On the Fully Turbulent Regime in Hydrodynamic Lubrication

Bernhard Scheichl [a], Alfred Kluwick [b]

[a] Austrian Center of Competence for Tribology, A-2700 Wiener Neustadt, Austria

[a, b] Institute of Fluid Mechanics and Heat Transfer, Vienna University of Technology, A-1040 Vienna, Austria

1. MOTIVATION AND PRELIMINARIES

The long-standing classical theory of lubrication in the fully hydrodynamic regime is essentially traced back on the assumptions of (i) a relatively slender gap formed by two rigid surfaces that exhibit a (counter-)sliding (and "squeezing") motion in the specific reference frame, (ii) a Newtonian lubricant, (iii) the neglect of inertia terms in the Navier-Stokes equations, and (iv) strictly laminar flow. Issues (i)-(iv) prove sufficient for a rigorous derivation of the well-known Reynolds equation (in the most general form) governing the pressure distribution in the gap.

In engineering applications as e.g. thrust bearings for oil- or steam-lubricated high-speed rotors, however, the Reynolds number *Re* formed with a typical gap height may take on rather large values, thus rendering prerequisite (iii) questionable. It is pointed out on the basis of quantitative results relevant for the global stability bounds of internal flows that relaxing assumption (iii) also involves a critical review of supposition (iv), which finally suggests the inclusion of turbulence. Here we restrict the investigation to incompressible fully developed turbulent flow between smooth surfaces.

2. EXTENSION OF CLASSICAL THEORY

As a consequence of the above findings, the present analysis contrasts with associated previous extensions of the usual lubrication approximation towards the regime of boundary-layer flow, both laminar (cf. [1]) and superlaminar or even turbulent (cf. [2]). In the latter case the few studies available rely on the rather *ad-hoc* inclusion of the turbulent shear stress in the Prandtl-type boundary layer equations exhibiting nonlinear convective terms. However, studying high-*Re* turbulent lubricant flow by rigorous asymptotic analysis of the ensemble-averaged Navier-Stokes equations has patently not attracted many researchers. Although desirable, the establishment of such a theory is severely hampered by the correct scaling of the a priori unknown pressure rise induced by the interplay of the counter-sliding motion and the wedge effect. Also, the yet limited understanding of laminar-turbulent transition in internal flows currently does not provide a pathway, but the well-accepted theory of turbulent channel flow does: the lubricant flow differs mainly due to crucial effects of inertia. First numerical results supplement the novel theory, which does not rely on a specific turbulence closure.

As a salient characteristic of the resulting multi-layered flow structure, showing a striking difference to that of well-understood fully developed turbulent pipe, channel, and boundary layer flows, the core layer comprising most of the flow exhibits a streamwise velocity deficit of $O(1)$ with respect to the sliding speed. By matching with the so-called intermediate layer separating the main from the essentially viscosity-affected wall layer, the leading-order boundary layer equations are subject to boundary conditions which allow for the prediction of internal separation at the surface relatively at rest, and the celebrated logarithmic velocity distribution provides the asymptotic skin friction law. Important further aspects include a first attempt to correctly describe phase transformation due to cavitation.

[1] Tuck, E. O.; Bentwich, M.: Sliding sheets: lubrication with comparable viscous and inertia forces. *Journal of Fluid Mechanics* (1983), 135, 51-69.

[2] Frêne, J.; Arghir, M.; Constantinescu, V.: Combined thin-film and Navier-Stokes analysis in high Reynolds number lubrication. *Tribology International* (2006), 39, 734-747.