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Characterization of an eigenfrequency adaptable machine tool carriage

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Abstract

Current machine tools feature fixed eigenfrequencies which are often excited by high performance cutting operations leading to unfavorable process conditions or poor workpiece quality, for example, due to chatter. Approaches to resolve this problem either constitute in changes of the process conditions, adaptable auxiliary mass dampers or vast and expensive changes within the machine tool structure. All of these approaches are either expensive, lead to a lower cutting ability or do not address the underlying problem.
A novel approach to avoid chatter is described in this paper. It deals with a frequency adaptable machine tool carriage made out of hollow carbon fiber reinforced plastic (CFRP) profiles. This light structure enables chambers to be filled separately. This allows a tuning of the eigenfrequencies by pumping fluid into the chambers of the carriage reducing the eigenfrequencies. The CFRP structure has a high "added mass to component mass" ratio due to the high stiffness in relation to the density of the CFRP. Thus shifting the eigenfrequencies on a larger scale in comparison to the carriages of the same kind but made out of steel or cast iron.
Within this paper, the approach as well as measurement results of the prototypical realization will be presented. The paper will address measurements of sloshing, the influence of added fluid mass regarding different filling levels and the influence of the control behavior of the feed axis. The paper shall conclude with a comparison of the measurements to a similar machine tool carriage made out of steel. In the end, an outlook on upcoming research topics and activities shall be given.

Keywords: Machine tool; component; shift; adaptable; eigenfrequency; natural frequency; modal analysis; dynamic; carbon; fiber; reinforced; plastic

1. Introduction

Vibrations in machining operations are one of the main limiting factors for an increase in productivity. There are three general types of vibration: free, forced and self-excited, whereas self-excited are also referred to as chatter. According to [1,2], chatter vibrations lead to a poor surface quality, an unacceptable inaccuracy, a disproportionate tool wear, a reduced material removal rate and an increase in production time (and so forth). Until now, chatter is not completely understood. In contrast, free and forced vibrations can be prevented easily [1].

[2] spells out two general approaches for avoiding chatter vibrations. The first approach aims at searching for cutting parameter combinations which allow for stable conditions during machining. An analytical differentiation between instable and stable machining may be performed with stability lobe diagrams which are subject to numerous examinations [3-5]. In flexible manufacturing systems, where the producer orders a whole production system, the system and machine center supplier creates numerical computer (NC)-codes based on stability lobe diagrams. So the NC-code is fitted to the dynamic behavior of the machine tool.

The second approach rests upon a change of the system's behavior. Here, it is referred to the system comprising of cutting tool, tool holder, workpiece material and machine tool structure [2]. In mass production systems, the producer has several plants spread all over the world. For an increase of annual output even more machining centers will be implemented, at which cutting tool, tool holder, workpiece material and NC-code remain unchanged. Consequently, the

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dynamic behavior of the machine tool needs to be adjusted to the NC-code.

Within this paper a new approach for a variable adjustment of machine tools' dynamic behavior is presented.

Nomenclature

$E_{\parallel}$	Young's modulus parallel to fiber direction
$E_{\perp}$	Young's modulus perpendicular to fiber direction
f	frequency
f_n	n^{th} eigenfrequency
$G_{\perp\parallel}$	Shear modulus
$G_{\perp\perp}$	Shear modulus
m_0	basic mass of component
Δm_{fluid}	amount of added fluid mass
N	Flexibility
t	time
x	position

2. State of the art

Chatter vibrations that can be avoided by modifying the machine tool structure, shall be subdivided according to [2] into passive and active strategies.

Passive strategies include the use of friction dampers, mass dampers or the redesign of the machine tool structure. Friction dampers are connected in parallel to the machine frame or they can be placed between the two contact surfaces, so that the vibration energy is dissipated by friction. Auxiliary mass dampers are modifying the eigenfrequency of the structure and are frequently used for tables, travelling columns and spindles [6]. The layout of such systems close to the cutting tool can also reduce vibrations to a great extend [7,8]. In case of a redesign of the machine tool, the weakest component (in that study: the spindle) should be replaced first, according to [9]. But redesigning is severely time-consuming and costly.

