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A novel approach for modeling the multiscale thermo-fluids of geared systems

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ABSTRACT

Geared systems are critical to the power generation and transportation industry. While thermal and multiphase flow physics are among the leading determinants of the performance, durability and life of these systems, limited capability has been developed to predict their thermo-fluid behavior. This is, in part, due to the significant complexity and multi-scale nature of the physical phenomena involved. This paper aims to address this issue and presents a novel modeling approach and supporting theoretical analysis for predicting the unsteady thermo-fluids of geared systems that experience periods of constant gear speed operation. A regime map is developed that characterizes the dominant heat generation mechanisms of geared systems. The regime map, along with a scaling analysis for the transient processes within the system is employed to quantify the separation of time-scales among various thermo-fluid phenomena. This leads to illustrate the impracticality of the conventional time marching methods of solving conservation equations to resolve the thermo-fluids of the system for the prevalent range of operating conditions. A set of numerical and mathematical approximations are established to reduce this separation based on physical motivations. In addition, a novel solution approach and associated mathematical derivation is presented that exploits the separation of time-scales and solves for the time-dependent stationary state of the system with modest computational cost. This comes at the expense of not capturing long term transient heat transfer phenomena such as the initial system warm up. The numerical approach is successfully verified against a traditional simulation approach for an artificial gear system specially constructed such that it is amenable to simulation using both approaches. Finally, the numerical approach is demonstrated on a realistic lubricated gear system. Results verify key assumptions associated with the approach and to enable the analysis of thermo-fluid physics of the system under various operating conditions.

1. Introduction

Efficiency of geared systems, such as power, propulsive systems and rotorcraft or aircraft applications, has been a renewed interest and increasingly important research topic due to more stringent energy economy requirements and environmental concerns. Although gearbox efficiency varies from 98% to 99% for the best designed high power applications, it still equates to losses in megawatts Weiss and Hirt [1]. Power losses in a gearbox can be classified into two basic groups: load-dependent (mechanical) power losses and load-independent (spin) power losses. The load-dependent losses are caused primarily due to friction at the gear and bearing contacts. The load-independent power losses are influenced largely by the lubrication method employed, such as oil churning in the dip lubrication and windage in the jet lubrication. These losses eventually are converted into heat and noise, and dissipated into surrounding environment, so improved gear efficiency also results in less heat generation within the gearbox and mitigates gear failures associated with temperature rise, such as scuffing.

In recent decades, many experimental and semi-empirical studies (e.g. [2–9]) have been conducted on various sources of power loss in the gearbox, predominantly towards ways of minimizing the power loss associated with windage and oil churning. For example, the experimental investigation by Winfree [2] indicated that geometric modification of the near-gear flow path could significantly reduce windage loss (by 80%) and lubricating oil consumption (by 40%). Dawson [3] and Diab et al. [4] developed empirical windage models, which were obtained by measuring the deceleration of a gear or disk once it was disconnected from the motor. In a separate work, Diab et al. [5] employed a dimensional analysis to define a windage moment coefficient accounting for the flow characteristics. While applicable to a single isolated gear/disk, these

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models did not consider the effects of meshing of the gears and their interaction with a lubricant, so that they can not be validated using geared transmissions. Anderson and Loewenthal [6] developed a model for meshed spur gears and resulted in a nearly cubic relationship between rotational speed and power loss.

More recently and thanks to the advances in computational techniques and resources, several researchers have paid special attention to modeling and simulation of fluid flow in gearbox systems using Computational Fluid Dynamics (CFD) (e.g. [5,10–13]). Along with the aforementioned dimensional analysis by Diab et al. [5], they developed a numerical model to analyze fluid trapping and squeezing in the case of windage by solving continuity equation for a matrix of intertooth volumes with flow restrictions. The results compared favorably to pressure measurements at the roots of the teeth. Rapley et al. [10] and Al-Shibl et al. [11] studied the flow around spur gears using a 2D model with the contribution from the gear side calculated using a correlation from Townsend [9]. Hill et al. [12] applied an unstructured overset moving mesh CFD model to isolated spur gears and a disc. The CFD results agreed well with measured windage loss data by Diab et al. [4]. Turbulence modeling choices, the relative importance of viscous and pressure torques with gear speed, and 3D unsteady flow field were studied. The numerical modeling approach was validated against experimental data in literature and data obtained at NASA Glenn; the model was then applied to parametric shroud configuration studies. The findings elucidated the mechanisms of gear windage loss and resulted in proposed loss reduction strategies as well as geometric modification. Along with extensive research, cited thus far, in area of single-phase flow calculation in gear systems, a few researchers have looked into the two-phase flow and the corresponding physics in these systems. For example Arisawa et al. [14] and Gorla et al. [15,16] studied the losses associated with splash lubrication in gearboxes and Li et al. [17], and Concli and Gorla [18] conducted high-fidelity VOF-based analysis of lubrication flow near the surface of the single rotating gear.

