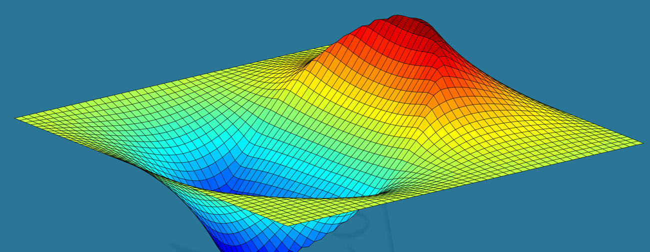
Hydrodynamic lubrication of textured surfaces: A review of modelling techniques and key findings



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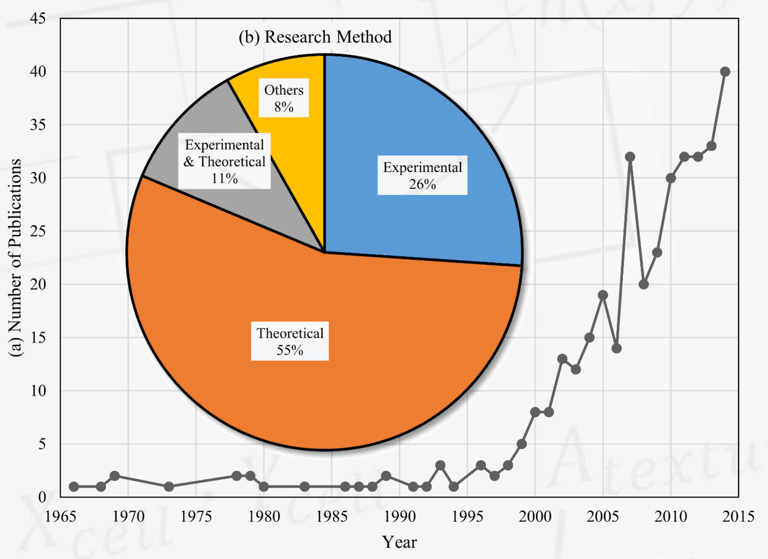
1. Introduction

Surface textures have been widely reported to be capable of enhancing the performance of journal and thrust bearings and other applications. Understanding the influence of surface properties (roughness, grooves, textures/dimples) on the performance of hydrodynamically lubricated contacts has thus been the aim of numerous theoretical and experimental studies. A variety of numerical models have been employed by many researchers in order to find optimal texture parameters (shape, size, distribution) to increase load carrying capacity and minimum film thickness and to reduce friction and wear. However, the large number of different modelling techniques and complexity in the patterns makes finding the optimum texture a challenging task and has led to contrary conclusions. Choosing the right models and making the correct assumptions is thus a key first step. Moreover the optimum texture design seems to highly depend on the operating conditions. Hence, successful industrial applications are still limited.