For actively avoiding chatter, the dynamic state of the machine is measured, evaluated and controlled in a stable range [2]. A widely known approach for eliminating the regenerative effect when chattering is the spindle speed variation [10-12]. The input shaping method is an integrated strategy using one control law for all feed drives simultaneously and an estimation of contour errors from the closed loop transfer function of the drive. It distorts the toolpath avoiding the harmonic excitation of eigenfrequencies and pre-compensates the arising contour error [13,14]. In case of the so-called double sided milling, the vibrations of two milling spindles are superimposed with the effect of avoiding the chatter [15]. [16] compares tuned mass dampers (TMD) showing non-linear behavior with conventional linear TMDs. In that case, the real part of the frequency response function is suppressed and in doing so, the stability is increased. The use of magnetorheological fluids is investigated by [17,18] in order to achieve adjusted stiffness as well as improved damping.

In this paper a new approach is presented. It is about the active shifting of eigenfrequencies by adding variable fluid mass to the machine tool structure.

3. Approach

A machine tool carriage could be established, whose supporting structure is made of CFRP. This CFRP lightweight construction features a chamber design, where the single chambers can be independently filled by a pump with a fluid, for example, water. Ideally, the CFRP contains high modulus carbon fibers and has a high fiber volume fraction. An example for this approach is shown in figure 1.

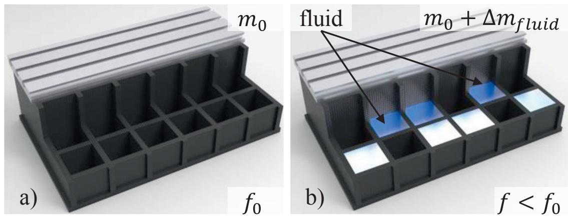

Fig. 1. Approach for shifting eigenfrequencies: (a) chamber design with unfilled carriage; (b) partially filled

The filling with fluid serves as a mass-increase of the machine tool structure in order to shift its eigenfrequencies in a wide range. Adding fluid mass is resulting in lowered eigenfrequencies.

If all chambers of the CFRP-carriage are fully filled, the carriage advantageously should have a lesser overall mass than a filled conventional carriage made of steel or cast iron. Under this condition, the dynamic of the moved components is not negatively influenced.

For similar drive power, this innovative approach is enabling increased cutting capacity, because chatter does not need to be reduced by an adjustment of cutting parameters. These critical vibrations are overcome by shifting the eigenfrequency of the instable machine tool structure by variable fluid filling. The active shift of eigenfrequencies generates new stability lobe diagrams for each filled chamber. In sum stability pockets shall be shifted to match with pre-defined NC-codes (cutting parameter combinations).

4. Results

4.1. Fundamental verification of the approach

Verification of shifting eigenfrequencies by modal analysis

For the verification of the approach, a simplified machine tool carriage has been built. The realization is shown in figure 2.

It has a chamber design and allows the conduct of experiments on the effect of shifting eigenfrequencies by adding fluids. The carriage consists of hollow rectangular CFRP profiles (1) which are glued together. It is connected to guide rails (2) and corresponding guide carriages. The linear motion is carried out by a ball screw (3) and an AC motor with motor break (4). A machine bed (7) made out of steel carries the whole arrangement. With this setting, a realistic reproduction of a machine tool was achieved.

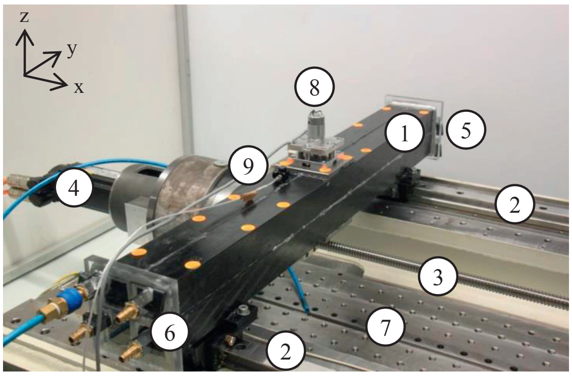

Fig. 2. Prototypic realization of the simplified CFRP-carriage

For the determination of system eigenfrequencies, the ball screw was clamped by the break of the AC motor.

