DESIGN OF AN ACTIVE FLUID DAMPING SYSTEM FOR VIBRATION CONTROL OF DISK-SHAPED TOOLS

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ABSTRACT

To meet the requirements of today´s cutting process of natural stones thin disk-shaped tools with large diameter are applied at high cutting velocities. To use these tools, guiding systems for the disks are needed. Therewith, tool vibration magnitudes and deflections can be reduced. The risk of producing scrap parts or tool damage are decreased. However, the guidance being placed close to the cutting zone reduces the cutting depth, so that the process is limited to the production of small slabs and tiles. To use the advantage of a guidance without limiting depth of cut, a new guidance concept is presented. Thereby the guiding areas are placed opposite to the cutting zone. This enables the reduction of tool vibration without decreasing the depth of cut. In this paper the compensation of tool vibration by this guiding concept is investigated. Different types of guidance are compared and the most suitable compensation approach is identified. Further on, the problem of the decreasing compensation effect, due to the increasing distance between the excitation and the guidance is considered. To increase the compensation effect, the guidance is optimized regarding to the number and positon of guiding areas. The capability of the presented concept is verified by a comparison with a conventionally placed guiding system.

KEYWORDS

Cut-off grinding, disk-shaped tools, guidance, fluid actuator, optimization

INTRODUCTION

Cut-off grinding with disk-shaped tools is preferred for machining of natural stones. It enables faster chip removal with a lower cutting width compared to wire or gang saws [2]. Nowadays, the market requires slabs and tiles with increasing lengths and widths but decreasing thicknesses, for instance as facade plates [5]. Simultaneously, the production costs should be reduced by increasing cutting velocity and decreasing tool width. To meet these demands, tools with increased diameters, reduced thicknesses and high cutting velocities are applied. However, an increasing ratio of blade diameter to thickness reduces the lateral tool stiffness. Therefore, the magnitudes of tool vibrations and the deflection are increased. The consequences are higher parallelism errors of cutting kerfs resulting in scrap parts and reduced tool life. Guiding systems are applied to compensate vibrations and deflections.

PRINCIPLES OF GUIDING SYSTEMS

Contact, aerostatic and hydrostatic principles are mainly used for guiding systems [3]. The contact guidance uses the mechanical contact between saw and guiding areas. Large contact forces are reached caused by the high stiffness of solid-state guidance. Therefore, the capability for compensation of tool vibrations and deflections is increased. The friction between guidance and saw generates thermal and mechanical stresses. These stresses are increasing with rising rotation velocities. Thus, unacceptable wear and heating of the tool and the guidance are induced [8]. To overcome this problem Fronius [3] and Szymani [8] recommend the application of an aerostatic or hydrostatic guidance.

The aerostatic guidance is a non-contact principle, generating counteracting forces by compressed air. There is no friction, no wear and negligible tool heating. High tool rotation velocities can be applied. The disadvantage of this principle is a reduced stiffness compared to contact guidance. This results in a reduced compensation of tool vibrations and deflections. Furthermore there is the possibility of pneumatic instability in form of self-excited vibrations. This could lead to an excitation of resonances.

Hydrostatic guidance is applied to overcome these problems. Instead of compressed air a hydraulic fluid is used. In case of cutting natural stones, water is applied. The higher viscosity of the water leads to an increasing compensation capability. Another advantage is the squeeze-film effect. It uses shear forces within fluids to damp vibrations. The vibration between saw and guidance induces time variant displacements of the fluid between the saw and guidance. Due to the inner fluid friction, energy dissipates, leading to a reduction of the vibration magnitudes [6]. More benefits are the process of cooling and the transport of chips out of the cutting zone. High power losses due to shear friction is a disadvantage of this principle. Viswanath [9] shows, that the power loss is directly proportional to the size of guiding areas. To reduce the power losses, the size of hydrostatic guidance has to be decreased, whereby the compensation effect is reduced. Due to the advantages, the hydrostatic guidance is the most suitable system to compensate tool vibrations.

The position of the guidance is also from great importance. Fronius and Schajer [7] have dealt with the influence of position of guiding systems on the compensation of tool vibrations and deflections. They recommend positioning the system as close as possible to the cutting zone, in order to get the highest reduction of parallelism error. The disadvantage of this positioning is the limitation of cutting depth. But to meet the demands of today´s cutting process the guidance must not be placed at this position. Therefore a new guiding system is proposed, being placed counterpart of the cutting zone and using the hydrostatic principle to compensate tool vibrations efficiently. The following investigation deals with the compensation capability of this guiding concept. To increase its compensation effect the guiding areas are optimized regarding to their number and position. A comparison between the optimized concept and a recommended placed guidance illustrates the compensation effect of the proposed concept.

