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Multi-criteria optimization of test rig loading programs in fatigue life determination

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ABSTRACT

Designing good test rigs for fatigue life tests is a common task in the automotive industry. The purpose of this work is to show that the problem to find an optimal test rig configuration and actuator load signals can be formulated as a mathematical program. A new optimization model that includes multi-criteria, discrete and continuous parts is introduced.

Block structure of the load signals is assumed from the beginning, which highly reduces complexity of the problem without deterioration of the overall result. Also, actuators' alignment is optimized, which makes it possible to take bending moments into account and thus improve quality of the test. As a result, the new model gives significantly better results, compared with the other approaches in the test rig optimization.

1. Introduction

Durability is one of the most important physical properties of vehicle components. The natural procedure to assess their structural damage is the test drive, but it is expensive, takes a lot of time and can be done only after the whole automobile is assembled. One of the possible ways to make the tests cheaper and faster is to use the test rigs, in which actuators create load signals to emulate the real test drive damage.

The goal of this work is to formulate and treat numerically an optimization problem that allows to design test rigs capable of approximating fatigue damage at several chosen hot spots, assuming that the signal consists of several blocks of constant amplitude and mean. Several models, varying in optimization parameters, are studied. The most general problem considers attachment point for fixation to the test rig, number and attachment points of the actuators, actuators directions, numbers of cycles and amplifying parameters of each actuator in every block.

2. Modelling

Let us start with a brief description of fatigue damage calculation and criteria that can be used to assess the quality of the test. The loading time signal generates a corresponding stress–strain signal during the test drive. A three-dimensional stress tensor has six components σ_{xx}, σ_{yy}, σ_{xy}, σ_{zz}, σ_{xz}, σ_{zy}, in general. However, the coordinate system can be rotated for each surface element so that the z-components are neglected. Hence, the stress tensor becomes two-dimensional with only three components σ_{xx}, σ_{yy}, σ_{xy}. For damage computation a scalar stress signal is needed. In this paper scalarization is done by the critical plane method [1]. The overall signal is irregular and should be converted to the block signal (Fig. 1) with the rainflow counting algorithm (see [2,3]). The block signal consists of several blocks with stress–strain cycles of constant amplitude and mean, which can directly mapped to the fatigue damage.

Consider a component (Fig. 2) that has several attachments for either an actuator or a fixation to the test rig. Hot spots, where the reference damage values have to be approximated, are selected by engineers for the damage field computed from real loading. Block structure of the loading signal generated by the actuators is assumed. Such signal is far from real loading cases. However, this is not important since only the resulting damage values are approximated but not the actual stress signal. Block structure

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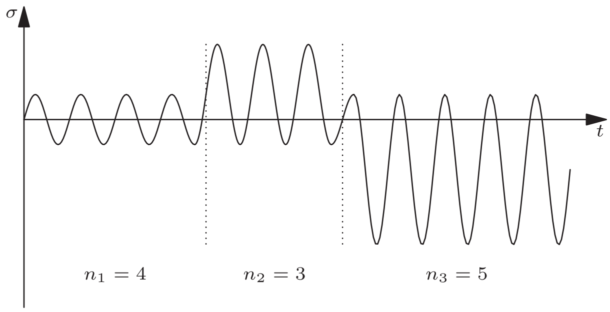

Fig. 1. Block signal with 3 blocks.

assumption helps to avoid the use of the rainflow counting and makes the optimization problem tractable.

2.1. Damage computation

There exists a hierarchy of models for damage calculation. The simplest model considers a uniaxial fully reversed signal, when stress is orthogonal to the surface element and it oscillates with zero mean from compression to tension. It can be extended to cope with more general stress signals. Here a basic fatigue computation is briefly overviewed in order to describe necessary tools for later damage approximation and optimization.

Uniaxial fully reversed stress. Fatigue damage depends on the number of stress–strain cycles and on their amplitudes in the case of uniaxial fully reversed stress, when mean stress equals to zero. Hence Basquin model [4] for one cycle damage is combined with Palmgren–Miner [5,6] rule which implies that the damage produced by block signals equals the sum of damages in each block. Consequently, the following relation for damage d at a hot spot is valid:

$$d = \sum_{i=0}^{B} n_i g(\sigma_i), \tag{1}$$

where n_i is number of stress–strain cycles with amplitude σ_i for block $i = 1, \ldots, B$ and $g(\sigma)$ is a Basquin curve:

$$g(\sigma) = \frac{1}{N}\left(\frac{\sigma}{\sigma_s}\right)^k \tag{2}$$

The map (2) is continuously differentiable and strictly monotonically increasing.

