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Influence of Selective Process Interfering on the Workpiece Fixture Dynamics in Precision Honing

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Abstract

In the area of precision machining processes, honing is of central importance for manufacturing high-precision functional components according to the current state of technology. This precision machining process usually represents the last machining step in the process chain and fulfills high requirements in terms of shape, dimensional and surface quality of less than 1 µm. Therefore, the knowledge of the process dynamics of the tool-workpiece fixture system is of major importance. This paper focuses on the process dynamics of the workpiece fixture in internal long-stroke honing for bore diameters less than 10 mm. In general, the dynamics of a moving system can be described by mass, stiffness and damping. These variables are experimentally included in the investigations as interfering variables in the workpiece fixture and the process dynamics are monitored using eddy current sensors. A gimbal-mounted workpiece fixture with four degrees of freedom is applied for this purpose. The aim of this work is the analysis of the dynamic behavior by variation of the interfering variables and the determination of the process limits. For this purpose, elaborate experiments are carried out and extensive results are presented.

Keywords: Honing; Precision machining; Workpiece fixture; Process dynamics; Selective process interfering; Mass; Stiffness; Damping

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1. Introduction

Honing is one of the most established precision machining processes for the manufacturing of high-precision functional components. Production engineers will have to face new challenges in terms of production accuracy, therefor honing is a key technology that is essential to many process chains. This requires continuous development of fine machining processes [1, 2]. Honing belongs to the separating production processes with a geometrically undefined cutting edge and is usually deployed at the end of the process chain [3, 4]. Honed surfaces represent a finished functional surface for sliding, sealing and guiding under mechanical load. This results in high requirements in terms of shape, dimensional and positional accuracy as well as edge zone and surface quality. The achievable tolerances are in the sub-micrometer range. [5, 6, 7] The honing process is basically characterized by the following properties [8]:

- the bore-filling tool
- cutting pads with bonded abrasives and large-area contact
- the self-regulating system for coaxial machining
- process kinematics and the resulting cross-hatch pattern

The areas of application extend to the entire metalworking industry, such as the automotive, hydraulic and pneumatic industries, as well as aerospace and medical technology. Applications include the machining of cylinder lines for combustion engines, air bearing spindles and gears. From the production technology and quality control point of view, high requirements are placed on the process reliability and reproducibility of this production process [1].

Fundamental and detailed investigations of the process dynamics of internal long-stroke honing for bores smaller than 10 mm diameter, in particular of the tool-workpiece fixture system and the distribution of forces during the process have already been carried out. Investigations in the area of resulting forces, torques and workpiece surfaces for forced-controlled honing with an experimental setup [9] and simulations [10] have been examined. Further studies are concerned with the investigation of the process dynamics by eddy current sensors. On this occasion, implementing a simulation model based on mathematical equations, the movement dynamics of a gimbal-mounted workpiece fixture during processing have been presented. [11, 12, 13]

In this paper, in addition to the basic contribution of the tool kinematics in long-stroke honing, the process behavior of the gimbal-mounted workpiece fixture is discussed in more detail. This fixture is a key factor in achieving the accuracies already mentioned above. In [11, 12] detailed investigations on the dynamics of the gimbal-mounted workpiece fixture have already been carried out, which show the contact process and the transfer of the tool kinematics to the gimbal-mounted workpiece fixture. Fig. 1 shows a simplified description of the process behavior that leads a resulting workpiece fixture dynamic under the influence of the tool excitation.

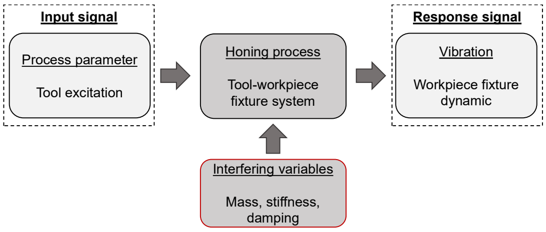

Fig. 1. Simplified description of the process behaviour by tool excitation and interfering variables

Based on the preliminary investigations, the main focus lies on the movement dynamics of the gimbal-mounted workpiece fixture under the influence of interfering variables. In this paper, these interferences are described by the system parameters mass, stiffness and damping. In context of detailed experiments, these system parameters are integrated into the honing process respectively to the degrees of freedom of the workpiece fixture. The resulting movement dynamics of the workpiece fixture are analyzed and stable as well as unstable process parameters are verified using a characteristic curve. As illustrated in Fig.1, the dynamic behavior of the workpiece fixture is determined by both the physical parameters of the fixture itself and the interaction with the tool. Consequently, the dynamics of the fixture are dependent on the chosen process parameters and the structural design. In contrast to the process parameters, a variation of the fixtures physical properties requires a geometric modification and cannot be changed during the machining process.