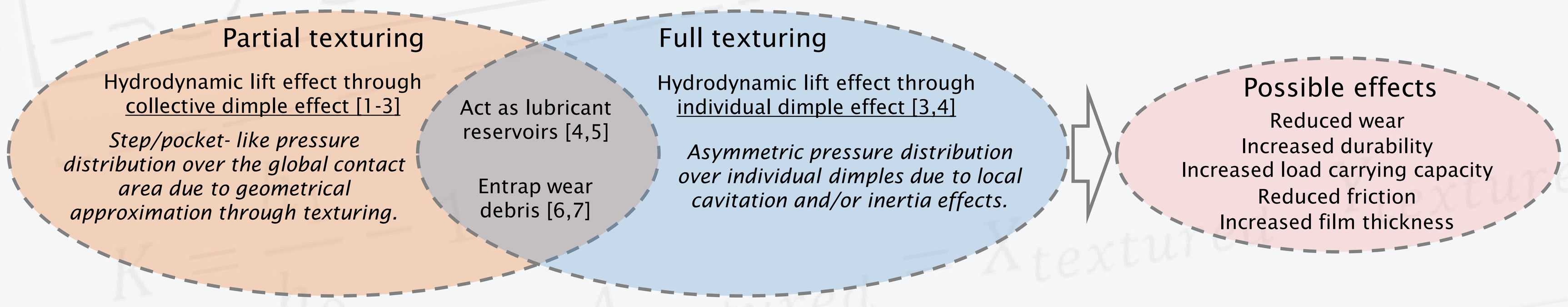


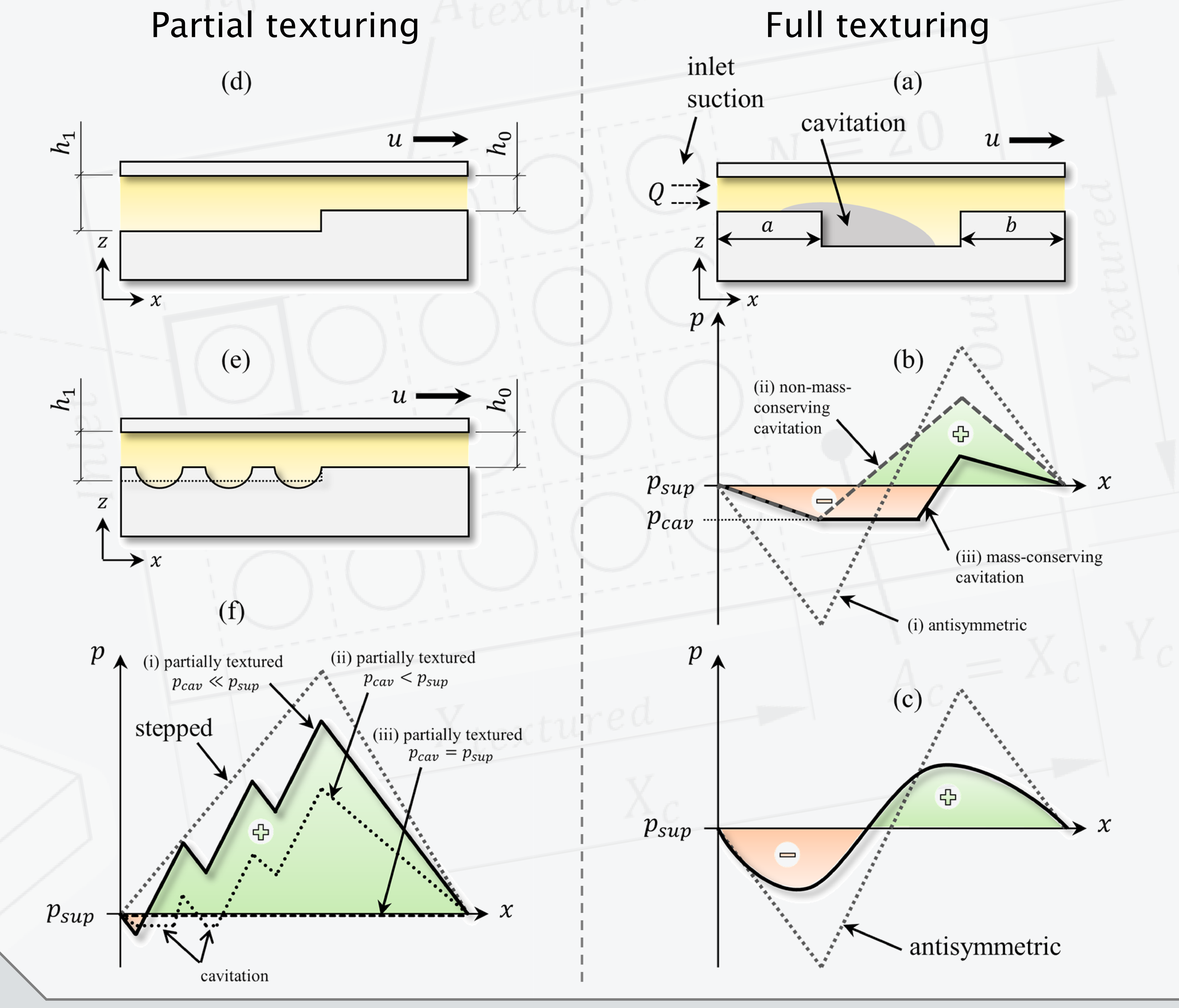
Worldwide research effort on surface texturing over the last 50 years: (a) Number of publications per year and (b) Research Method

A detailed review on the state of the art in surface texturing is a necessary first step in standardising mathematical models and restricting mistakes in this field. A consistent understanding of the phenomena involved and standard theoretical methods will improve and facilitate future research and the industrial application of this technology. This work is aimed at making a contribution in this direction.

