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APPLIED METHOD FOR DESIGN OPTIMIZATION OF HYDROSTATIC GUIDEWAY ON REAL MACHINE TOOL

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Abstract: *The main advantages of hydrostatic bearings are: design flexibility, excellent structural damping, and zero friction at low speeds; this is a great opportunity for various types of machine tools. However, the need to determine many parameters at the design stage and a lack of a general approach to their optimization pose a large obstacle to wider application. This paper suggests a general iterative method for design optimization of hydrostatic bearings for linear and low-speed rotary axes. The method uses automated generation of load combinations, multi-objective optimization for determining design parameters and FEM for predicting structural deflection of machine frame parts.*

Keywords: ***Hydrostatic, guideway, bearing, optimization .***

1. Introduction

1.1. Background

Hydrostatic (HS) guideways represent one of the guidance types ensuring linear and rotating movement of machine tool parts that fulfil the above-mentioned requirements. The use of HS guideways in engineering is of a relatively recent date: with some earlier exceptions, this type was introduced in the 1960s and 1970s (Lewis, 1966). The main component of a HS guideway is a HS pocket containing pressurized fluid. This guideway type is a very good option for high-precision machines, machines requiring very small positioning steps, machines for hard machining (high damping needed), and large machines (design flexibility needed). Conditions for HS operation:

- Very thin fluid layer (gap height) in the bearing (*0.005* to *0.2 mm*);
- Very low fluid compressibility;
- Sufficient parallelism and planarity of bearing surfaces in all operating modes;
- Relatively constant viscosity of fluid (stable temperature).

In practice, a distinction is made between two types of HS guideways: open guideways (preloaded by gravity of parts or other dominant load) and closed guideways (mutually preloaded pockets placed opposite each other). The characteristic dimensions of HS pockets, the pressure distribution, and a graphic representation of open and closed guideway types are shown in Fig. 1. HS guideway can generally operate in two operating modes corresponding to the settings of the hydraulic unit and the flow control methods:

- Constant flow provided by the pump (One pump for each pocket, Flow dividers);
- Constant pressure provided by the pump (Control by means of constant hydraulic resistance such as capillary tube or orifice, advanced flow control such as PM flow controller (source: Hyprostatik) or membrane, self-compensating systems used especially for radial HS bearings).

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Tab. 1: Nomenclature.

Symbol	Quantity	Units
c, C	Inner / outer pocket width	m
d, D	Inner / outer pocket length	m
l	Land width	m
b	Effective perimeter	m
A_{eff}	Effective area	m^2
R_T	Pocket hydraulic resistance	$Pa.s.m^{-3}$
R_K	Capillary tube hydraulic resistance	$Pa.s.m^{-3}$
l_K	Capillary tube length	m
r_K	Capillary tube radius	m
η	Dynamic viscosity	Pa.s
h	Gap height	m
h_0	Initial gap height	m
$h_{I,II,III,IV}$	Gap heights in HS pocket corners	m
h_D	Allowable gap height	m
p_P	Pump pressure	Pa
p_T	Pocket pressure	Pa
p_0	Atmospheric pressure	Pa
Q	Flow	$m^3.s^{-1}$
F	Load	N
F_T	Pocket reaction	N
$F_{max,mid,min}$	Maximal / medium / minimal load of reaction spectra	N
$h_{min,max}$	Minimal / maximal allowable gap height in working space	m
F_s	Force range defining maximum and minimum of pocket load	N
$F_{a,b,m}$	Crucial points of force – deflection characteristic	N
K	Stiffness	$N.m^{-1}$
k	Safety load coefficient	-
k_h	Safety gap height coefficient	-
rot X, rot Y	Pocket tilt in X / Y direction	rad
rot X_D, rot Y_D	Allowable pocket tilt in X / Y direction	rad
ε_D	Allowable pocket tilting	m

The advantages of HS guideways include: a very low friction coefficient; long service life (the guide surfaces do not touch); good damping in the direction perpendicular to the guide surfaces; and high stiffness (depending on the thickness of the pressure oil layer). Disadvantages include: a more complex design; demanding manufacturing process; demanding maintenance (the guideways are vulnerable to dirt); and costly operation.

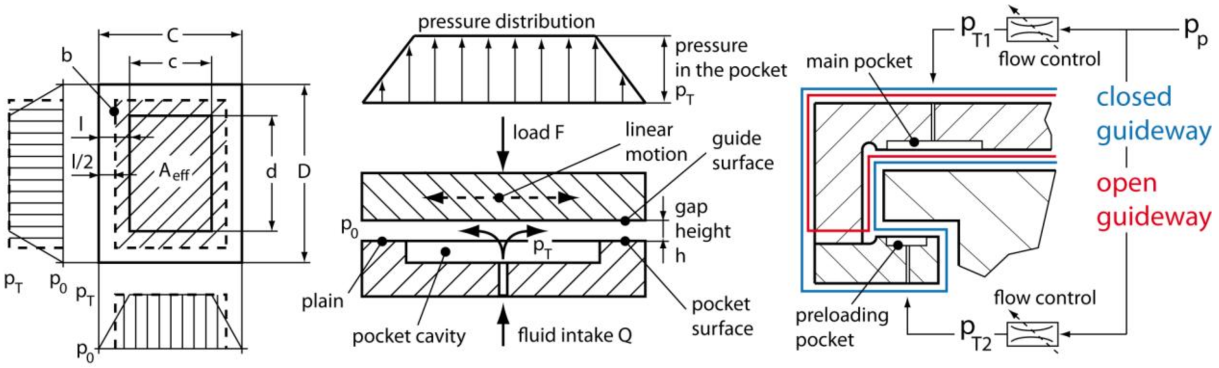

Fig. 1: HS pocket parameters and gudeway types (partially taken from(Brecher & Weck, 2006)).

