Analytical Solution of Hydrostatic Pocket Tilting

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Abstract: Tilting (parallelism error) of guiding surfaces may cause reduction of load capacity of hydrostatic (HS) guideways and bearings in machine tools (MT). Using coupled finite element (FE) computational models of MT structures, it is nowadays possible to determine the extent of guiding surfaces deformation caused by thermal effects, gravitational force, cutting forces and inertia effects. Assessment of maximum allowable tilt has so far been based merely on experience. The paper presents a detailed model developed for description of the impact of HS bearing tilt on the load capacity characteristics of HS guideways. The model allows an evaluation of the tilt influence on the change of the characteristics as well as determination of the limit values of allowable tilt in interaction with compliant machine tool structure. The proposed model is based on the model of flow over the land of the HS pocket under extended Navier-Stokes equation. The model is verified using an experimental test rig.

Introduction.

Hydrostatic (HS) guideways are considered as one of the fundamental types of sliding guideways in the machine tool industry. HS guideways are used for its low friction, high precision, load capacity, stiffness and damping. HS guideways consist of two sliding surfaces. One of the sliding surfaces is fitted with HS pockets, designed as cavities bounded by land. The cavities are connected to regulators and pressurized oil supply. Throttling of the pressurized cavity oil occurs between the land and the other sliding surface. This results in the creation of a thin oil film, which provides fluid friction between sliding surfaces.

A parallelism error (tilting) of guiding surfaces causes a change in the hydraulic resistance of an HS pocket and a corresponding reduction in the reaction force in the guideways. It is the aim of this paper to propose a detailed model of load capacity characteristics of HS guideways taking into account tilting without the demand for a numerical solution of the problem. This model can be used in an iterative approach to optimize the entire design process for HS machine tool guideways, combining a finite element (FE) model of a compliant MT structure coupled with nonlinear characteristics of HS guideway and multiparametric, multi-criterion optimization [1].

Analytical solution.

Pressure distribution on the land is generally described by the Reynolds equation. Under certain conditions, this equation can be solved exactly, for example tilted bearing of infinite length solved by Beek and Ostayen [2]. The presented calculations use the perturbation theory to simplify the Reynolds equation and boundary conditions describing a real HS pocket. The pressure boundary condition on the inner inlet into the land takes into account the Bernoulli effect as it may cause a significant pressure drop if kinetic energy of a fluid volume element is comparable with its pressure energy. The influence of HS pocket tilt on hydraulic resistance R of HS pocket is shown in Eq.1, where a and b are inner dimensions of the cavity, D is width of the land, μ is dynamic viscosity of hydraulic oil, Δ_a and Δ_b describe the tilt around x and y axis of the HS pocket, ρ is density of hydraulic oil, p_T is pressure inside pocket.

$$R \approx \frac{3\mu D}{H_S^3(a+b)}\left[1 - \frac{a+3b}{a+b}\Delta_a^2 - \frac{3a+b}{a+b}\Delta_b^2 + \frac{\rho H_S^4 p_T}{240\mu^2 D^2}\right]. \quad (1)$$

The influence of the HS pocket tilt on the hydraulic resistance of the HS pocket is also illustrated in Fig. 1 on the left. The tilt ratio Δ is plotted on the X axis and the pocket surface to pocket land surface ratio Ψ is plotted on the Y axis. For a pocket with $\Psi = 0.5$, three tilt ratios have been selected. Their influence on the load capacity F with respect to the height of the throttling gap in the center of the pocket h_{centre} is shown in Fig. 1 on the right.

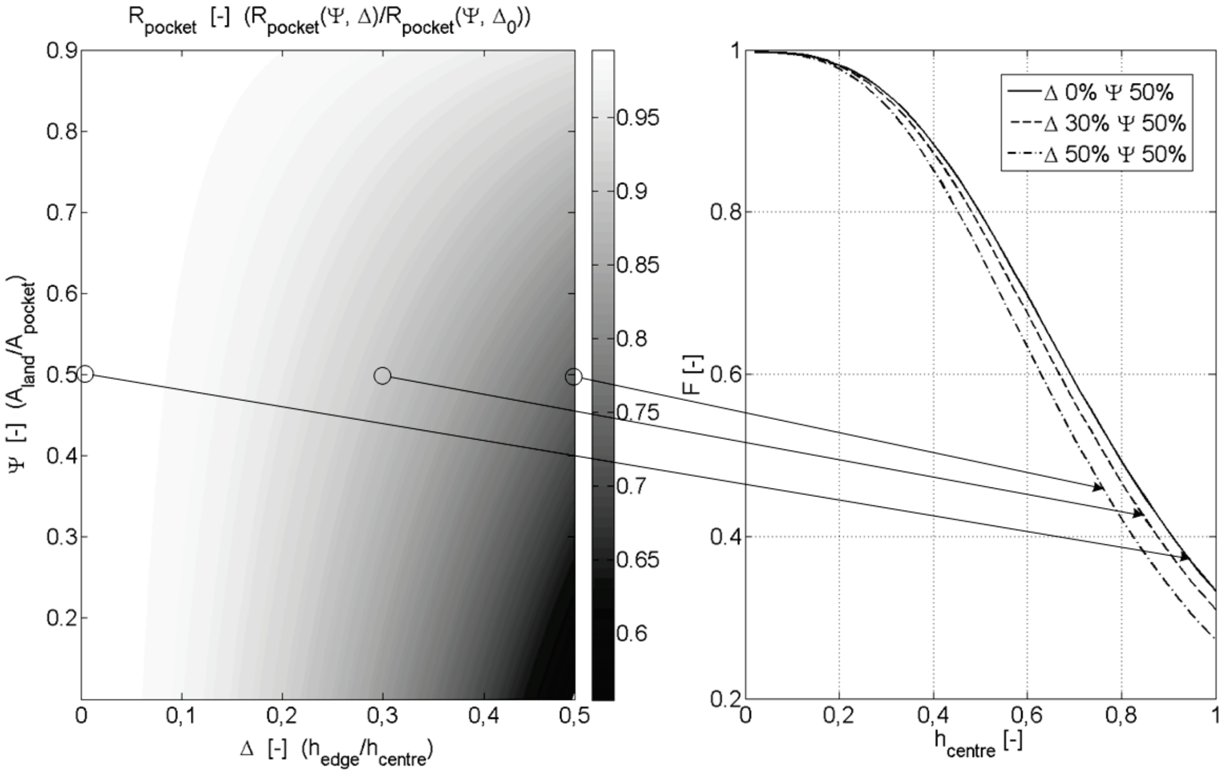

Fig. 1: Influence of tilt ratio Δ and pocket surface to pocket land surface ratio Ψ on hydraulic resistance R and on load capacity F of HS guideways

Verification

The presented calculations were verified on laboratory test rig STD21 used for experiments with high speed HS. The test rig also allows tilt and throttling gap change of HS pockets. The influence of tilt on oil flow rate and pressure in the HS pocket cavity was measured and compared with the values based on the hydraulic resistance calculation (Eq. 1). The experimental results are in good agreement with the calculated values.

Summary

Coupling a FE model of a compliant MT structure with the presented detailed model of nonlinear load capacity of HS guideways allows us to include the influence of tilt on load capacity directly in the calculation, instead of sequential evaluation of tilt at each pocket and comparison with allowable values given by experience.

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References

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