About 400 papers have been reviewed and analysed. This work outlines the research effort on surface texturing worldwide, reviews the key findings and, in particular, provides a comparative study of different modelling techniques and numerical methods commonly used to predict the performance of textured surfaces.

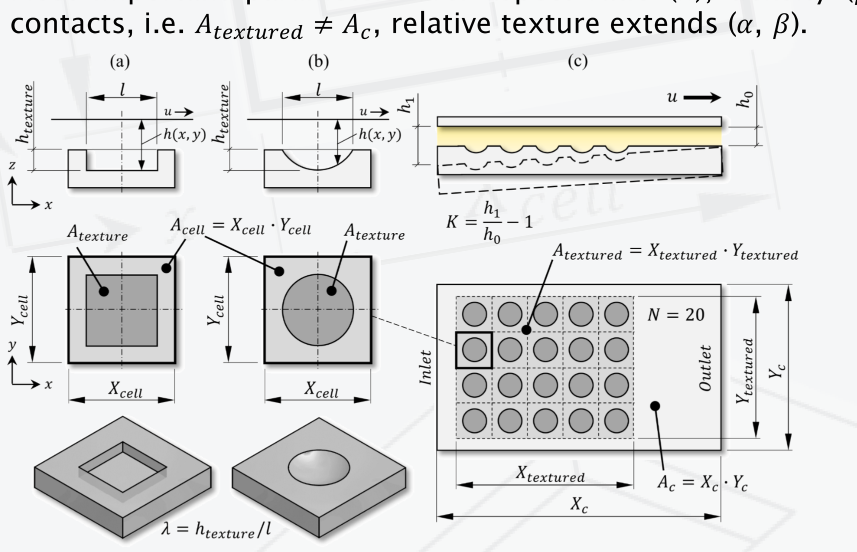
2. Functions of surface textures



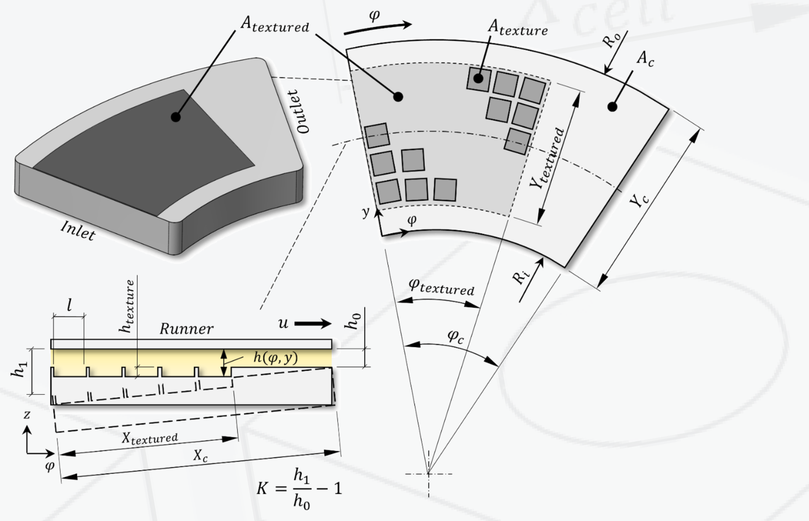


3. Texture design

- A large number of geometrical parameters is necessary to fully describe a textured contact.
- Most important parameters are: aspect ratio (λ), density ($\rho_{texture}$), relative depth (S) and for partially textured contacts, i.e. $A_{textured} \neq A_c$, relative texture extends (α, β).