A great deal of research has been dedicated to the design of HS pockets and its influence on guideway characteristics. A large number of these works focus exclusively on radial HS bearings. For example, paper (Sharma et al., 2002) compared the characteristics of HS pockets with circular, rectangular, elliptical and annular pocket cavity. He also considered different controllers, such as capillary, orifice and constant flow valve restrictors. He used the FEM method to analyse the properties of HS pockets. Another study worth mentioning is the follow-up study (Shie & Shih, 2010), where were (knowing the pump parameters and the gap height) found the optimum parameters for a radial HS bearing (such as orifice location and diameter and the ideal pocket cavity dimensions) using the FEM method and an optimization method combining Genetic Algorithms and Gray Relation Analysis. Some papers focus on HS pocket materials (Wang & Yamaguchy, 2002), the influence of the pressure medium properties (Wang & Yamaguchy, 2002), research on smart controllers (Slocum et al., 1995), and the effects of temperature on HS bearings (Ting & Mayer, 1971).

However, research on methods for design and optimization of entire motion axis guideways realized by a system of more HS pockets has been sporadic. There is a marginally related study by (Sharma et al., 1995), where were examined the differences in using sets of four and six hybrid HS pockets of comparable performance. In most of the available literature, however, research on entire HS planar guideways is only done as part of the design of the whole machine, and is not paid much attention (e.g. (Kim & Cho, 2006), or (Tlustý, 1993)). In an interesting project (Mekid, 2000) the author tried to further the research on the design of high-precision machines by introducing adjustable, preloading bearings for closed HS guideways.

1.2. General design method

The primary aim of this paper is to present an iterative approach to optimizing the entire design process for HS machine tool guideways (lacking in the available literature), combining the *finite element method* (FEM) and multiparametric, multi-criterion optimization. The method is robust, taking into account all possible load situations which can arise in operation, and is not dependent on the selection of a specific optimization criterion.

The first part of the paper is dedicated to a general description of the design optimization approach. It provides an overview of the outputs and applications of the partial results of the iteration process which include: reaction spectra based on a rigid FEM model; HS pocket parameters found through minimization and a well-selected object function; and force reactions and deformations computed on the basis of an FEM model of the entire machine, which are decisive for feasibility of the whole design.

In the second part of the paper, the approach is presented on an example of a real machine tool linear axis with a closed HS system controlled by constant hydraulic resistors—capillary tubes. *Genetic algorithms* (GA) have been used as a tool for optimizing dimensions for the HS pockets and the controllers. The HS pockets have been optimized with respect to the required force-deflection characteristics. The limits for the minimum pocket gap and the maximum allowable tilting of the HS pockets have been selected as the convergence criteria.

2. The design process

The iteration process is general, independent on the selected pocket shape, the type of HS guideway used (closed or open), or the selected type of control (constant flow, constant pressure, flow divider, capillary tube, membrane, orifice plate, etc.). It is applicable for any type of these elements with sufficient mathematical description from the fluid mechanics. Diagram in Fig. 2 shows the process for optimizing the position and design parameters of a HS pockets providing guideway of a machine tool moving axis. The iterative process can be divided into three parts, each of them with a specific result (see Fig. 2):

- Computing the reaction forces and adjusting the position of the HS pockets;
- Suggesting new characteristics for the next iteration step, taking into account the geometry and force boundary conditions;
- Checking for undesired conditions and checking the selected or prescribed criteria.

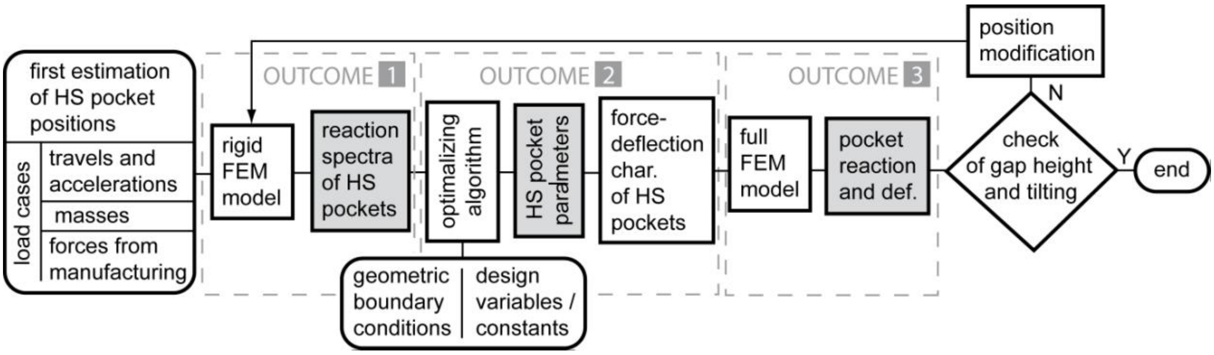

Fig. 2: Diagram showing the iterative design process.