DEFINITION OF TOOL AND GUIDING PARAMETERS

Fig. 1 illustrates the geometry of the tool and guidance. For the optimization, a disk-shaped tool with a diameter of D = 1000 mm, a thickness of w = 5 mm and a flange diameter of D_f = 300 mm is assumed. The guidance is described by the number of guiding areas n, their diameters $D_{d,i}$ and positions being presented by the radial and angular positions $r_{d,i}$ and β_i. The index i describes the parameter of the guiding area i. To simplify the optimization process, the number of variable parameters has to be reduced. Therefore, the parameters $r_{d,i}$ and $D_{d,i}$ are defined as constant. The radial positions of the guiding areas are $r_{d,i}$ = 400 mm and the area diameters are $D_{d,i}$ = 30 mm. Preliminary tests determined that these values enable a high compensation effect. The number and angular positions of guiding areas are variable parameters. Thereby, the number of guiding areas n is a discrete parameter with a domain from 1 to 3. The angular positions β_i are continuous parameters defined between 90° and 270°. The boundaries ensure that the guidance is positioned counterpart to the cutting zone. To evaluate the optimized guidance a reference guidance is defined. It is represented by one guiding area being positioned close to the cutting edge (β_1 = 0°) with a guiding area radius of $r_{d,i}$ = 400 mm and a guiding area diameter of $D_{d,i}$ = 30 mm. To compensate tool vibrations, the guidance areas are defined as dampers. The damper have a constant damping ratio of 2 Ns/mm. This value is determined by a convergence analysis of the tool vibration magnitude depending on the damping ratio of three dampers. Thereby the tool magnitudes, presented in Table 2 for three dampers, are reached. A further increase of the damping ratio does not lead to an additional increase of the compensation effect. Fig. 1 summarizes the tool and guidance parameter.

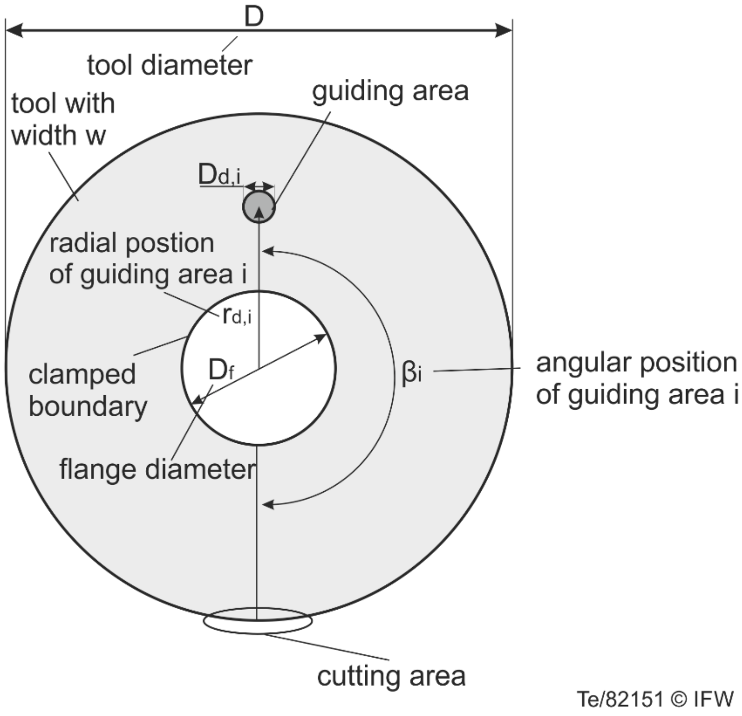

Fig. 1: Definition of tool and guiding parameter

OPTIMIZATION OF GUIDING PARAMETERS

After defining constant and variable parameters the optimal configuration of area, number and their angular positions are determined. Fig. 2 illustrates the optimization process exemplarily for two guiding areas. The compensation effect of the guiding system is maximized. This effect can be quantified by the tool vibration magnitudes within the cutting zone of the first and second eigenfrequency. Asche [1] and Bockhorst [2] mentioned, that dynamic loads induce high parallelism errors. The highest vibration magnitudes occur during the excitation of the first and second eigenfrequency. The reduction of these vibration magnitudes describes the compensation effect of the guidance. Therefore, it is used as optimization criterion. The tool vibration magnitudes are determined by a numerical harmonic analysis. A finite element model is created, that exists of shell elements with a total of 2910 nodes. Shell elements are chosen due to the abstinence of the locking effect by a large element length-to-thickness ratio compared with solid elements. The minimum number of required nodes is determined by a convergence analysis of the eigenfrequencies.