To verify the approach of shifting eigenfrequencies, water was filled into the hollow CFRP profiles (5) and in doing so, the mass of the system was increased. In the unfilled state, the carriage has an overall mass of 10.5 kg. Each profile can house about 1.8 kg. All in all, the mass of the carriage can be increased up to 7.2 kg which equals about +70%.

The eigenfrequencies were measured by experimental modal analysis. For each measurement, each chamber was filled consecutively and completely. An impulse hammer was used for excitation and eigenfrequencies and eigenmodes were determined by harmonic frequency response.

In figure 3, the results of modal analysis measurements in x-direction are shown. For better clarity, the three spatial frequency response functions (FRF) were summed up. The carriage position is close to the AC motor (fig. 2 – 4) at x = 30 mm.

At maximum fill level, the first eigenfrequency can be shifted around 22 Hz (-21%), the second around 30 Hz (-13%) and the third around 64 Hz (-16%). In other spatial directions, the evaluation of frequency responses shows similar results. These measurements confirm the expectation of this approach and the dependence of adding fluid mass and lowering eigenfrequencies is approved.

The summed FRF is showing a high flexibility, which can be explained with the domination of x-direction for the first two eigenmodes (see fig. 5, eigenmode of ball screw) and the high elongation of the sheared glue joining the CFRP profiles.

Quantification of amplitude reduction

The amplitude reduction which is achieved by active eigenfrequency shifting should be quantified. For showing this, a DC motor with an unbalanced mass attached to it was mounted on the carriage. Together, the unbalance and the rotating motor represent the oscillating cutting force during milling. A converter is used for the adjustment of a defined excitation frequency. For the measurement, the unbalanced excitation (8) was started and tuned in resonance frequency, fluid was filled into a chamber (via 5) and the vibrations were measured continuously by an accelerometer (9).

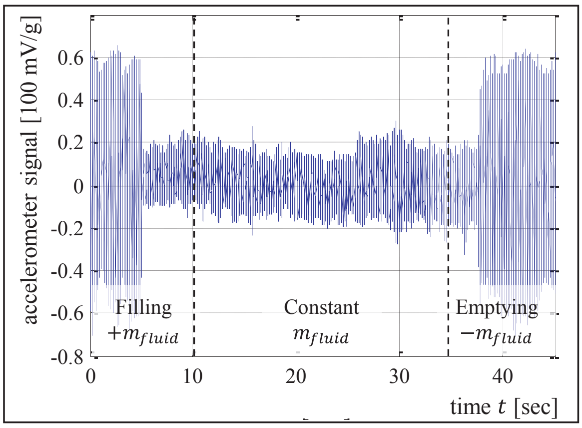

Fig. 4. Amplitude reduction by filling one chamber

Figure 4 shows that a considerable amplitude reduction is occurring after about 5 seconds of measurement. The amplitude was reduced by up to 70 %. At that particular time, only 0.9 kg of water was filled. Filling more water did not reduce the amplitude significantly.

Together, the measurements for frequency shift and amplitude reduction prove the basic verification of this new approach. The fluid fill of machine tool components is representing a new, promising approach for the active treatment of vibration problems, if the components have a chamber design. In order to assure a practical set-up, the following chapter discusses the capability for dynamic property calculations by using finite element simulation.