2.1. Rigid FEM model

This design stage involves computations of a statistical distribution: the *reaction spectrum* (Fig. 3) in HS pockets using automatic load case generation and a rigid FEM model. In order to reduce computation time, the flexibility of the machine parts is not taken into account at this stage. The model considers the machine tool frame as rigid and uses spring elements with substituting stiffness for modelling the HS pockets. During the computations various relevant kinematic configurations, load configurations and machine acceleration combinations are generated.

In a case where the machine parts connected by the guideways could be considered as absolutely rigid, the reaction computations would end here, and the stage of designing the pocket geometry and accessory parameters would follow. However, this is generally not the case.

2.2. The optimization algorithm

The next step involves finding optimized pocket dimensions and flow controller parameters for the reaction spectra (possibly multiplied by a safety coefficient), using multiparametric optimization tools. A sensitive approach is necessary when setting the collision boundary conditions, and the geometric boundary conditions need to be respected. The optimization task can be defined as a minimization task.

Results of this design stage are parameters of HS pockets and their flow controllers together with resultant HS pocket force-deflection characteristics. These comply with all pre-defined limits, convergence criteria and safety factors.

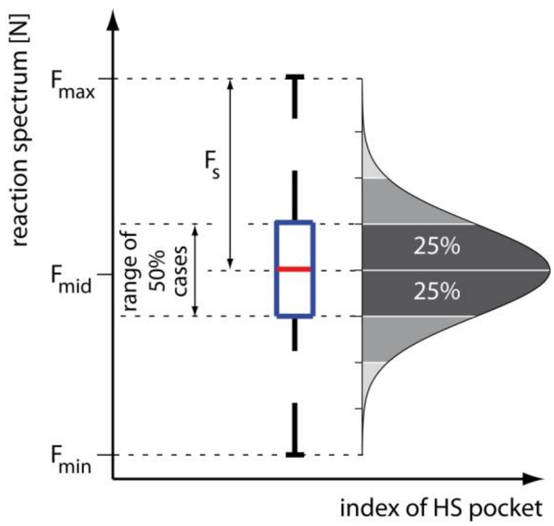

Fig. 3: Reaction spectrum of one bearing point.

2.3. A detailed FEM model

Mainly in order to check for various undesired conditions resulting from structural flexibility, a detailed FEM model of the whole system is created. Elements representing properties of each of the HS pockets are added at appropriate points between models of the two moving parts.

The FEM model is loaded with a *symmetrical load case* (corresponding to F_{mid} force resulting from the rigid FEM model shown in Fig. 3) which represents medium load from alternating (two-way) loads—the acceleration of the motion axes and the cutting forces. The model also needs to be in the medium kinematic position.

Based on the results of the detailed detailed FEM model (deformation of HS guideway and pocket tilting), the positions of the HS pockets are sensitively adjusted and new F_{mid} values for the reaction spectra are computed (condition: the force range F_s, which the pocket has to transfer, remains unchanged). The new spectra serve as input for the next iteration step.

3. Application

The design method is demonstrated on one half of the hydrostatic X axis of a real portal milling machine (Fig. 4).

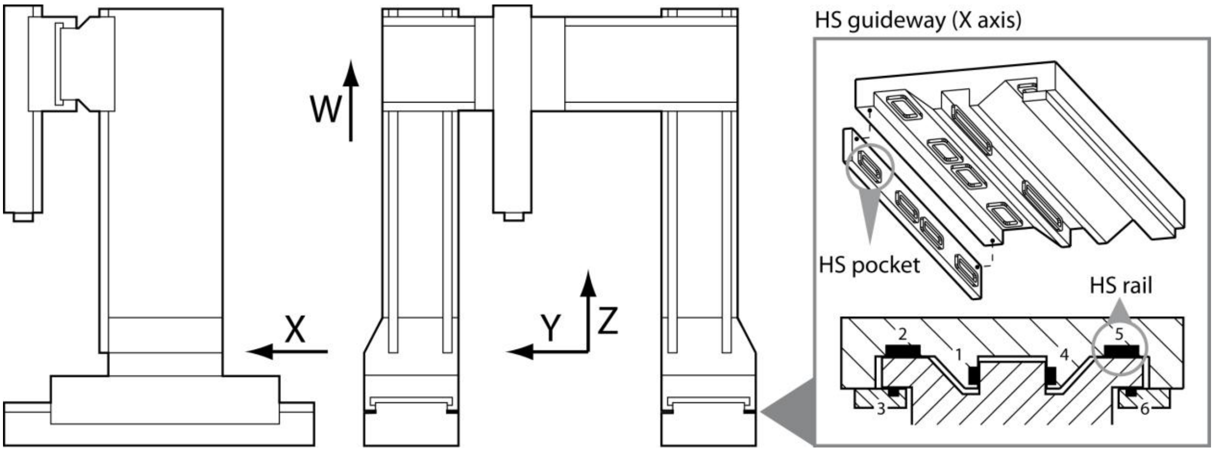

Fig. 4: A diagram showing a portal milling machine.

The design method can be applied to any assignment where sufficient and verified mathematical description of the HS components is available. The application example shown here uses the following input information for the iteration process (Fig. 2):

- Knowledge of the load cases;
- Pump and pressure medium parameters;
- Checking Required gap height.

The aim is to create a suitable HS guideway design (positions and geometry of the HS pockets) for a control system using capillary tubes. The design has to account for loading with the machine's own weight, reactions caused by axis acceleration, cutting forces and compliance of machine parts which influences the distribution of load on the pockets.

