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Model validation and uncertainty analysis in the wear prediction of a wet clutch

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ABSTRACT

An uncertainty quantification analysis is performed to further investigate the nature of the "two-stage" wear process of the paper-based friction lining in a wet clutch. In this approach, the results of a computerized wear prediction model are examined through sensitivity analysis and a model validation that utilizes the Monte Carlo (MC) method. Extensive computational results that take into account the uncertainty and variability in the input data are presented to gain insight into the evolution of temperature and wear during the engagement process.

1. Introduction

The study of wear of the friction lining in a wet clutch has long been of interest to the tribology community because of its critical role in vehicle transmission and the overall durability of the drivetrain. Experimentally, Lingesten et al. [1] reported an intriguing two-stage wear behavior after a large number of engagement cycles that had not been observed before. Subsequently, Li et al. [2] developed a model with the relevant degradation mechanisms to explain the change in the wear rates during the cycles and to provide predictions with different power inputs. While the general trend and magnitude of the predictions yielded satisfactory results compared with experiments, some discrepancies remain that are attributed to the uncertainty in the input data. In this paper, we perform statistical interpretation of the model to gain better insight for such consideration. According to Roy and Oberkampf [3], a direct figure comparison between test and simulation is insufficient for the verification and validation framework because it gives little information on the extent of agreement that depends on the uncertainties involved in both test and simulation. In contrast, the statistical methods and relevant computation usually work better for quantification purpose.

The predicted wear rate, which is the system response quantity (SRQ) of interest, is influenced by various sources of uncertainties: model inputs, model form, and accuracy of numerical solution. Compared with deterministic simulations, the computational costs in uncertainty quantification are much greater. For quantitative characterization, these uncertainties are recognized as either "aleatory" or "epistemic". Aleatory uncertainties emerge from the inherent randomness in the experimental measurements (precision errors) of the input data. For a sufficiently large sample, it follows a distribution that can be described by the probability density function (PDF) or cumulative distribution function (CDF). Epistemic – also called ignorance uncertainty or reducible uncertainty – is generated due to the lack of knowledge, which could possibly be eliminated by obtaining additional experimental data or performing theoretical analyses. Usually the epistemic uncertainty is irrelevant to specific PDF and is thought to be any value in the interval of equivalent probability. These sources of uncertainties can be estimated for evaluating the total variation in the simulation. For this purpose, Monte Carlo (MC) methods are widely used for stochastic computations. With the deterministic system with random input data, the repeated sampling of relevant distribution would calculate the variation in the predictions. We apply the MC method because of its simplicity, robustness and the fact that with access to high performance computing recourses, the numerical experiments necessary for prediction of wear will not become prohibitively expensive.

Composed of a series of separator disks, automatic transmission fluid (ATF) and friction material bonded to core disks, a wet clutch system is a complex device whose performance

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Nomenclature

c	heat capacity (J/kg K)
d	disk thickness (m)
d^*	area validation metric (same unit with SRQ)
E	elastic modulus (Pa)
f	friction coefficient
h	convection coefficient (W/m^2 K)
H	thickness of the friction lining (m)
ΔH_i	wear rate (m/cycle)
I	inertia of friction disk
k	conductivity (W/m K)
K_i	wear coefficient (1/cycle)
P_0	engagement load (MPa)
n	surface asperity density (m^{-2})
q	frictional heat flux (W/m^2)
R	Boltzmann constant (J/K)
R_i	inner radius (m)
R_o	outer radius (m)
T	temperature (K)
Δt	duration of an engagement cycle (s)
U	activation energy (J)
$\overline{\Theta}$	dimensionless temperature
ω_L	angular speed of separator disk (rpm)
ω_H	angular speed of friction disk (rpm)
β	asperity radius (m)
ε	compressive strain of the friction lining
η	numerical precision of MC simulation
γ	asperity tip radius (m)
κ	thermal diffusivity (m^2/s)
σ	standard deviation of surface heights (m)
μ	viscosity (Pa s)
ρ	density (kg/m^3)
θ_0	section angle

Subscripts

1	first stage wear model
2	second stage wear model
b	friction material
f	ATF
s	separator disk
c	core disk

Superscripts

p	prediction
t	test

characteristics depends on multiple, coupled physical effects involved during the operational cycles. The friction material is paper-based type and is porous, rough, and deformable. Once squeezed under the applied engagement load, it experiences micro asperity contact with the separator disk at the surface asperity level. As a result, a large amount of heat is generated at the sliding interface. The lubricant, i.e. ATF, produces hydrodynamic pressure and the cooling action by the flow of lubricant that reduces the overall temperature. The engagement behavior and the temperature profile are closely related to different material properties and operational configurations. For prediction of the friction lining wear after multiple engagement cycles, thermal degradation and thermomechanical wear must be properly taken into account. These factors depend on the temperature history and the stress conditions during the engagement cycle and, therefore, the investigation of SRQ with respect to model parameters and the uncertainty quantification can potentially contribute to more complete knowledge of the clutch model and the quality of wear prediction.

This paper presents the framework for the verification, validation, and uncertainty quantification (VV&UQ) in the application of wear prediction in a wet clutch. First, in Section 2, the procedure of computerized prediction is presented to give an overview of deterministic simulation, including comprehensive modeling, numerical error analysis and the sensitivity of SRQ to model parameters. In Section 3, the sources of uncertainty in the model and the test are discussed and characterized. The relevant validation metric results are presented in Section 4 through the MC simulation. The paper ends with summary and concluding remarks in Section 5.

2. VV&UQ framework for computerized wear prediction

While a test rig designed and operated by Lingesten et al. [1] is available to measure the wear of the friction lining, the costs involved in time and recourses motivate a reliable computational model. If successful, accurate predictions will complement physical testing and allow further consideration of different wear factors, including energy levels, groove design, and material properties.

A flow chart demonstrating the procedure of wear prediction with model validation and uncertainty quantification is shown in Fig. 1. Based on the two-stage wear observations by Lingesten et al. [1], the degradation mechanism of wear translates into the material's thickness reduction as a function of the energy level and the stress conditions. Thus, an engagement model is necessary to compute the wear rate by obtaining the thermal and mechanical conditions [2]. As shown in [4], a thermohydrodynamic (THD) analysis is needed to accurately predict the behavior of the lubricant. However, given the complexity of the model and limited inputs, a simplified heat transfer model is initially used to investigate the effectiveness of wear modeling as preliminary analysis. Next, based on the obtained information, the simulation is improved by implementing a comprehensive THD model. With sufficient accuracy and appropriate simplified assumptions, an optimal model is proposed to effectively achieve the prediction purpose. The last, but an important step, is validation of the model by using statistical analysis, which provides SRQ variation over the uncertainty involved in the model and the inputs. The above procedure is generally applicable for many other engineering simulations.

2.1. “Two-stage” wear observations and wear mechanism

Fig. 2 shows the observed “two-stage” wear behavior of the friction material during the engagement in a wet clutch experiments as reported by Lingesten et al. [1]. It reveals that the thickness of the friction lining is initially reduced at a low rate and later, after a certain number of engagements, is translated to a faster – but still steady – wear rate. According to Li et al. [2], the cumulative thermal degradation of the cellulose fiber is responsible for the reduction of the friction lining volume during the first wear stage. The change in thickness can be described by the