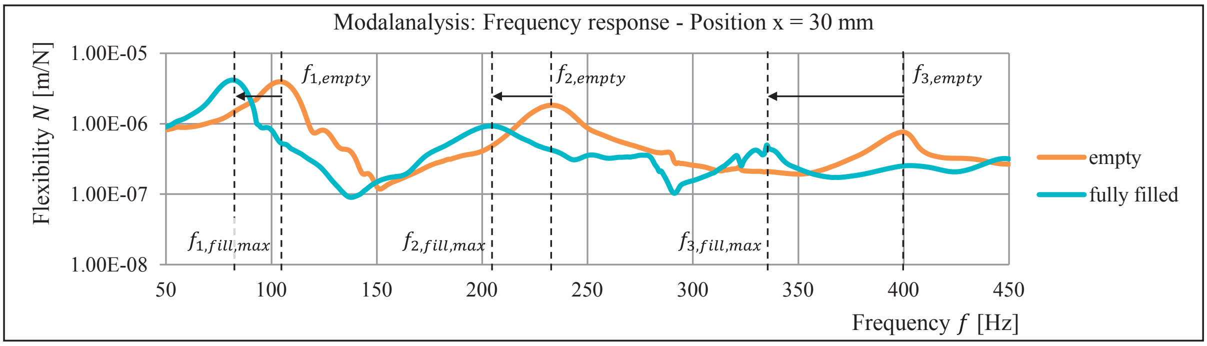

Fig. 3. Experimental modal analysis: Comparison between unfilled and fully filled state

4.2. Finite Element Simulation

The constructed carriage consists of four square pipes made of CFRP (HT-fibers, epoxy resin, fiber volume fraction 65%), two standard guide rails and one ball screw. The pull wound CFRP pipes are glued together (adhesive: methacrylate) and form a cross beam with open endings. These endings are closed with glued acrylic glass plates and realize an easy control of the filling quantity. The ball screw nut is mounted on an aluminum block, which is fixed to the carriage via an adapter plate made of steel.

All material properties are given in table 1. The composite properties for CFRP are estimated with the rule of mixtures (Young's modulus) [19,20] and the data sheet of the supplier (fiber orientations, density) [21].

Table 1. Material properties for finite element simulation

Material	Young's modulus [GPa]	Density [g/cm³]	Poisson's ratio	Shear modulus [GPa]
CFRP (HT fibers, epoxy resin, fiber volume fraction 65%)	$E_{\parallel} = 145.2$ $E_{\perp} = 9.82$	1.54	0.28	$G_{\perp\parallel} = 4.39$ $G_{\perp\perp} = 3.58$
Aluminum	70	2.7	0.34	Isotropic
Steel	210	7.85	0.3	Isotropic
Acrylic glass [22]	3.3	1.19	0.37	Isotropic
Adhesive [23]	1	0.98	0.4	Isotropic

The guide rails are modeled with springs pointing in y- and z-direction which represent the overall stiffness between guide rails and guiding carriages. Therefore, these guiding carriages are simulated as rigid bodies with a homogenous density distribution equaling the total mass (1.6 kg measured). The spring rate was measured too, and evenly distributed over the surface contact. In total, the spring rate in both directions is 380 N/µm. With this modeling technique also torsional stiffness can be allocated. The ball screw is also modeled with springs. The spring rates depend on the position in x-direction and are calculated with formulas from [24,25]. In position x = 30 mm, the spindle stiffness of the ball screw is supposed to be 90.35 N/µm and the bending stiffness around y-axis and z-axis is 444.43 N/mm. In addition, inertia influences are considered by implementing 1/3 of the ball screw total mass. It is coupled to the aluminum adapter block with a mass point (1.195 kg).

All screw joints are modeled with tie-contacts and a small circular surface contact around the screw axis. The radius of the circle corresponds to the compressive stress of the screw.

The filling and emptying of the chambers is carried out by valves and tubes which are connected to the acrylic glass plate. Each valve is represented by a mass point with a mass of 60 g. The mass of the tubes is neglected.

Modeling of the fluid filling

Modeling the fluid filling is based on the assumption that the added fluid is just influencing the inertia characteristics. Changes in dynamic behavior are considered to depend on the added mass and accordingly, the stiffness is not supposed to change.

Under this presumption, three simplified approaches could be identified which meet these criteria. The total additional mass of a water filled chamber is 1.77 kg and can be modeled in Abaqus/CAE with "surface elements", "nonstructural-mass" and "acoustic medium". "Surface elements" need to be distributed equally over the inner surface of the hollow CFRP profile. In contrast, the "nonstructural-mass" distributes the additional mass proportional to the volume. The third approach with the "acoustic medium" is using an extra three dimensional part with acoustic elements. For this approach, the following properties have been assigned: density 1.0 g/cm³, compressive modulus 2.0 GPa [26].