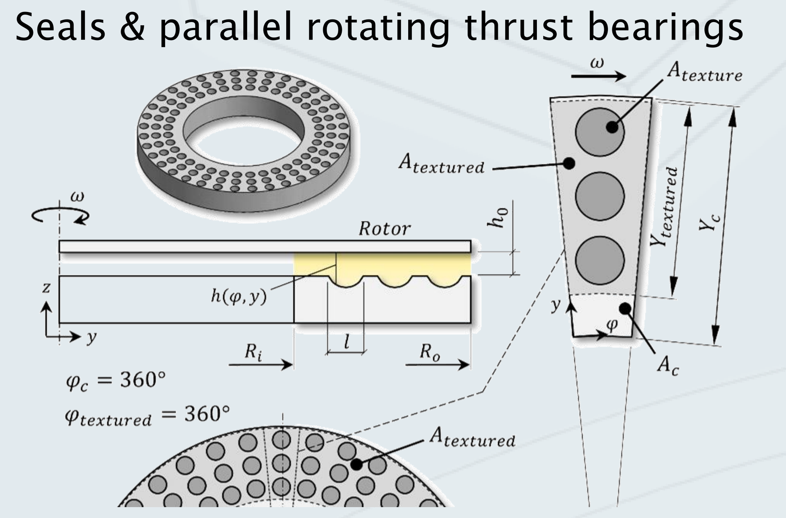
Texturing parameters for parallel/convergent slider bearings



Texturing parameters for parallel and convergent bearing pads

3.1 Key findings for parallel contacts

Seals & parallel rotating thrust bearings



- Full texturing can improve performance only for certain conditions and improvements are rather small.
- Optimal values for λ and $\rho_{texture}$ for full texturing exist, but highly depend on operating conditions. $\rho_{texture,opt} \approx 5 \ldots 20\%$
- A mass-conserving treatment of cavitation is crucial.
- The p_{cav}/p_{sup} ratio is essential.
- Partial texturing of seals in radial direction can lead to significant performance improvements by reassembling a virtual step.

Parallel slider & parallel thrust pad bearings

- Beneficial effects have been only reported for certain cases, e.g. when the inlet is textured, and are very limited.
- Partial texturing on the other hand is capable of generating significant load support and reducing friction. Texturing the inlet is an efficient way to further improve performance.
- The key to obtain best slider/pad performance is to as closely as possible approximate an optimal step bearing. The best approximation can be achieved with rectangular textures having a flat bottom profile and a maximal possible texture density. The relative dimple depth should be just under 1 for rectangular dimples and slightly higher for other shapes.
- A mass-conserving treatment of cavitation is crucial.
- The p_{cav}/p_{sup} ratio is essential.
- Optimal texturing parameters are generally independent of speed and viscosity. However, changes in this values may result in the occurrence of cavitation, which can ultimately change optimal texturing parameters.

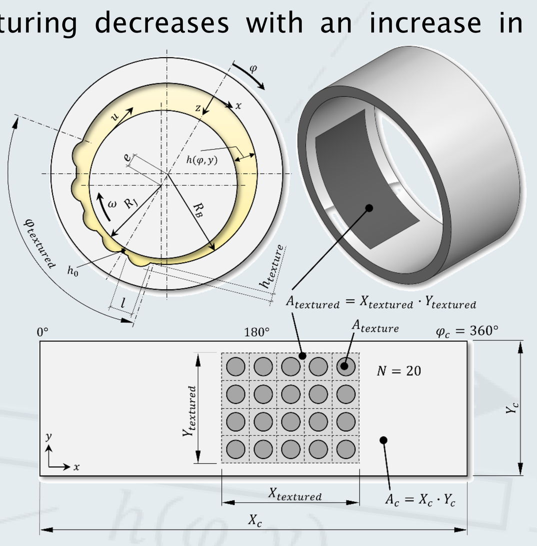
3.2 Key findings for non-parallel contacts

Convergent contacts

- At convergence ratios close to 0, the summary given above for parallel sliders holds true.
- Full texturing is detrimental and partial texturing can lead to mild performance improvements, however, only at low convergence ratios ($K < 1$). At larger convergence ratios the influence of texturing diminishes completely.
- Optimal texturing parameters (α, β and S) highly depend on the convergence ratio and the slider's/pad's width to length ratio. Best performance is always achieved with a maximum possible texture density, i.e. the best configuration is actually a stepped/pocketed slider, as is the case for parallel contacts.
- Generally, cavitation effects are important, causing sudden changes on the performance and optimal texturing parameters.