2. State of the art

2.1. The honing process

The tool kinematics in internal long-stroke honing is composed of three simultaneously operating movement components as shown in Fig. 2:

- an oscillation movement along the tool axis
- a rotation movement in tangential direction
- and an infeed movement of the honing stone in radial direction [5, 8]

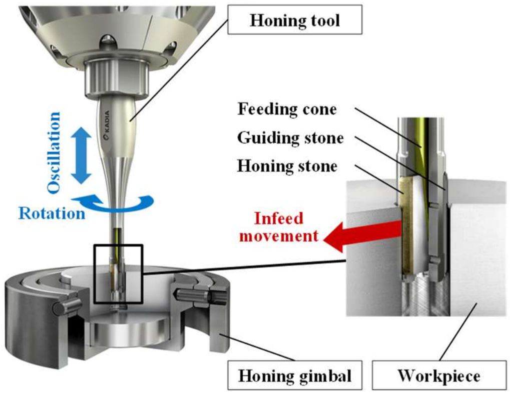

Fig. 2. Tool kinematics of the honing process [12]

The tool shown in Fig. 2 is a single honing tool with an abrasive honing stone and two guide stones. The overlay of the kinematic movements results in a characteristic cross-hatch pattern on the honed surface, which defines a specific honing angle. This crosshatch pattern helps to keep oil at the surface of the workpiece and improves the friction conditions [13].

In addition to the tool kinematics, the adaptation of the workpiece fixture is a crucial factor for the reproducible process control. To achieve the accuracies, a coaxial orientation of the tool and workpiece is necessary. Thus, the workpiece centerline is oriented towards the honing tool centerline and builds a coaxial system. The requirement for coaxial machining is given by the movement possibility of the tool-workpiece system. The lighter component, the workpiece, is generally assigned the required degrees of freedom. [5] For the experiments, the workpiece is clamped in the manner of a gimbal-mounted workpiece fixture (short: honing gimbal) and the tool is rigid. The honing gimbal allows four degrees of freedom during the honing process. Fig. 3 illustrates the degrees of freedom of the honing gimbal.

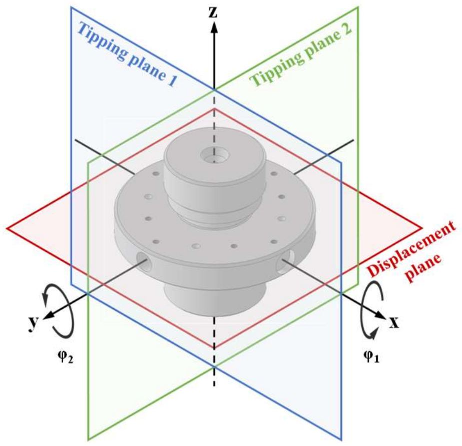

Fig. 3. Degrees of freedom of the honing gimbal [12]

Two translational degrees of freedom cover the displacement plane (centering, x-y plane) via the x- and y-displacement axes. Further two rotational degrees of freedom φ1 and φ2 around the two displacement axes build the two tipping planes 1 and 2 (tipping, x-z-plane, y-z-plane) according to the respective inclined position. The given degrees of freedom enable a centering and tipping of the bore during the infeed movement of the honing stone due to the diametrical expansion, i.e., a coaxial honing process is established.

2.2. Design of a workpiece fixture

Basically, fixtures, tools, measuring and control equipment belong to operating resources that are used in production facilities. In addition, with machine tools they combine a production resource [14]. Regardless of the manufacturing application or design, a fixture can fulfill three main functions as a separate subsystem of the production facility: positioning, clamping and holding the workpiece, and guiding the tool [15]. Based on the general functions of a fixture and the requirement for coaxial machining in precision honing, it is necessary to design a honing gimbal accordingly. The position of the displacement and tipping axes is crucial for the proper function of the honing gimbal. Fig. 4 shows this aspect schematically.