Following conditions are defined for the simulation: the tool is clamped at its center and is excited in the cutting zone by a lateral frequency variant oscillating force with an amplitude of 10 N. A frequency band from 0 to 200 Hz is considered. The resonance excitation of 10 N over 200 Hz of the unguided tool induces tool magnitudes in the cutting zone being less than 0.1 mm (Fig. 3). Due to the small amplitudes, frequencies over 200 Hz are neglected. Initially discrete design points are created with a design of experiments (DOE) to describe the magnitudes of tool vibration in the cutting zone for certain parameter configurations. The design points are used to create a response surface. The response surface is a multidimensional continuous function representing the magnitudes of vibration depending on the variable guiding parameters. To exactly describe the multidimensional system, a minimum number of design points is required. This number increases exponentially with the number of variable parameters. Therefore, just the number and angular positions of the guiding areas are varied in this investigation. Five optimization processes are executed to analyze the influence of the number of guiding area and angular positions on the compensation effect of guiding systems being placed counterpart to the cutting zone. The defined values of tool and guiding parameter are shown in Table 1.

Table 1: Parameter configuration for the optimization processes:

Optimization process **Parameter**	1	2	3	4	5
Tool diameter D [mm]	1000	1000	1000	1000	1000
Flange diameter D_f [mm]	300	300	300	300	300
Tool width w [mm]	5	5	5	5	5
Radial position of guiding areas r_{di} [mm]	400	400	400	400	400
Guiding diameter D_{di} [mm]	30	30	30	30	30
Angular position of guiding areas β_i [°]	**Var.**	**Var.**	**Var.**	**Var.**	**Var.**
Number of guiding areas n [-]	1	2	3	2	3
Number of design Points $n_{p,i}$ [-]	42	200	400	500	1000

The first three optimization processes differ on the number of guiding areas n. The guiding angular positions are the optimization parameter of each optimization process. Initially the first optimization considers one area with the optimization parameter β_1. To analyze the influence of the angular position on the compensation effect exactly the number of design points should be as high as possible. Referring to the diameter $D_{d,i}$ = 30 mm and the radii of $r_{d,i}$ = 400 mm, a number of positons $n_{p,1}$ = 42 are created for one guiding area. This number realizes a small variation of β_i between neighboring design points without an overlapping. The determined design points include information about the magnitudes of the tool in the cutting area depending on the angular position β_1. Subsequent two (β_1, β_2) and three (β_1, β_2, β_3) guiding areas are examined. The increasing number of areas induces an increasing number of design points to create an exact response surface. Based on the number of design points of n_p = 42 for a guiding area, the possible number of design points for two areas is $n_{pmax,2}$ = 903 and for three areas $n_{pmax,3}$ = 796446. These numbers are too high for an efficient optimization. Therefore, a reduced number of design points have to be applied for two and three guiding areas. To reduce the number of design points a Latin hypercube sampling is applied as DOE. It enables the reduction of design points with a simultaneously uniform distribution in the definition ranges of β_i. However, if the number of design points is too low, the response surface will describe the vibration magnitudes inaccurately. For the optimization of two and three areas, the number of design point are $n_{p,2}$ = 200 and respectively $n_{p,3}$ = 400. These numbers are significantly lower than the possible numbers $n_{pmax,2}$ and $n_{pmax,3}$. Therefore the correctness of the response surface based on these design points have to be evaluated. For the evaluation, the optimization processes four and five are executed. These simulations have the same parameter values like process two and three, but the numbers of design points are increased to $n_{p,2}$ = 500 and $n_{p,3}$ = 1000 respectively. The comparison between the results of the optimization processes two and four as well as three and five illustrates the influence of the number of design points on the optimization results.

