al. (2011) presented a model to describe the spatial variability in tillage forces and the methods that can be used to estimate the life time of tillage machines.

In addition to stress data from the machine chassis, the acquisition of operating surface data is also crucial for fatigue analysis. The combination of surface characteristics, wheel parameters and tractor speed significantly affect the accelerations that are produced on the axle of the implement (Biller, 1981). These accelerations play an important role on strains and forces that are developed on the main chassis of the machine. During prototype development when the actual machine is not yet available, agricultural vehicle simulation can be also performed using digital road profiles (Bitsch, Dreßler, Marquardt, Nikelay, & Gölzer, 2007).

A project was set up to investigate agricultural machine stress under present day operating conditions as a response to reports by farmers about damaged or failing components (Paraforos, Griepentrog, & Sturmfels, 2013). The aim was to establish a generic methodology for performing accelerated structural tests on agricultural implements by simulating their transport and working life in test facilities, using data