Validation of simulation and measurements

For the evaluation of eigenfrequency simulation, the first three eigenfrequencies will be considered. The validation of the FE model is carried out along the presented measurement results.

Figure 5 is showing the first three eigenmodes of both, virtual simulation and real measurement.

In comparison, all three modes have been exactly confirmed, indicating a realistic FE model replication and the choice of sufficient boundary conditions.

Beside the evaluation of eigenmodes, an eigenfrequency investigation is important. Table 2 summarizes the deviations between simulation and measurement.

Table 2 is showing that the unfilled FE model gives a good approximation with a relative deviation between -3.8 and +24.8%. For modeling the fluid filling, the results of the nonstructural-mass approach are also shown in table 2.

Although this modeling technique tends to lower the eigenfrequencies a bit more than in reality, these simulations show adequate results with deviations from -7.8 to 22.6%. As the other approaches show quite similar results, they are not given here.

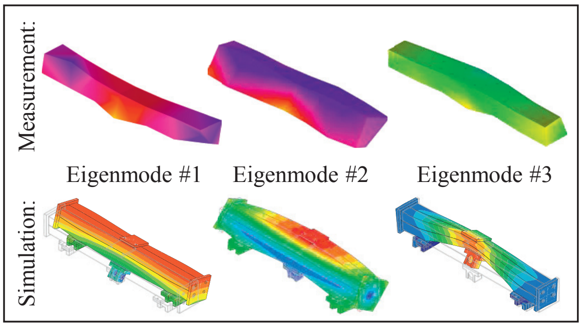

Fig. 5. Eigenmodes 1, 2 and 3 (from left to right): Comparison between measurement and simulation

Table 2. Evaluation of eigenfrequency analysis: Simulation and measurement

	Eigenfrequency of mode #1 [Hz]				
Number of filled chambers	Empty	One	Two	Three	Four
Measurement	104	96	89	87	82
Simulation with “Nonstructural-mass”	123	110	100	96	93
Deviation [%]	+18.3	+14.6	+12.3	+10.3	+13.4

	Eigenfrequency of mode #2 [Hz]				
Number of filled chambers	Empty	One	Two	Three	Four
Measurement	234	221	213	210	204
Simulation with “Nonstructural-mass”	292	271	259	253	248
Deviation [%]	+24.8	+22.6	+21.6	+20.5	+21.6

	Eigenfrequency of mode #3 [Hz]				
Number of filled chambers	Empty	One	Two	Three	Four
Measurement	399	371	358	343	335
Simulation with “Nonstructural-mass”	384	356	342	321	309
Deviation [%]	-3.8	-4.0	-4.5	-6.4	-7.8

4.3. Comparison to a steel carriage

In the previous chapter, the validity of the FE model could be shown by confronting the measurements and the simulation of the CFRP carriage. Now, a comparison with other materials is interesting because materials with a higher Young’s modulus offer the possibility to reduce wall thickness which leads to a higher amount of filled fluid. If more fluid and therefore more mass can be added to a chamber, this topic is influencing the shift of eigenfrequency and needs to be considered.

As already mentioned in the introduction, casted iron and steel are the common construction materials in machine tools. For this comparison, steel was chosen because of its higher Young’s modulus.

To reassure the comparability of the CFRP carriage and the steel carriage, the static stiffness was simulated by applying a force of 100 N at the top center in negative z-direction (see fig. 2.). While the thickness of the CFRP pipes was fixed to 2.85 mm, the steel pipe thickness was adjusted with iterative simulation turns. Almost the same stiffness was reached with a wall thickness of 0.75mm steel. Using this value each steel chamber can be filled with 2.12 kg of water. In total, this is 1.4 kg additional water than in the CFRP version.

In the next step, an eigenfrequency simulation of the steel carriage with completely filled chambers was carried out. In figure 6, the shift of eigenfrequencies for the first three eigenmodes is depicted.