Based on the different number of design points a response surface for each optimization process is created. Thereby, the design points are interpolated by the Kriging method to get continuous functions of the tool vibration magnitude depending on the appropriate variable guiding parameter β_i. Kriging is a statistical method using the number and distribution of the design points for interpolation to enable a good estimation of interim values [4]. The Kriging result is a multidimensional continuous function of tool vibration in the cutting zone depending on β_i. The created response surfaces are used by the optimization algorithm to calculate the optimal damper positions for each number of damper. A genetic algorithm is used for optimization of damper positions with 20 iteration steps and 1000 individuals per step. An investigation has determined that this combination of steps and number of individuals produces repeatable and plausible optimization results.

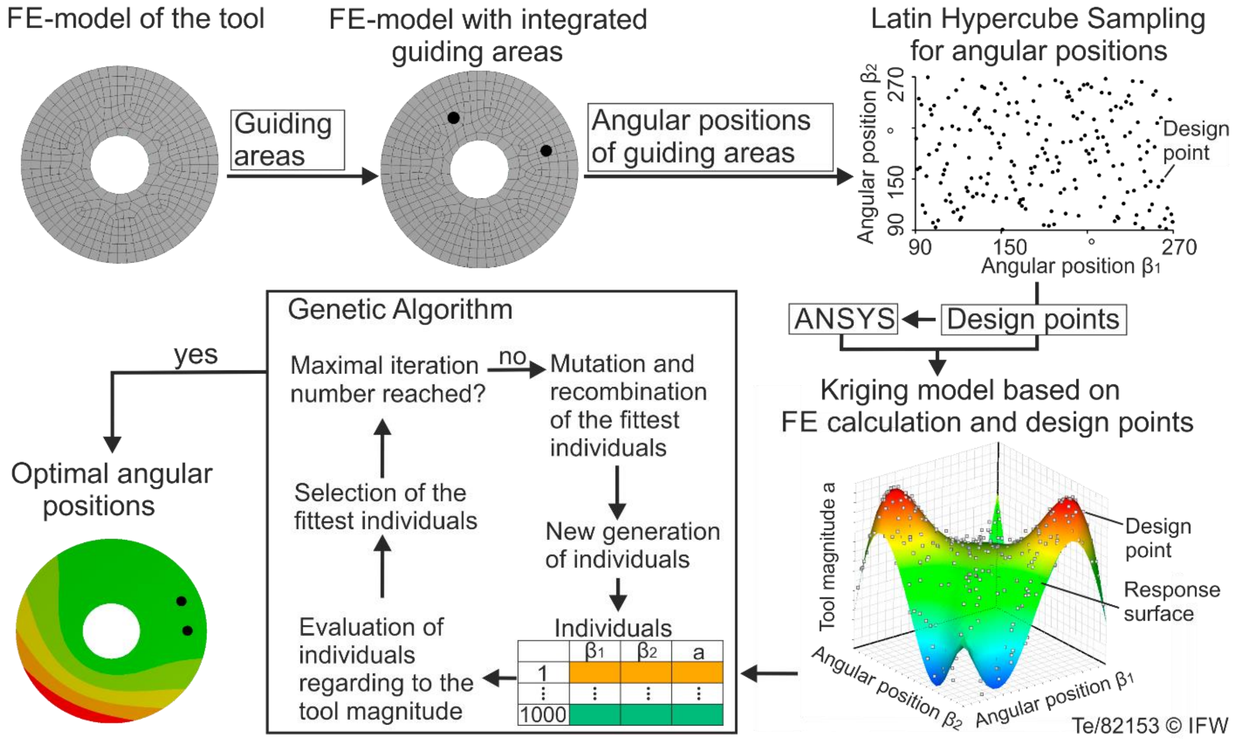

Fig. 2: Schematical process of optimization for two guiding areas

Fig. 3 and Table 2 show, that the compensation effect increases with rising number of guiding areas. An application of three guiding areas reduce the tool magnitude by 36% for the first and 52% for the second eigenfrequency compared with an unguided tool. Two dampers can reduce the magnitude by 31% and 40%, respectively. One guiding area is not able to compensate the resonance effects of the tool. The optimal positions of the guiding areas are not directly counterpart of the cutting zone. The optimization determined nearly rectangular positions between guiding and cutting area. A possible reason is the shorter distance between the cutting zone and guiding areas. Thereby induced tool vibrations are damped earlier and the resonance effect can be reduced. The number of design points has a small influence on the determined angular positions. The differences between the calculated angular positions are small, whereby low differences of the magnitudes with 2.5% for the first eigenfrequency and 2.1% for the second eigenfrequency are induced. Further on Table 2 illustrates that a damper being positioned close to the cutting area can reduce the magnitude more effective than a counterpart positioned guidance. The magnitudes are decreased by 99% and 91% respectively for the first two eigenfrequencies. The high compensation effect is caused by the increase of local tool stiffness. Thereby, the resonance frequencies are changed to higher values. The frequency response spectrum in Fig. 3 illustrates the vibration magnitudes of an unguided and guided tools in a frequency range of 0 to 200 Hz. The results shows, that the guiding systems are able to reduce the vibration magnitude of further eigenfrequencies at 70 Hz, 110 Hz and 165 Hz.