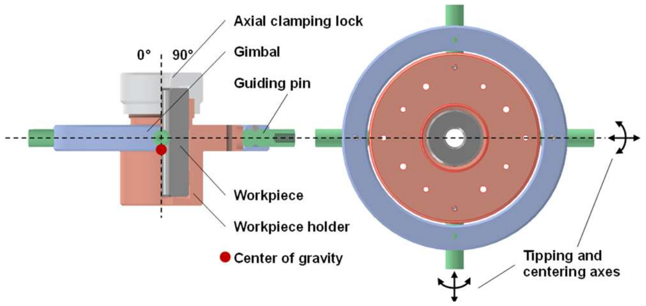

Fig. 4. Design of a honing gimbal in side and top view according to [5]

The rotary cross axis should be at the center of gravity level of the moved total mass for coaxial honing or rather a few millimeters above it for stable conditions [1, 5]. In addition, experience has shown that the mass of the honing gimbal should be adjusted so that the rotary axes are in the middle of the bore length.

In this paper, the system parameters of mass, stiffness and damping are specifically integrated to the degrees of freedom of the honing gimbal. Subsequently, the influence on the honing process is evaluated.

The paper in [16] describes that during milling, workpiece vibrations were reduced by process damping. At the same time, the surface quality has improved. The investigation in [17] develops an active workpiece holder with actuator and springs that avoids chatter vibrations of the workpiece. In the area of honing, additional masses can also be applied to fixtures to compensate smallest imbalances [1].

2.3. Design of a workpiece fixture

To effectively design a honing gimbal and to closer understand its process performance, it is necessary to consider the basics of the dynamic behavior of machine tool components and its variables. Unbalanced dynamic properties further vibration phenomenon or increased displacements, which lead to reduced process quality and higher tool wear. Machine tools, including honing machines, usually consist of several oscillatable components which can be described as a system of decoupled so-called Single Degree of Freedom Oscillators (SDOF's) [14, 18, 19]. A SDOF is often used to characterize dynamic systems and their properties. It is comprised of a spring-mass-damper system, defined by the parameters mass, stiffness and dampening rate with a time-dependent force initiating a dislocation, as depicted in Fig. 5 [14, 20].

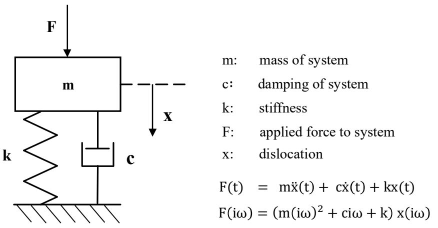

Fig. 5. Single Degree of Freedom oscillator and parameters [20]

One possibility to describe the dynamic behavior is the so-called Compliance (G) Frequency Response Function (FRF) by forming the quotient between the frequency dependent dislocation x(iω) and the causal dynamic force F(iω). By including both the natural angular frequency ω_n and Lehr's damping ratio D [19]:

$$\omega_n{}^2 = \frac{k}{m} \quad \text{and} \quad D = \frac{c}{2m\;{}_n} \tag{1}$$

the Compliance FRF is given by the following equation:

$$G(i\omega) = \frac{x(i\omega)}{F(i\omega)} = \frac{1}{m(i\omega)^2+ci\omega+k} = \frac{\frac{1}{k}}{(\frac{i\omega}{\omega_n})^2+2D\frac{i\omega}{\omega_n}+1)} \tag{2}$$

It becomes apparent that the Compliance FRF is governed by the parameters mass m, stiffness k and damping D, with the dependence of the position of the compliance maximum at the natural frequency on those parameters being illustrated in Fig. 6 [20, 21].