Multiaxial fully reversed stress. The direction of principal stresses can change under the multiple loading signals and thus normal stresses σ_x, σ_y and shear stress σ_{xy} may be involved. All components are combined in a stress vector $\boldsymbol{\sigma} = [\sigma_x, \sigma_y, \sigma_{xy}]^T$. Scalarization of the stress vector with Mohr's circles [1] allows us to modify Eq. (1) for multiaxial stress damage computation:

$$d = \max_{\alpha} \sum_{i=0}^{B} n_i g(|\mathbf{c}(\alpha)^T \boldsymbol{\sigma}_i|), \tag{3}$$

where the critical plane is a plane in which the fracture or crack nucleates first and its normal $\mathbf{c}(\alpha)$ is defined as:

$$\mathbf{c}(\alpha) = [1 + \cos\alpha, 1 - \cos\alpha, 2\sin\alpha]/2 \tag{4}$$

Overall damage d in Eq. (1) is maximized with respect to the critical plane angle α.

Arbitrary mean stress. The assumption of fully reversed loading can be relaxed by using mean stress correction methods, such as Goodman and Gerber curves and their modifications [7,8]. These methods use turning points of a stress–strain cycle σ_1 and σ_2 to compute corresponding fully reversed stress σ. Hence, Eq. (3) takes the following form:

$$d = \max_{\alpha} \sum_{i=0}^{B} n_i g[h(\sigma_{1,i}(\alpha), \sigma_{2,i}(\alpha))], \tag{5}$$

$$\sigma_{j,i} = \mathbf{c}(\alpha)^T \boldsymbol{\sigma}_{j,i} \quad \text{for} \quad j = 1, 2, \tag{6}$$

where $h(\sigma_{1,i}, \sigma_{2,i})$ is a mean stress correction depending on turning points $\sigma_{1,i}$, $\sigma_{2,i}$ of the stress–strain cycles in block i and $\boldsymbol{\sigma}_{j,i}$ are respective stress vectors. If the fatigue damage d exceeds 1 then the component fails, i.e. a fracture happens.

2.2. Stress computation

Eqs. (5) and (6) allow to calculate damage in case of multiaxial block loading given turning points of stress–strain cycles. Computation of the stress vectors depends on many parameters of the test rig including the placement and alignment of actuators and the choice of fixation and loading signals applied in every block. In this section, these notions are formulated and a damage model that suits for optimization is provided.

Equilibrium equation. Load, attachment and mount point have to be defined. After that a load equilibrium equation can be derived for a chosen configuration of the test rig.

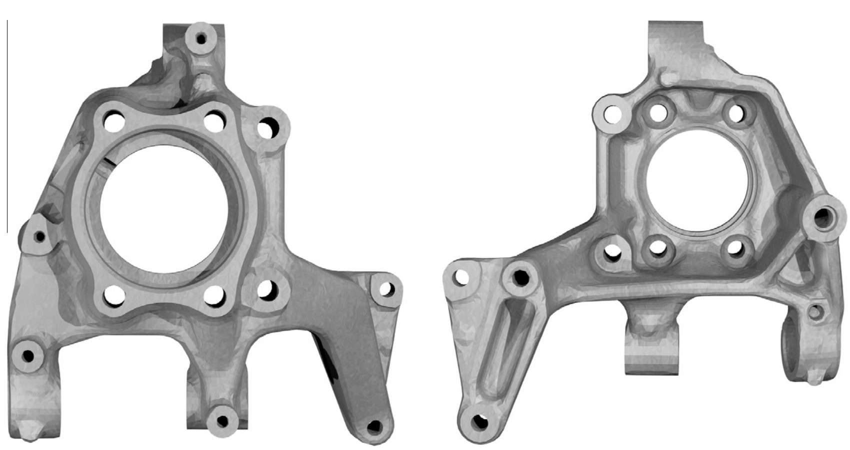

Fig. 2. A knuckle for passenger cars.