3.1. Reaction spectra of the HS pocket

Computations of the reaction spectra for the pockets are based on the 'rigid FEM model' which uses substituting spring elements for the HS pockets. The machine frame, however, is considered to be absolutely rigid. ANSYS FEM software is used for creating the rigid structure of nodes representing points of applied external forces, inertia forces and gravities. HS pockets are modeled as linear springs. The variations are generated and computed automatically using APDL (ANSYS parametric design language) routines. The specific input for the computations includes:

- The mass of the parts and the position of their centers of gravity;
- The positions and orientation of the pockets in relation to the selected coordinate system;

- Travel and acceleration of each axis;

- Maximum values of cutting forces in each direction;

- Some cases the stiffness of the drive of a given axis needs to be entered.

In the model case (the X axis of a portal milling machine) the HS guideways were designed as a system based on pairs of pockets preloaded against each other (close guideway - Fig. 1). The initial position of the pockets was selected intuitively. The description and distribution of the HS pockets on one half of the X axis of a portal milling machine is shown in Fig. 5. Through the iteration process (Fig. 2) the positions of the pairs of HS pockets, preloaded against each other, were adjusted with a view to finding their optimum distribution in terms of load and deflection.

At this design stage the computations automatically generate different kinematic configurations and load case combinations. In the example presented here the different configurations of the model are found along the *W*, *Y* and *Z* axes; the position of the portal on the *X* axis does not have an impact on the loading of its guideway (Fig. 4). Different combinations of acceleration and cutting forces needed to be taken into account as well. Acceleration potentially occurs along the *X*, *Y* and *Z* axes.

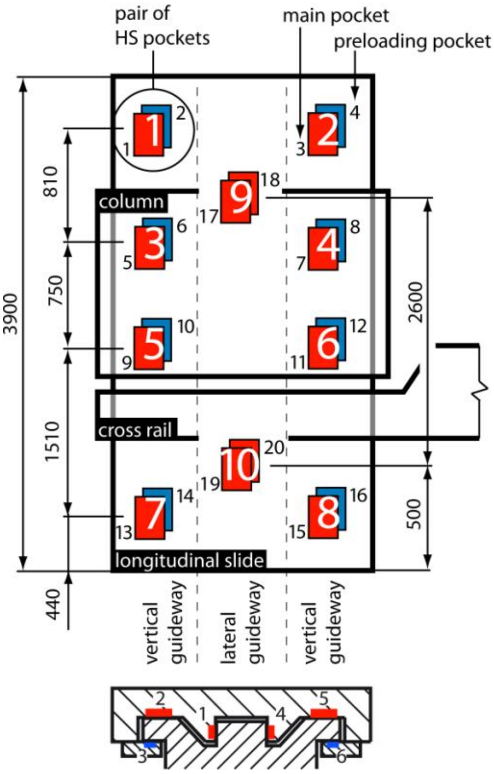

Fig. 5: Initial HS pocket positions.

Each of the three axes can reach one of two extreme positions; therefore, there are 2^3 kinematic configurations (the position of the portal does not have an impact on the *X* axis guideway). Combinations of acceleration and cutting forces also needed to be taken into account (again, for the *X*, *Y* and *Z* axes). After integrating the parts that move together, this represents a total of 2^9 load configurations. Therefore, altogether $2^3 * 2^9 = 4096$ load cases need to be examined, each of which can potentially be a case of extreme load for one of the points on the guideway.

The whole system is absolutely rigid, with the exception of the HS pocket substituting elements (all of them are considered to have the same stiffness) and the substituting elements for the X axis drives. The case where the drives are considered as highly (almost absolutely) rigid is closer to the real situation. When finding optimum pocket dimensions, however, the stiffness of the drives was considered to be zero, which means greater demands placed on the lateral pockets. The resulting reaction spectra for each HS pocket pair (the numbering corresponds to the system introduced in Fig. 5) obtained in the first iteration step are shown in Fig. 6.

As the longitudinal slide of the *X* axis is flexible due to its length and relative slenderness, the computed reaction spectra do not reflect the real situation accurately, and it is necessary to adopt an iteration approach to the design of the HS guideway of the *X* axis.

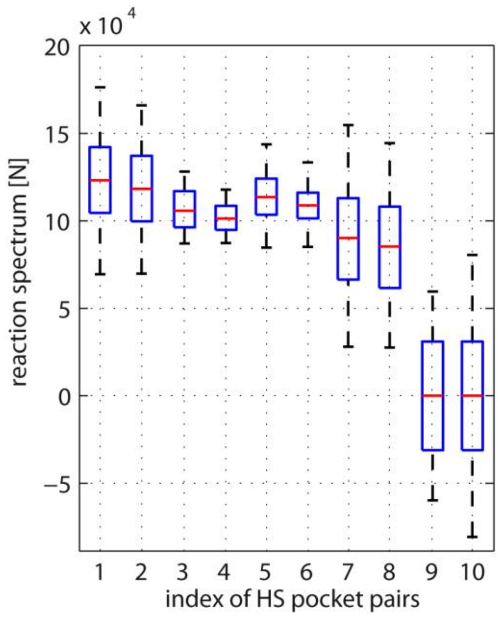

Fig. 6: Reactions in the pocket pairs; flexible positioning along the X axis.

3.2. Determining the HS pocket parameters

The HS system in question works in a mode of constant pressure set on the pump (p_p = *const.),* and regulation is ensured by constant hydraulic resistors (capillary tubes) placed before the HS pockets. A diagram representing the system is shown in the following figure.