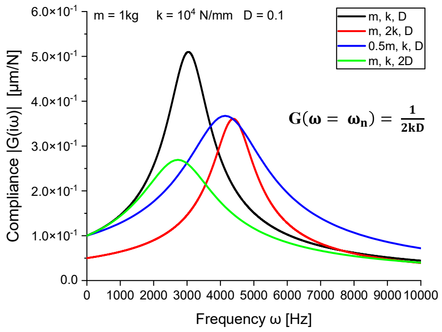

Fig. 6. Dynamic compliance and the influence of m, k, D [20, 21]

Both, a mass decrease and a stiffness increase, shift the critical frequency range to higher values. Additionally, the maximum compliance magnitude is reduced. An increase in dampening has no effect on the peak position but reduces its magnitude as well [19, 20, 21]. In conclusion, the dynamic behavior of a machine tool, including honing machines, is dependent on three system variables [19]:

- mass and its respective distribution
- (static) stiffness and its respective distribution
- system damping, primarily in joints/coupling points

Transferring the presented knowledge to the honing process, the following suppositions are formulated regarding the honing gimbal:

- the components of the gimbal are each represented by decoupled SDOF's
- the guiding pins connecting the components are represented by spring-damper-systems
- the interfaces between the guiding pins and the fits are joints with system damping

Each component can be represented by a separate SDOF with its own Compliance FRF. The dynamic behavior of the honing gimbal is therefore also dependent on mass, stiffness and system damping. Experiments in [22] showed an apparent resonance behavior at a certain rotational speed during honing processes for the translational movement, which manifests itself in the form of higher displacement values of the honing gimbal. A decrease in mass by structurally adapting the gimbal in [23] resulted in a shift of the increased values to higher rotational speeds for the translational movement of the gimbal. Since only the effect on the translational movement was investigated, follow up experiments are carried out to examine the influence of the system parameters on the entire honing process itself.

3. Preliminary investigation on honing gimbal dynamics

3.1. Experiments with additional masses

The machine used for the honing experiments is a vertical single spindle machine by the German manufacturer Kadia Produktion GmbH + Co of type LH 30/300R.

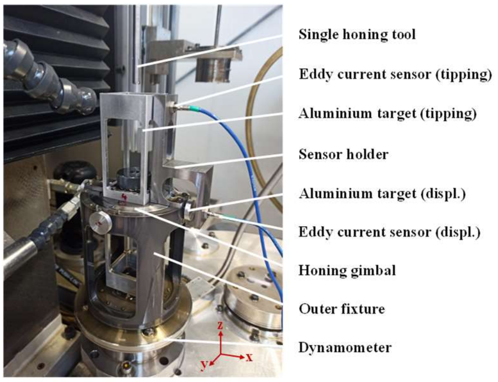

Fig. 7. Experimental basic setup

It includes a single honing spindle, a pneumatic measuring device to determine the diameters after machining as well as a deburring station. The stroke position is determined by an external control unit. A four-component dynamometer mounted beneath the honing gimbal measures the axial force of the honing tool and the torque.

The associated signals are transferred to a Genesis 2i high-speed data recorder by Hottinger Baldwin Messtechnik GmbH for analysis. Further, an eddy current measuring system with a resolution of <0.05 µm allows the detecting of displacement and tipping movements of the honing gimbal. Fig. 7 depicts the general experimental setup. A single honing tool by KADIA Produktion GmbH & Co. with a diamond grain size of 64 µm is applied for machining cylindrical workpieces made of steel 16MnCr5 (1.7131). Each workpiece has a bore diameter of 7.98 mm. The aimed material removal is set to 10 µm.

In this section, the influence of the system parameter mass or mass distribution on the movement dynamics of the honing gimbal was investigated based on the preliminary investigations in [11, 12, 24]. As shown in Fig. 7 the aluminum target for tipping was used to attach additional masses. Additional masses could be attached to the upper or lower end of the aluminum target. The distances of the additional masses from the axis of rotation remained the same in all tests. An overview of the series of experiments are summarized in Fig. 8 and Table 1.