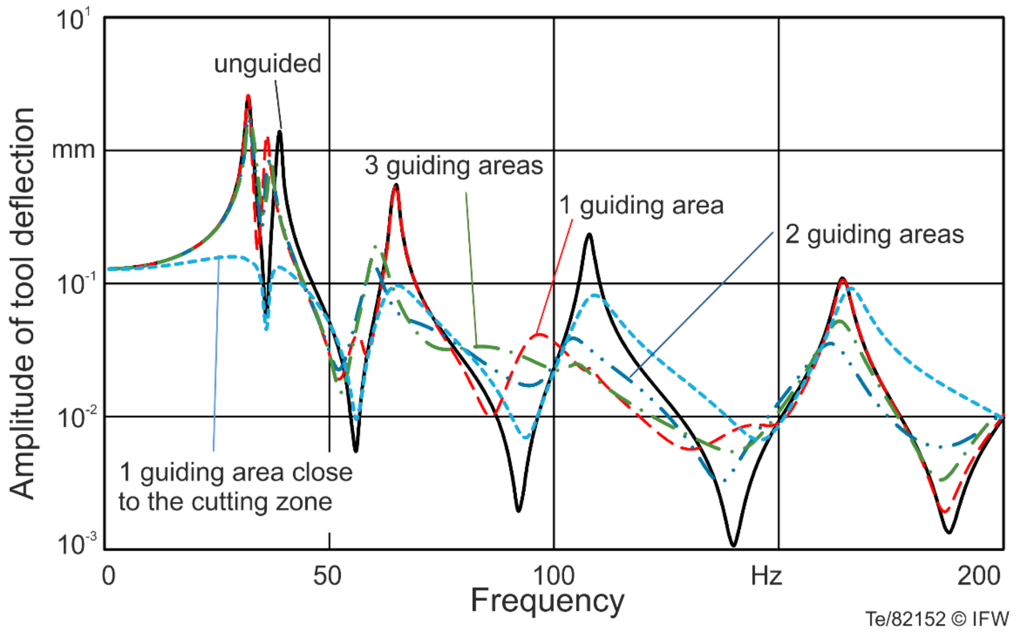

Fig. 3: Frequency response of tool vibrations at the cutting area of guided and unguided tools

Table 2: Results of the optimization process

Number of guiding areas n	Number of design points n_p	angle of damper β_1 / β_2 / β_3	Magnitude 1. eigenfrequency a_1	Magnitude 2. eigenfrequency a_2
0	1	-	2.56 mm	1.38 mm
1	1	0°/ - / -	0.15 mm	0.13 mm
1	42	270.0°/ - / -	2.57 mm	1.45 mm
2	200	132.8°/ 90.1° / -	1.85 mm	0.86 mm
2	500	114.0°/ 90.1° / -	1.77 mm	0.84 mm
3	400	115.5°/ 98.4°/ 260.0°	1.67 mm	0.69 mm
3	1000	110.5°/ 91.8°/ 248.4°	1.63 mm	0.67 mm

SUMMARY AND OUTLOOK

The guiding system being placed counterpart to the cutting area can reduce the magnitude of tool vibration significantly. A rising number of guiding areas leads to an increasing compensation effect. But the long distance between excitation and guiding zone induces a decreasing compensation compared with a damper placed close to the cutting area. With respect to a constant damping ratio the guidance being positioned close to the cutting area is more effective but decreases the depth of cut significantly. The presented investigation has dealt with a variable number and angular position of the guiding areas. Following analysis could consider the influence of the diameter of the guiding area D_{di} and their radial position r_{di}. This enables the calculation of an optimum for all guidance parameters. But the effort of time and resources increases due to more parameters. Therefore the DOE has to be adapted. Another approach to raise the compensation effect is the use of a time variant guiding force instead of a constant damping ratio. Thereby, the effects of destructive interferences between the excitation of the cutting process and the guidance are investigated to reduce the tool vibration.

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