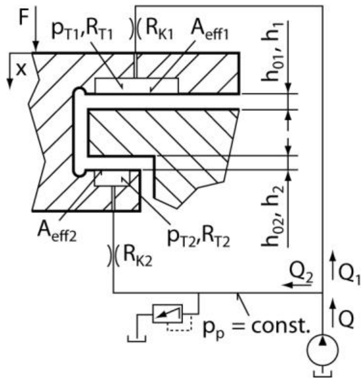

Fig. 7: Diagram representing the HS system.

The force characteristic of the system is the result of substituting the continuity equation (1) in the force balance equation of the HS system (2). The continuity equation:

$$\mathrm{Q_i} = \frac{p_{Ti}}{R_{Ti}} = \frac{p_p}{R_{Ti} + R_{Ki}} \rightarrow p_{Ti} = \frac{p_p \cdot R_{Ti}}{R_{Ti} + R_{Ki}}, \tag{1}$$

where the hydraulic resistances correspond to the following relations:

$$R_{Ti} = \frac{12 \cdot \eta \cdot l_i}{b_i \cdot (h_{0i} \mp x)^3} \text{ and } R_{Ki} = \frac{8 \cdot \eta \cdot l_{Ki}}{\pi \cdot r_{Ki}^4}, \text{ where } i = 1,2.$$

The force characteristic of the pair of HS pockets preloaded against each other is determined by the following relations:

$$\mathrm{F} = p_{T1} \cdot A_{eff1} - p_{T2} \cdot A_{eff2}, \tag{2}$$

$$\mathrm{F} = p_p \cdot \left(A_{eff1} \cdot \frac{R_{T1}}{R_{T1} + R_{K1}} - A_{eff2} \cdot \frac{R_{T2}}{R_{T2} + R_{K2}} \right). \tag{3}$$

The stiffness of the bearing is then determined by a derivation of relation (3) according to the x coordinate:

$$K = \frac{dF}{dx}. \tag{4}$$

At this computation stage the aim is to find optimum parameters for the HS pockets. Some of the parameters are given (or selected) as fixed; other parameters as free, i.e. variable within prescribed limits:

- Fixed parameters (p): pump pressure, oil viscosity, one characteristic HS pocket dimension;
- Free parameters (q): the remaining pocket and capillary tube dimensions (Fig. 1).

These parameters, bound in equations expressing the force characteristic of the HS pocket pairs, have to meet the prescribed boundary conditions:

- Geometric boundary conditions - preventing contact between two neighboring pockets; respecting the structural space required for the HS pockets on the guideway;
- Force boundary conditions - the pairs of pockets need to safely transfer loads determined by the rigid FEM model.

GA (Houck et al., 1999) represent one of the options for obtaining optimum results from this multiparametric task. In the case presented here the genetic algorithms are created using *Matlab GA toolbox.*

A fitness function can be selected in many different ways (e.i. maximizing stiffness with minimizing oil flow and energy consumption), depending on the needs of a particular application. One of the possibilities for setting the fitness function is to minimize the working space of the HS pocket. Fig. 8 and detailed description provides more information about the selected fitness function.

The F_s force range (Fig. 3) defines the maximum and minimum load cases F_{max} and F_{min} (around the medium load position F_{mid}) to which the HS pocket pair is expected to be exposed during operation. Therefore, the minimization task using GA aims to situate the gap height under maximum load (in one direction or the other, marked as h_{min} and h_{max} in Fig. 3) within the prescribed range +/- k_h around the balanced position h_0 (loading with own weight). This first safety range must be selected appropriately at the beginning of the GA iteration process. The range has two direct impacts:

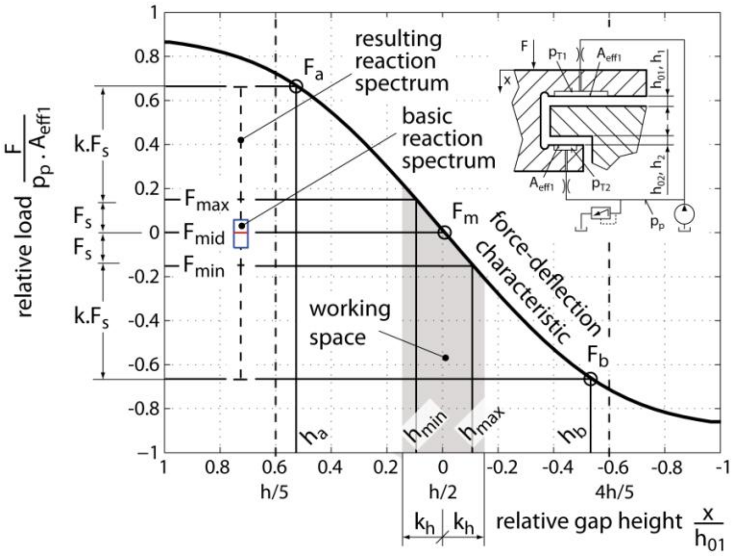

Fig. 8: The Force-deflection characteristic and description of the fitness function.

-It influences the slope of the force characteristic around the inflection point, and thus impacts on the stiffness of the bearing in the working space;

- By defining these limits the solution is ‘forced’ to be symmetrical and the inflection point of the characteristic (extreme stiffness of the bearing) moves to the center of the working space.