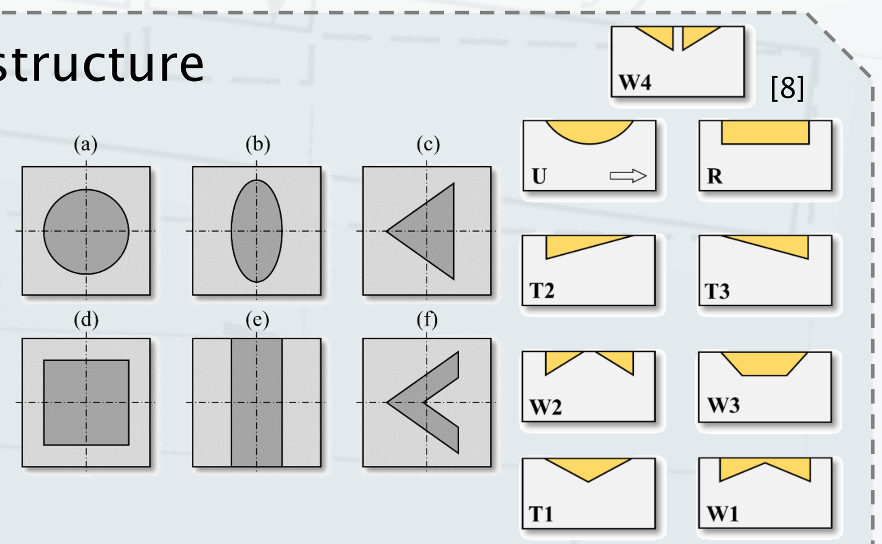
Journal bearings

- Full texturing is generally reported to be detrimental, however, contrary results have been obtained.
- Partial texturing can have beneficial effects, however, performance improvements have not been spectacular.
- The efficiency of texturing decreases with an increase in eccentricity ratio.
- Optimal texturing parameters highly depend on operating conditions and eccentricity ratio.
- The angular location of the textured area appears to be very important, however, very contrary results regarding the location have been reported.



3.3 Texture shape and internal structure

- Individual texture shapes can be optimized for given operating conditions.
- Asymmetric textures, e.g. ellipses and chevrons, seem to be the preferable option.
- An additional tuning of texture performance may be achieved by a careful selection of bottom profiles containing micro-steps, micro-wedges or both.
- Partially textured contacts are an exception. Here, the optimal shape is the one most closely approximating a step/pocket, i.e. rectangular with flat bottom profile.



4. Modelling

4.1 Fluid mechanics

$$\nabla \cdot \boldsymbol{u} = 0$$
$$\rho(\boldsymbol{u} \cdot \nabla)\boldsymbol{u} = -\nabla p + \nabla \cdot (\eta \nabla \boldsymbol{u})$$

Navier-Stokes

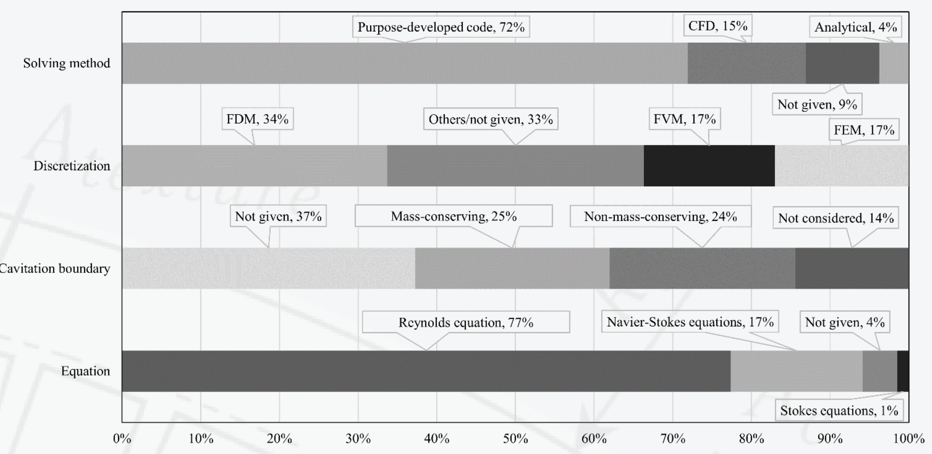
- More accurate (Three dimensional flow phenomena, inertia effects)
- Usually solved with commercial software (CFD)
- Computation time high

$$\frac{\partial}{\partial x}\left(h^3 \frac{dp}{dx}\right) + \frac{\partial}{\partial y}\left(h^3 \frac{dp}{dy}\right) = 6\eta u \frac{\partial h}{\partial x} + 12\eta \frac{\partial h}{\partial t}$$