While the aforementioned research studies have shown rigorous development on iso-thermal flow analysis and optimization of geared systems, the thermal analysis of these devices has largely been limited to developing modeling capabilities for the temperature rise preceding the scuffing phenomenon, which is known to be as one of the most common surface failure modes observed at lubricated contacts Liou [19] and Proctor et al. [20]. This has led researchers to focus on the sub-micron phenomena within the contact region to predict the friction-oriented, instantaneous temperature rise at the contact zone [21], a practice commonly referred to as the "thermal" extension of the elastohydrodynamic lubrication theory or TEHL. The method was originally developed in 1960s by Sternlicht et al. [22] for loaded surfaces and later matured and extended by Cheng [23], Murch and Wilson [24] and Sadeghi and Sui [25]. The reader is refereed to the work by Sadeghi and McClung [26] for the summary of the governing equations and the associated assumptions. While the model and its variations have been extensively used to simulate and predict the thermal phenomena of the highly loaded surfaces in general (e.g. [27–31]) and the contact regions of gear surfaces in particular (e.g. [32–39]), they all require a critical simplification of the so-called "bulk" events, that is the large-scale thermal-fluid phenomena inside the gearbox (e.g. [40–42]). That, in effect, decouples those large-scale physics from the contact region. Further simplifications include solving for transient heat-conduction inside the solid components while representing the fluid side by some heat-transfer coefficient approximation (e.g. [32,33,43,34,35]).

The present work aims to propose a modeling strategy to study the interaction of various thermo-fluid phenomena within the gearbox systems. A regime-based map of operation is developed to quantify the significance of various physical phenomena for a given set of conditions which, along with the associated time-scale analysis, give rise to the modeling methodology proposed in this paper. This modeling approach enables investigation of temporal and spatial evolution of the thermo-fluid phenomena, so long as the operation of the system is within the range of applicability of the assumptions and approximations.

The paper is organized as follows: a scaling analysis is presented in Sections 2.1 and 2.2 to illustrate the separation of physical length-scales and time-scales associated with various thermo-fluid physics within a gear system. The governing equations along with the proposed solution approach is presented in Section 2.3. The model implementation is discussed in Section 3. The numerical approach is verified against a full-fidelity simulation of a simplified gear system in Section 4.1 and then demonstrated on a jet-lubricated rotating gear in Section 4.2.

2. Model formulation

The general gear system illustrated in Fig. 1 consists of a set of interlocking gears in an enclosure which are being lubricated by a certain oil-feeding mechanism (e.g. jet lubrication in the schematic). The thermo-fluids of this system involve multiple physical phenomena. For instance, the multiphase flow along with the large and small scale turbulence are among the primary physics governing the fluid flow. In addition, the fluid heat-transfer and its conjugate interaction with the solid components are the main elements of thermal physics in these systems. Despite the often ill-determined boundary conditions, particularly for the thermal field, the spatial and temporal evolution of these phenomena are well-governed by established conservation equations. However, the sheer range of physical length and time-scales along with the geometrical complexity of these systems prohibit the direct approach to simulating the thermo-fluid phenomena, prompting approximations that are motivated by the underlying physics.

2.1. Length scale analysis

The scaling analysis presented in this section is to motivate the physical approximations and assumptions that are employed in the modeling approach to be presented in the subsequent section.

2.1.1. Two-phase turbulent flow

For a gear system involving two-phase fluid flow and operating at gear speeds of $O(1000\ \text{RPM})$, length scales span many orders of magnitude, from the Kolmogorov scale (i.e. $\sim< O(1\ \mu\text{m})$) to the geometric length scale (i.e. $D \sim O(1\text{m})$) which makes the direct numerical simulation of such systems practically prohibitive. The use of physics based sub-models to simplify the governing equations such as done in Unsteady Reynolds-Averaged-Navier Stokes (URANS) have resulted in reducing this length-scale gap and are

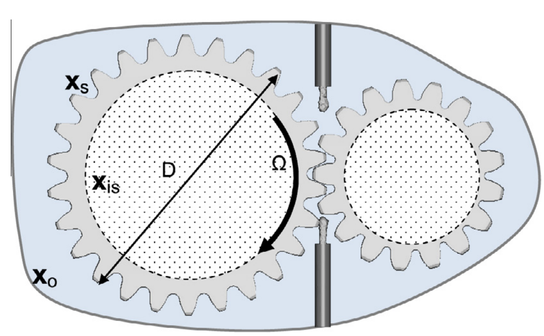

Fig. 1. Schematic of a gearbox system that is to be analyzed using the proposed approach in this paper.