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Research Paper

Methodology for designing accelerated structural durability tests on agricultural machinery

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Structural durability assessment is one of the last stages before an agricultural machine prototype reaches the market. Accelerated structural testing (AST) aims at reducing the time and resources required for this stage. According to existing AST methodologies, strain measurements are used to characterise machine loads under real-world operating conditions, and calculate resulting accumulated fatigue damages. An operation profile is defining the conditions to be monitored but also the target damages of the accelerated testing. Next, rainflow cycles are extrapolated to include non-measured high-amplitude loads. Finally, the machine prototype travels on suitable proving grounds to replicate real-world service loads. The number of laps required to reach the target damage values is the result of optimisation, given the fatigue damages accumulated during each lap.

In this paper the above AST methodology was implemented on a four-rotor swather, which is an agricultural implement that *drastically changes structure configuration* during its working life, depending on its operating mode. Furthermore, recognising the fact that the damage accumulated during each lap varies, automated test facilities were utilised, and Monte-Carlo sensitivity analysis was introduced as part of the AST methodology, to study the effects of damage-per-lap variance on the required numbers of laps calculated via optimisation. When average values were used for lap damages, the total testing time was 1228 h with an acceleration factor of 3.3. However, conservative test design using the 99.9th percentile of the testing time simulation results, required 7.1% longer testing time, leading to a lower acceleration factor equal to 3.1.

1. Introduction

Agricultural machinery developers face the challenge of ever-reducing available time to bring a new product to market. Assessment of fatigue life is necessary to avoid machine breakdowns and at the same time keep weight and cost at reasonable levels. Accelerated testing techniques that can predict the fatigue life of a developed product are very important and play a major role in the design process. This is accomplished by extrapolating results from a limited set of measurements and by performing tests under controlled conditions that can characterise a machine's lifetime fatigue.

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Nomenclature

b	fatigue strength exponent
D	accumulated fatigue damage
D_i	accumulated fatigue damage of i th stress amplitude
$D_{SC_1,j}$	accumulated fatigue damage of j th channel for one lap at the test facilities under swathing condition and speed 4.5 km h^{-1}
$D_{SC_2,j}$	accumulated fatigue damage of j th channel for one lap at the test facilities under transport condition and speed 5.5 km h^{-1}
$D_{TC_1,j}$	accumulated fatigue damage of j th channel for one lap at the test facilities under transport condition and speed 4.5 km h^{-1}
$D_{TC_2,j}$	accumulated fatigue damage of j th channel for one lap at the test facilities under transport condition and speed 6 km h^{-1}
$D_{TRG,j}$	target accumulated fatigue damage of j th channel for use at the test design procedure calculated from the machine operation profile
E	modulus of elasticity, Pa
k	number of load levels
N_f	number of cycles to failure
$N_{i,f}$	number of cycles to failure at i th stress amplitude
n_i	number of applied stress cycles for the i th stress amplitude
S_a	stress amplitude that caused failure at N_f, Pa
SC	swathing condition
S'_f	fatigue strength coefficient, Pa
S_m	mean stress, Pa
S_σ	calculated stress, Pa
[Target]	vector with the damage values that represents the entire life of the machine
TC	transport condition
[TT]	matrix with the damage values for each tested mode
[X]	solution vector that represents the required number of laps of each tested mode
X_{SC_1}	required number of laps under swathing condition and speed 4.5 km h^{-1}
X_{SC_2}	required number of laps under swathing condition and speed 5.5 km h^{-1}
X_{TC_1}	required number of laps under transport condition and speed 4.5 km h^{-1}
X_{TC_2}	required number of laps under transport condition and speed 6 km h^{-1}

Many techniques have been examined, mainly from the automotive sector, to improve the accuracy of life time prediction (Berger et al., 2002). One of the first investigations of structural durability of agricultural implements was conducted by Kloth and Stroppel (1936), who measured the loads on a binding mower. On-farm service loading of a rotary cultivator was also examined (Harral, 1990).

In order to perform structural durability tests of agricultural machinery, the test designer should have solid knowledge about the operational (service) loads that the machine will face during its life (Johannesson & Speckert, 2013). The loads under all possible operating modes, the number of hours per year under each mode, and the total number of years of the machine's lifetime, define the *operation profile*. This varies significantly, and depends strongly on many factors such as customer usage, farm and field size, field structure shape, etc. In order for the test designer to acquire an operation profile, one option is to use questionnaires addressed to farmers that use the machine. New methodologies, like machine communication information analysis, as standardised in ISO 11783 (ISO 11783-10, 2015), can help to extract the required operation profiles (Kortenbruck, Griepentrog, & Holzhauer, 2014).

Agricultural machines are subjected to repeating loads that vary depending on their different operating modes and associated operating surfaces (Paraforos, Griepentrog, & Vougioukas, 2016). Fatigue life due to variable amplitude loading is often assessed by counting the number of cycles in the loading history and then the Palmgren-Miner's method (Miner, 1945; Palmgren, 1924) in combination with the S–N curve of the material, is adopted (Johannesson & Speckert, 2013). A cycle counting algorithm is used to estimate the equivalent load cycles of varying load amplitudes. The most common is the rainflow cycle method (Matsuishi & Endo, 1968), which has been reported to give the best results compared to other cycle-counting techniques (Dowling, 1971).

However, the high cost and the limited time available for the necessary tests limit the duration of the repetitions that can be made under real-life conditions. These limited tests and measurements cannot fully describe the entire life of the machine. This is why extrapolation methods are used to evaluate conditions of high amplitude loads that have not been recorded. These unrecorded loads will typically occur only a few times during the machine life (i.e. big holes on the ground or big bumps), yet they have a high impact on its fatigue life. Although load extrapolation in time has been examined (Johannesson, 2006), the most common extrapolation method is the *rainflow matrix extrapolation* (Dressler, Gründer, Hack, & Köttingen, 1996; Johannesson & Thomas, 2001). In the present study extrapolation in the rainflow domain was performed, because it requires less computation and is suitable for the large amounts of data that result from long duration tests.

At the first stages of machine development, test rigs that simulate operating loads are utilised to determine structural durability limits of the entire machine or its components. A durability test for a rotary cultivator was introduced by Harral, Chisholm, and Chestney (1985). During this test hydraulic actuators were used to simulate complex field loading. Mattetti, Molari, and Vertua (2015) presented a methodology for accelerating durability testing of tractor structural parts using 4-post benches. In recent years virtual durability test rigs have been utilised by the automotive industry, which rely on numerical simulation to analyse and optimise the design (Dressler, Speckert, & Bitsch, 2009).