Reynolds

- Computation time lower
- Usually solved with purpose developed source codes
- Less accurate (no inertia, no recirculation, Validity should be evaluated based on Re & texture aspect ratio [9])

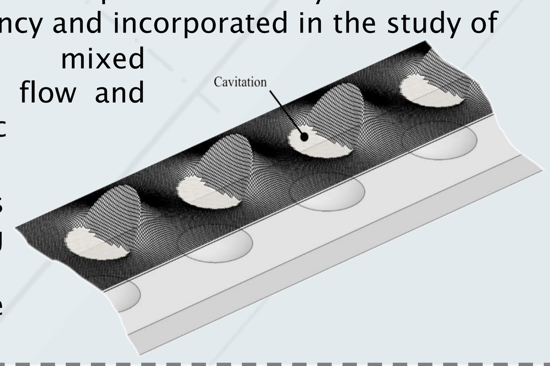
The Reynolds equation remains the more attractive choice in most cases, especially for more complex simulations involving, for example, transient conditions, rough surfaces or mixed lubrication.



Results of the literature survey on theoretical models for textured and rough surfaces

4.2 Cavitation

- Cavitation may occur not only globally in divergent contact areas, but also locally inside textures or in-between asperities -> Mass-conserving treatment of cavitation is crucial [10].
- Large number of different algorithms have been developed over the past 40 years. They are generally based on the JFO boundary conditions and either iterative or based on LCP.
- Algorithms were optimized for different discretization methods, modified for improved stability or enhanced computational efficiency and incorporated in the study of rough surfaces, mixed lubrication, transient flow and thermo-hydrodynamic lubrication.
- No standard methods -> Time consuming implementation remains with the individual researcher



4.3 Micro-hydrodynamic

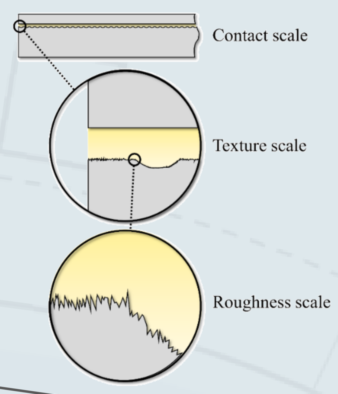
Direct/deterministic

Mesh fine enough to capture surface features. Accurate but rarely applicable due to high computation time.

Indirect/stochastic

The averaged influence of roughness and/or textures is incorporated in the global, smooth Reynolds equation.

Flow factor methods | **Homogenization**



5. Conclusions

1. Optimal texturing parameters for best performance enhancement highly depend on the type of contact and the operating conditions and if designed wrong, textures may even become detrimental. This means that profitability and effectiveness of surface texturing have to be evaluated for a given application and range of operating conditions.
2. Robust numerical models allow the evaluation of texture designs prior to being manufactured and can avoid time consuming experimental trial and error approaches. Although a range of theoretical models have been developed and applied for textured surfaces, the textured study still involves three major challenges: (i) The complex mass-conserving treatment of cavitation, (ii) The issues caused by the discontinuous character of the film thickness equation and (iii) the large discretization effort caused by the large differences in scale.

Surface texturing remains a feasible method for contact performance enhancement in terms of load carrying capacity, minimum film thickness, friction and wear. Robust models are crucial for a successful application, however, the lack of publicly available implementation details has led to a large variety of different numerical models, which makes it difficult to compare results and develop new and improved codes, especially for new researchers in the field. Public availability of source codes is an important step towards standard techniques and ultimately robust and accurate models that will facilitate and extend the applicability of this technology.

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