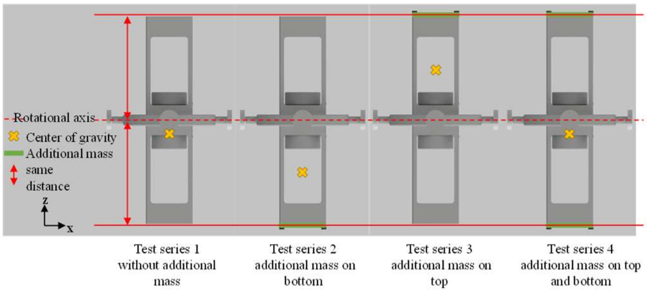

Fig. 8. Test series and different orders of additional masses [24]

Table 1. Order of the test series, the additional masses and the resulting center of gravity positions

	Series. 1	Series. 2	Series. 3	Series. 4
Additional mass [g]	0	140	140	70 + 70
Position of the additional mass, starting from the axis of rotation	-	bottom	top	top + bottom
Center of gravity, starting from the axis of rotation [mm]	-0.29	-11.38	+ 10.85	-0.28

The experiments include four series, whereby the first test series does not include any additional mass and represents a reference compared to the remaining test series. Test series two to four, each received 140 g of additional mass depending on the order. The different order of the additional masses accordingly resulted in a change in the center of gravity of the honing gimbal including the workpiece (see Table 1). Each series of tests was carried out with the same process parameters to ensure identical conditions. The oscillation and rotation speed varied in five parameter levels to represent the gimbal dynamics at different cutting speeds. Per parameter level three workpieces were honed. The process parameters are listed in Table 2.

Table 2. Process parameters

Parameter level	Oscillation speed [mm/s]	Rotation speed [min^{-1}]
PL 1	86	500
PL 2	172	1000
PL 3	258	1500
PL 4	344	2000
PL 5	429	2500

Due to the large amount of data and for reasons of clarity, the signal curve of the third parameter level is depicted. A summary result follows in the next subchapter. For the analysis and illustration of the results, the signals of the eddy current sensors for displacement and tipping of the honing gimbal were considered in particular as a function of the current stroke position. Fig. 9 shows the results of the four test series for the third parameter level (258 mm/s and 1500 min^{-1}).

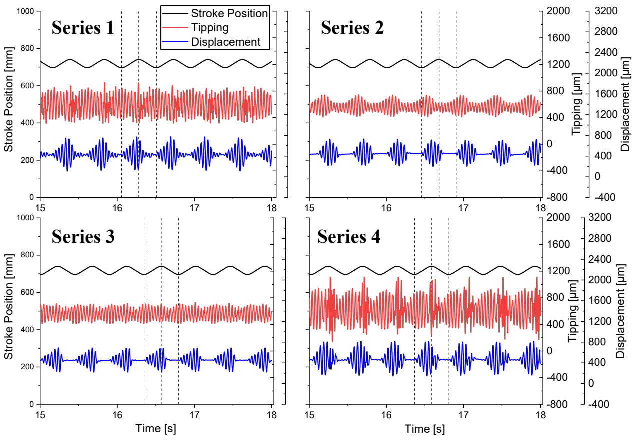

Fig. 9. Results of test series for third parameter level [24]

As an assist, vertical dashed cursors have been inserted at the lower and upper tool reversal points. The basics of this issue are already covered in detail in [22], so the analysis will not go into details. The observation of the test series four shows an increase of the displacement with the highest range of 560 µm. At the same time, the tipping signal reached a value of 800 µm. In summary, for this parameter level, the distribution of the additional mass at the top and bottom was the most unstable.

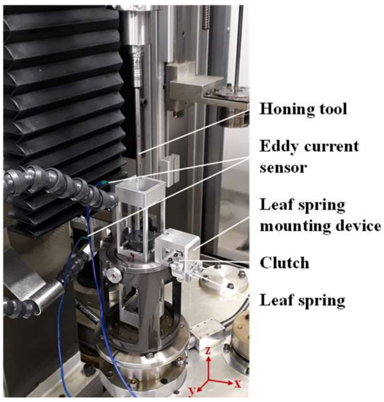

Fig. 10. Experimental setup with attached leaf spring [25]

Based on the preliminary work from [25], the system parameter stiffness was considered next. For this purpose, a mechanical spring was integrated into the basic experimental setup as shown in Fig. 7. The extended experimental setup is shown in Fig. 10.