In order to prevent a collision between the pocket surface and the guide surface (i.e. to maintain a sufficient gap height), a second safety range was defined. On the horizontal axis of the chart in Fig. 3 this range is defined by the limit values of *20% (h/5)* and *80% (4h/5);* within these limits the force-deflection characteristic of a pair of pockets has to equal no more than the *k*-multiple of the F_s range, where *k* is an appropriately selected safety coefficient defining the *resulting reaction spectrum*. In the chart this range is defined by the F_a and F_b values . A flowchart representing the GA for obtaining an optimum force characteristic for the system based on pairs of pockets preloaded against each other is shown in Fig. 9.

The condition for ending the GA iteration process was a total of 20 generations where the fitness value remained basically unchanged. Where the result was not satisfactory from the point of view of both safety criteria, the limits for these criteria needed to be adjusted. In the opposite case the resulting characteristic of the HS pocket pair was saved in a file for further verification in the detailed FEM model.

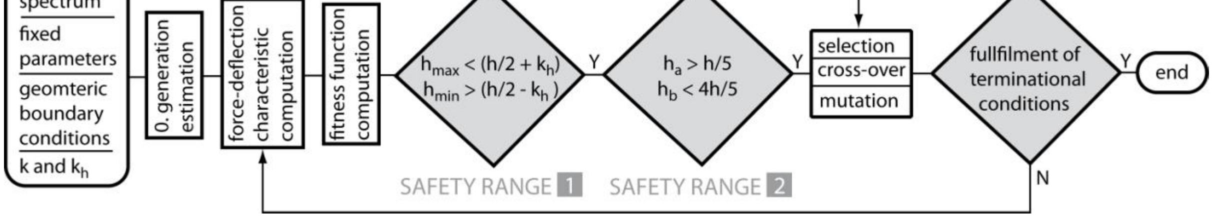

Fig. 9: Genetic algorithms based optimization.

3.3. Force reactions and deflections

The relevant conditions for the HS axes of the portal machine, which needed to be checked for in order to prevent undesired contact between the HS pocket surface and the guide surface were selected as the convergence criteria (in equations (5) and (7)) for the whole design process, include:

- The minimum gap height on the perimeter of the HS pocket (Fig. 10);

$$\min\{h_I, h_{II}, h_{III}, h_{IV},\} < h_D \tag{5}$$

- The tilting of the HS pocket in relation to the guide surface.

$$\text{rot X} < rot\,\text{X}_\text{D} \wedge \text{rot Y} < rot\,\text{Y}_\text{D} \tag{6}$$

However, as each of the HS pockets had different dimensions, the criterion defining the maximum allowable tilting (6) needed to be unified:

$$\max\{h_I, h_{II}, h_{III}, h_{IV},\} - \min\{h_I, h_{II}, h_{III}, h_{IV},\} < \varepsilon_D \tag{7}$$

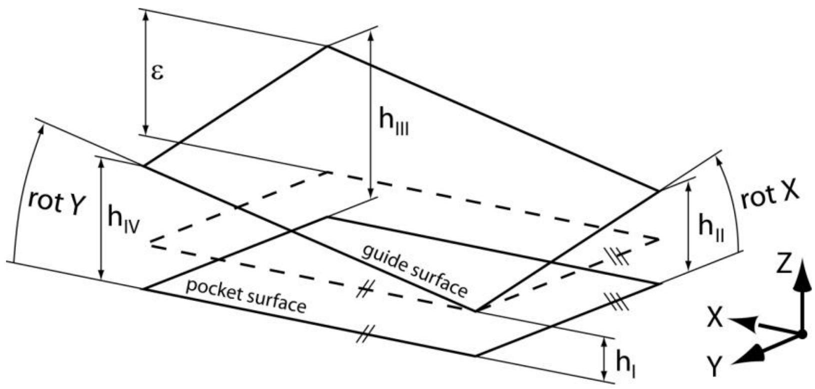

Fig. 10: Checking for undesired conditions of the HS pocket.

This check is performed for all pairs of HS pockets (Fig. 5) of the machine axis in question, in each iteration step of the design process, using the detailed FEM model of the whole machine loaded with a symmetrical load case (the F_{med} force from Fig. 3). The detailed FEM model of the whole machine is shown in Fig. 11.

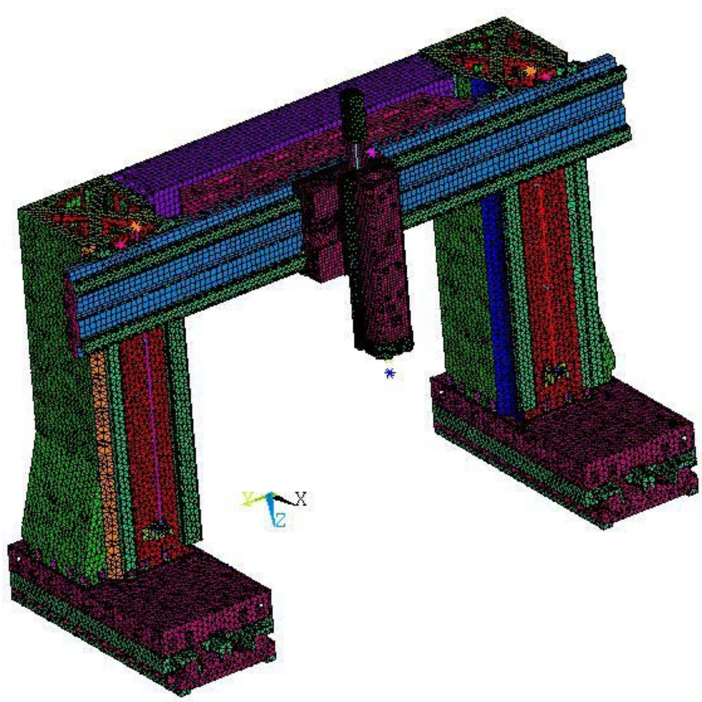

Fig. 11: Detailed FEM model of the machine.

