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Physical model based reliability analysis for accelerated life testing of a fuel supply system

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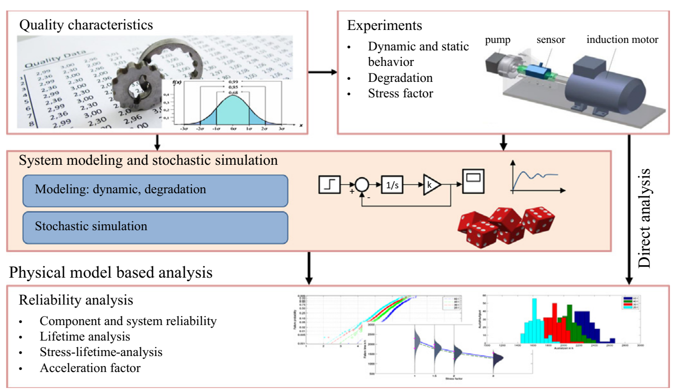
HIGHLIGHTS

- A simulation approach for physical model based reliability analysis is introduced.
- A fuel supply system of a household oil burner is analyzed as a test case.
- The fuel supply system is modeled inclusive component and fuel degradation.
- A functional relation of stress factor and acceleration factor is described.

GRAPHICAL ABSTRACT



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ABSTRACT

In a fuel supply system of a conventional household oil heating system the fuel degrades over time depending on the system temperature, the tank volume and the flow rates. The test fuel is a blend of 80 vol.% conventional domestic heating oil and 20 vol.% fatty acid methyl ester from rapeseed oil feedstock. The fuel will increase the deposits in the fuel supply which lead to system failures. In this paper a model based approach is introduced for the analysis of accelerated life testings. The impact of the tank volume on the failure time is analyzed. A well balanced physical model is set up for stochastic simulation. The model contains short term dynamic and long term transient degradation effects that have an important impact on the system reliability. The degradation effects of the components and the used fuel cause a system failure over time. A system failure is detected when the volume flow of the fuel supply declines. The analysis shows that the typical variances of characteristic parameters lead to a significant distribution of failure time. Furthermore, the functional relation between tank volume as stress factor and failure time is described.

1. Introduction

A major problem of the reliability analysis of experimental data is that a large number of tests is needed in order to describe the statistical relations of component characteristics and failure time. With a low number of experimental samples a statistical analysis is difficult to achieve. Consequently the analysis is reduced to general statements and a complete statistical analysis of failure data is not possible. Commonly, due to cost and time reduction, only a part of a system can be analyzed in detail. Models for lifetime analysis are generally either data-driven or derived from physical principles via stochastic processes [1]. However, only a few methods

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Nomenclature

Roman letters

A	surface area
AF	acceleration factor
C	capacity
Da	Damköhler number
d	deflection distance
i	current
J	mass inertia
k	constant
L	inductance
M	torque
m	mass
$\dot{m}$	mass flow
n	rotation speed
p	pressure
$\dot{Q}$	thermal power
R	resistance
s	stress factor
t	time
U	voltage
$\dot{V}$	volumetric flow
V	volume
v	velocity

Greek letters

α	heat transfer coefficient
β	shape parameter
γ	location parameter
ϵ	motor specific constant
Φ	source term
ϕ	dynamic viscosity
ψ	motor specific constant
ρ	density
θ	temperature
τ	residence time
ζ	pressure loss coefficient
μ	mean
σ	standard deviation
ω	angle speed

Indices

a	accelerated
Byp	bypass
Cap	capacitor
F	filter
fl	fluid
K	cake
lam	laminar
$MTTF$	mean time to failure
Mot	motor
Noz	nozzle
n	non-accelerated
O	orifice
oxi	oxidation
P	Piston
Pre	preheater
PRV	pressure relief valve
r	rotor
s	stator
th	theoretical
tur	turbulent

have been introduced so far to support Model Based System Engineering (MBSE) and Reliability, Availability, Maintainability, Safety (RAMS) activities e.g. MeDISIS [2], SysML models [3], RAMSAS [4,5] or physical models maintenance modeling [6]. The reason is mainly due to absence of a consistent modeling framework including physical models and degradation effects. A major benefit of a physical modeling approach, however, is that the simulation of validated models can be repeated under different boundary conditions.

1.1. Principles for accelerated life testing modeling

Accelerated tests are distinguished on the observed property. While accelerated life testing (ALT) generate information on failure time, the accelerated degradation test (ADT) is used for the explicit temporal description of degradation data [7]. Most of the underlying principles are the same for both ALT and ADT. ADT modeling is commonly performed using regression models for the description of degradation paths. In this paper physical models describe the aging behavior, hence, in the following the more general principles of ALT are introduced. ALT is a standard technique in industry to reduce the test time of products and has created numerous literature and industry standards [8–15]. However, most of the approaches use statistical analysis of experimental data only, without considering physical background using models. A good overview on data-driven regression models are found in the works of Lu, Meeker, Escobar and others e.g. [16–19]. A generic design of an ALT program is summarized by Escobar and Meeker [19].

- The ALT related to an *increased use rate* is performed by increasing load cycles per time. An example of this approach is described in Dowling [20]. In this work, the crack growth of metals has been described as a function of the load cycles.
- In ALT related to *increased environmental influences*, the degradation is accelerated by chemical or physical mechanism. Examples are found in the degradation of fuels by UV radiation [21].
- In ALT with *increased aging rate* temperature and humidity are changed in such a way that chemical processes lead to certain failure mechanisms. For the temperature-dependent aging behavior of liquids and gases the Arrhenius approach and Eyring approach is chosen. Liška [21] used the Arrhenius approach for the description of the aging behavior of fuels.
- In ALT related to *increased stress*, degradation will be caused by increased tension, pressure, voltage or other process variables.

The ALT models contain an *acceleration factor*, that is defined as the relation of accelerated and non-accelerated failure time [19]. The *stress factor* is a characteristic change in the system operation in order to force the degradation behavior. It is commonly defined as the relation of two physical values (e.g. load cycles, temperatures, etc.). The choice of a suitable stress factor is determined by the materials and the operation of the technical system. In ALT, methods are used to specify the effects of stress factors on the system behavior. In general, one or multiple stress factors can be used simultaneously [22]. Besides the standard approach different variants exist. When the stress factor is gradually increased with time, the test is called a step-stress accelerated life testing (SALT). The