An aluminum mounting device enables the integration of the leaf spring made of polylactic acid (PLA) and by that the implementation of different stiffnesses. The leaf spring is fixed by screws and coupled with a gimbal joint by a clutch to interfere with the displacement movement during honing. The fifth test series is performed with a stiffness of 50 N/mm and the sixth test series with 500 N/mm. The application of leaf springs results in significant reductions in displacement, compared to conventional honing. The amplitudes of the displacement are considerably reduced because of the offered counterforce [25].

3.2. Summary results

A complete overview of the displacement and tipping ranges of test series one to six is shown in Fig. 11 and Fig. 12. The characteristic curves shown are divided at the abscissa into the parameter levels from Table 2.

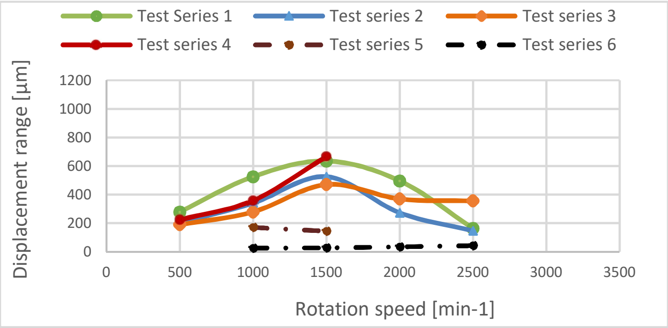

Fig. 11. Characteristic curves for displacement range

The displacement ranges of the second and third test series showed a significant reduction compared to the first test series. This indicates a limitation of the gimbal in its moveability due to the additional mass [24]. However, starting from the fourth parameter level, the dynamics of the third test series increased. The fourth test series became unstable due to the third parameter level. For this reason, the two higher parameter levels were cancelled. In this case, the position of the center of gravity barely changed due to the symmetrical distribution of the additional masses. Nevertheless, the moving additional mass has an unstable influence on the honing gimbal dynamics. The characteristic curves of test series five and six show a significant reduction in the displacement range for both stiffnesses. The stiffness with 500 N/mm is noticeable. Up to the highest parameter level, the displacement range remains at about 35 µm.

For the consideration of the tipping range in Fig. 12 with regard to the second and third test series, the same evaluation above applies, whereby an additional mass applied upper the gimbal axis achieved a tipping range of 1200 µm at the fourth parameter level. This result is very unstable for the honing process and also for the tool. For the fourth series of tests, the instability starts earlier, although the center of gravity remained the same. The stiffener also shows a significant reduction of the dynamics during the tipping.

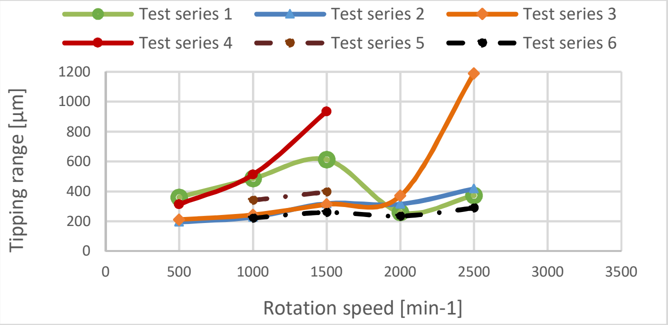

Fig. 12. Characteristic curves for tipping range

4. Extension of the experiments with damping

4.1. Constructive design and application of dampers

Finally, the system parameter damping in the honing process is considered. In chapter 3, the different orders of the additional masses led in some cases to instabilities in the process. One way of capturing this instability is the use of dampers. The fourth test series with additional masses at the top and bottom actually simulates a component with a larger mass or mass moment of inertia.

In this section, two additional test series will be shown (see Table 3). A higher parameter level is added to the two test series. This is to test the process limits.

Table 3. Extension of the test series with dampers

	Series 7	Series 8
Setup	Additional mass on top and bottom and damper	Without additional mass and damper
Parameter level	PL1 to PL5	PL1 to PL5
Additional Parameter Level	Oscillation speed 516 mm/s, Rotation speed 3000 min^{-1}	Oscillation speed 516 mm/s, Rotation speed 3000 min^{-1}

Since the honing gimbal has four degrees of freedom, a damper is used for each direction of movement. In Fig. 13 the construction of the dampers is shown. The dampers from the company ACE Stoßdämpfer GmbH have an external thread so that they can be mounted on a holder. These holders were then attached to the lower part of the outer fixture. Thus, every 90° there is a damper that can absorb the kinetic energy of 0.68 Nm/stroke from the lower aluminum target.