Non-linear elements characterizing the force-deflection properties were added between the guideway parts in the direction of the *X* axis.The material and geometry of the model parts are defined by the specific brief. Connected mass elements: ca. *18 t*. Total mass of the model with connected masses: ca. *152 t*. The FEM model elements used in the ANSYS software: Solid45, Shell63, Mass21, Combin39.

In the detailed FEM model (Fig. 11) the guideways for the *Y*, *Z* and *W* axes (which are not part of the design process) are represented by linear springs with approximate stiffness. Non-linear elements characterizing the force-deflection properties of the HS guideway pockets (Fig. 8) were added between the guideway parts in the direction of the *X* axis.

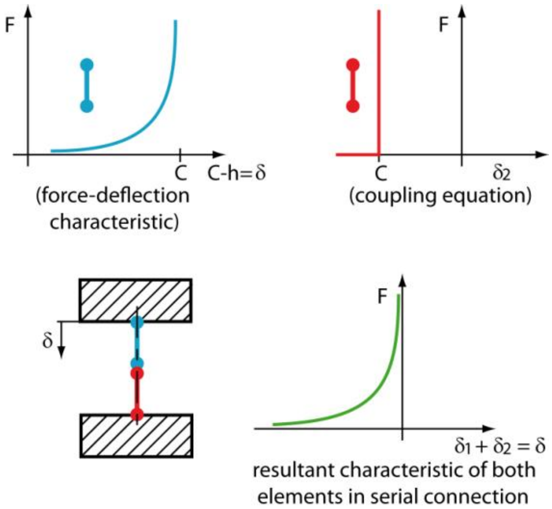

Fig. 12: Force-deflection characteristics of elements representing HS pockets.

Using ANSYS, each of the pockets is represented by a CONTA39 nonlinear spring and a preloading constraint equation to model the pocket characteristic and the nominal pocket gap as well, Fig. 12.

In case the conditions of inequations (5) and (7) are not met, the positions (numbers) of the HS pockets in the detailed model are sensitively adjusteded (according to detailed FEM model results) and new values for the medium load of the reaction spectra F_{mid} are computed (positions on the y axis of the chart in Fig. 6). The absolute magnitude of the reaction spectra (determined by the F_s value) does not change (based on the premise that data provided by the rigid FEM model correspond to all possible combinations of load cases, and their adjustment is not necessary due to the safety factors). In case the above-mentioned convergence criteria are met for the HS axis as a functional unit, the iteration process (Fig. 2) is terminated and the solution is considered to be complete.

4. Results

Satisfactory results were obtained-i.e. the convergence criteria (equations (5) and (7)) were met already in the second step of the iteration process shown in Fig 2. A comparison of iteration steps 0 (initial - Fig. 6) and 2 (final) is shown in Fig. 13.

During the process new pocket positions were found, their dimensions and capillary tube parameters were optimized; the number of pockets remained unchanged. As Fig. 13 shows, the reaction spectra (output from the rigid FEM model – Fig. 2) only change their position on the *y* axis (the position of medium load F_{med}); their magnitude (i.e. the range of the F_s forces) remains unchanged during the iteration process.

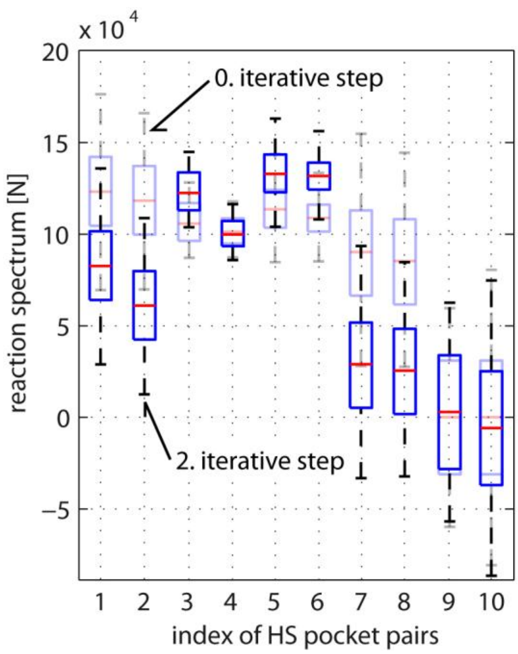

Fig. 13: Resulting reactions in the pocket pairs.

A total of 100 individuals in 500 generations were sufficient in each GA iteration step of the process shown in Fig. 9 to find suitable solutions (force-deflection characteristics of the HS pocket pairs) using GA.

The limits within which the resulting force characteristics of the HS pocket pairs have to be situated are determined by the coefficients *k* and k_h. For the vertical guideway the value of the safety coefficient *k* (a multiple of the load spectrum) equals *2.5*; for the lateral guideway (which already has large safety margins in the condition of zero drive stiffness) the value equals *2*. The k_h coefficient (defining the working space) is the same for both guideways and its values equals *0.01 mm*. Two examples of the resulting characteristics from the final, second iteration step of the whole design process for HS guideways of the X axis are shown in Fig. 14 (the marked areas and limits are the same as the marking in Fig. 5).