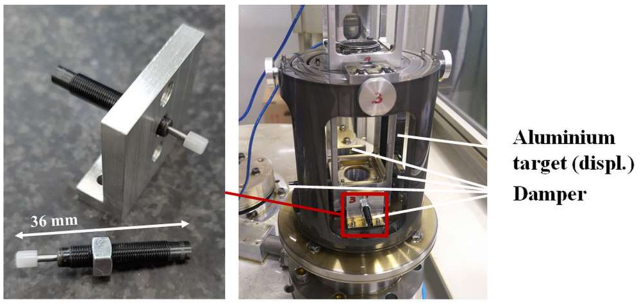

Fig. 13. Constructive design and application of four dampers (right), enlarged view of the damper mounting and the damper (left)

4.2. Results

The results for test series seven and eight are shown in Fig. 14 and Fig. 15. Overall, the dampers show their effect and change the displacement range. At parameter level five, the peak increases due to the additional masses. The increase to parameter level six shows no instabilities for either test series.

For the tipping range, the increase can be seen starting from the fourth parameter level. In particular, the seventh test series shows a tendency of instability in the tipping with increasing parameter level.

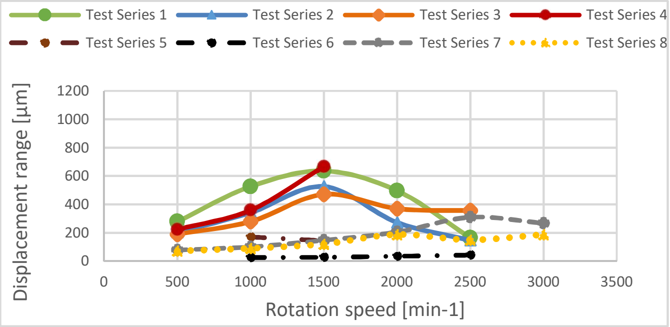

Fig. 14. Extension of the characteristic curve for displacement by dampers

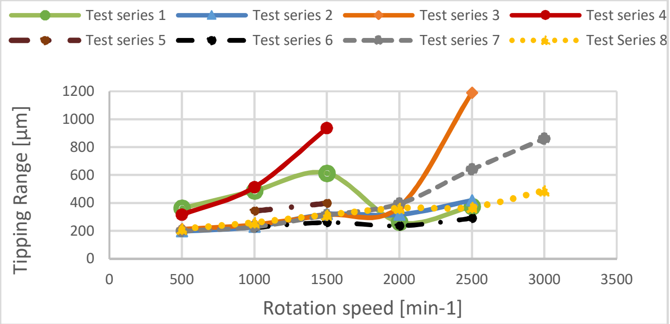

Fig. 15. Extension of the characteristic curve for tipping by dampers

5. Conclusion and outlook

Based on Fig. 6, the detailed experiments were able to show the influence of the system parameters on the honing gimbal dynamics. A shift of the mass above the rotational axis definitely leads to instabilities, since the center of gravity is also shifted upwards.

Stiffening the degrees of freedom in translational direction reduces the movement of the honing gimbal. In particular, it was possible to reduce the amplitude. The investigations have shown that by using of dampers, the process limits can be shifted to higher parameter levels. A comparison of the component qualities showed that in the seventh series of tests, the components acquired a conical shape. This may be due to the strong tipping caused by the additional masses. The honing gimbal dynamics are strongly influenced by mass and center of gravity.

Overall, in this work it was possible to establish detailed characteristics for precision honing under the influence of mass, stiffness and damping. In addition, the process behavior for different variation of the gimbal have been identified within the framework of several test series. The main focus so far has been on the kinematic and dynamic properties of the tool-fixture system. Further investigations regarding the component quality are to be conducted in the near future. Preliminary experiments have shown an expected increase in both geometrical deviations and surface roughness using the process parameters defined as critical. These findings need to be verified in more thorough examinations. Further work should focus more on actively influencing the honing gimbal movement.

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