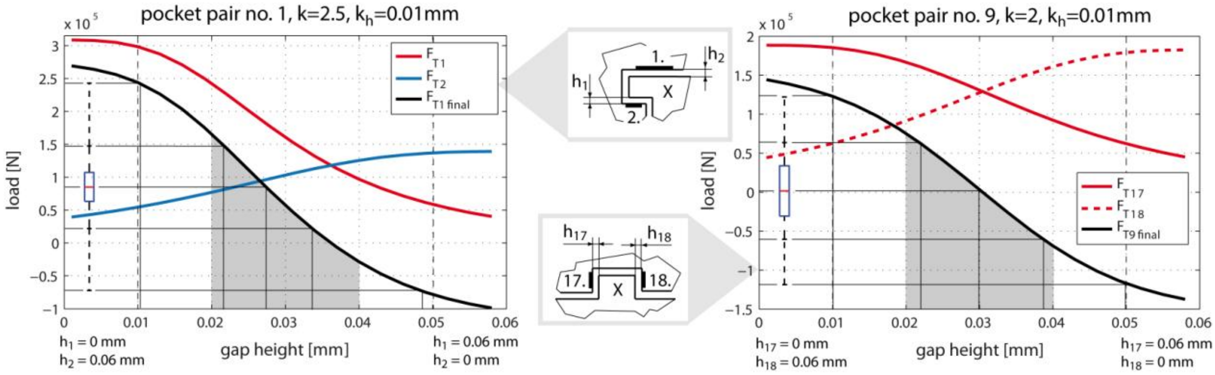

Fig. 14: An example of the resulting characteristics for pairs of HS pockets of the vertical (left) and lateral (right) guideway.

Due to loading (namely the weight of the parts) and to the overall flexibility of the longitudinal slide and the bed, significant local deflection occurred in the HS guideway of the X axis. The HS guideway pockets also tilted considerably, which reduced their load-bearing capacity.

Example results of the initial and the final design are shown in Fig. 15. The overall deflection after the longitudinal slide is loaded by the parts' own weight is shown.

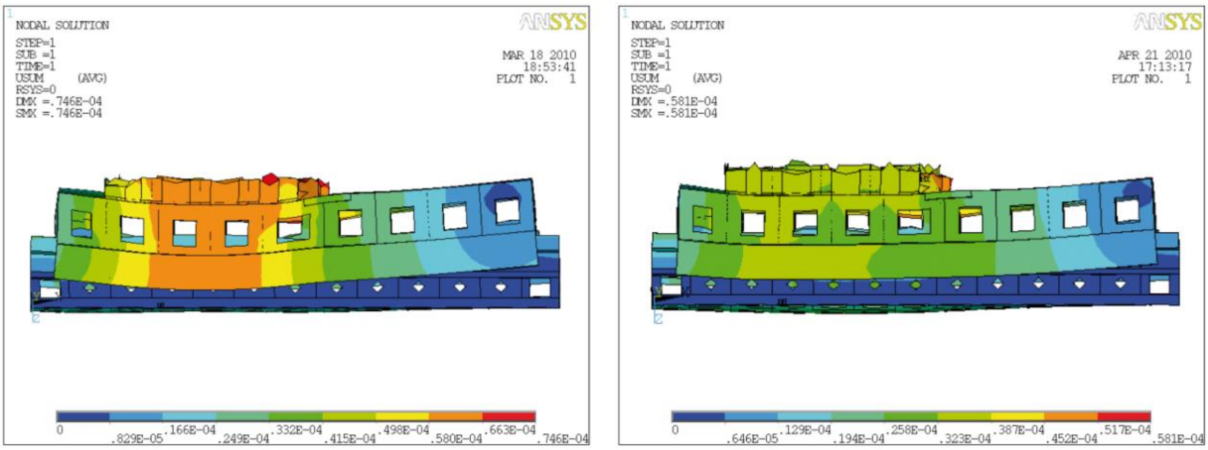

Fig. 15: Visualization of the results of the initial and the final design.

The convergence criteria (5) and (7) were set as follows: the minimum gap height on the perimeter of the pocket could not be less than $h_D = 0.010$ *mm*, and the tilting of the pocket in relation to the guide surface could not exceed the prescribed value of $\varepsilon_D = 0.007$ *mm.* When these criteria were met for all pockets of the HS guideway of the *X* axis, the design was considered to be complete.

5. Conclusions

An iterative approach to designing HS guideways for a machine tool has been presented, based on the finite element method (FEM) and an optimization method using the minimization task. The design aims to find suitable dimensions, location and number of HS pockets and controllers for the HS guideways in order to meet load-bearing requirements and minimize deflection.

The process was demonstrated on one half of the HS quideways of the *X* axis of a portal milling machine. Optimum results were obtained in the second iteration step. The whole iteration procedure has been automated.

The advantage of this design process combining multiparametric optimization and FEM lies in its robustness (the possibility to check for any parameter of the pocket or the guideway) and variability. The drawback are its demands on detailed FEM modeling. Any pocket shape and controller type can be taken into account, if their clear description exists in the fluid mechanics domain. Great variability of the optimization process is another indisputable advantage. The optimization can be based on any parameter or a combination of parameters. Instead of simple GA, the approach to designing HS guideways could be further developed by using NSGA II optimization (Deb et al., 2002), which does not use weight coefficients, and thus optimize the dimensions of the pockets and the controllers used from the point of view of more performance characteristics (e.g. adding stiffness and flow characteristics to force-deflection characteristics).

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