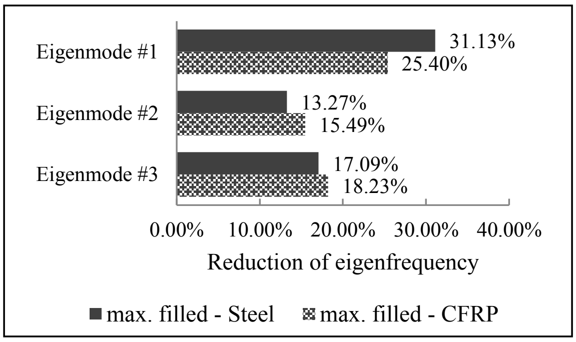

Fig. 6. Influence of carriage material on shifting of eigenfrequencies

Figure 6 shows that both, the steel carriage and the CFRP carriage, have an almost equal relative shift of eigenfrequencies. This proves the great advantage of the CFRP carriage, as the eigenfrequency level is higher and so, a subcritical operation of the machine tools is possible. In addition, the total weight of the maximum filled CFRP carriage is about 12% lower (CFRP: 19.58 kg; steel: 21.98 kg). Further weight savings can be reached by using carbon fibers with high modulus.

4.4. Sloshing

For determining the influence of sloshing, the carriage’s oscillation at an abrupt stop was measured with empty and partially filled chambers. If sloshing occurs, an increased oscillation due to the partially filled chambers would be expected. This oscillation was expected to present a difference in phase and amplitude to the one measured with empty chambers. After acceleration, an emergency stop was performed and the oscillation on top of the carriage was measured. No difference in oscillation between partially filled and empty could be detected. Therefore, it can be stated that no effects due to sloshing were determined. In the future, further tests will be performed regarding a mechanical amplification of the oscillation.

4.5. Control

Since a variation in the carriage’s mass would lead to a different system behavior, this needs further consideration. Therefore, the system was modeled as well as measured. It showed that an increase in mass of 70 % according to the carriage’s unladen mass does not lead to a different system behavior. The step responses of the carriage showed no difference in the empty and filled state. This can be explained with the transmission of the linear inertia into a rotational inertia. Since the step response of the carriage featured no significant differences, it can be stated that an additional load of 70 % does not significantly change the system behavior and thus, no change in the control parameters is necessary.

5. Conclusion and Outlook

In production systems with many chained machine tools, the machining processes are often predefined by the customer. Many times, the adjustment of single processes is unwelcome due to reasons of cycle times and profitability, resulting in chatter. These critical cutting parameters need an easy capability of adapation for eigenfrequency in order to assure sufficient workpiece quality and a good running process chain.

An innovative approach to enable users and manufacturers to increase flexibility and quality of the products is the filling of machine tool components with fluids.

The feasibility and the potential of this approach could be shown in first experiments. In modal analysis, an eigenfrequency reduction up to 21% for certain eigenmodes was shown. These measurements were confirmed by a coupled fluid and structural dynamic finite element simulation. The deviations between experiment and simulation are around -7.8 to +24.6% and maybe tuned more exactly, if damping is considered. In further investigations, the advantages of CFRP in comparison to steel were shown.

First tests showed no influence of partially filled chambers on sloshing. This can also be avoided by filling each chamber completely.

Investigations of the system behavior showed no significant difference between an unfilled, partially filled and a filled state. This can be explained by the transmission of the linear inertia to a rotational inertia.

Upcoming research topics will concern an improved CFRP chamber design and the simulation of frequency responses under consideration of damping. In addition, the vibrational behavior of the carriage inside the whole machine tool could be analyzed.

For the fluid filling, a best practice strategy should be developed which is depending on machine structure, workpiece and cutting parameters. First, a steady state control with constant adding of mass is going to be researched. In later work, an online control dealing with non-stationary process and vibration conditions should be identified. In this context the change of eigenfrequency caused by material removal [27] or different machine component positions [28] might be compensated.

All in all, if this approach is made available for work in machine tools, vibration problems do not slow down the process, since the NC program does not need any change. With this technology, eigenfrequencies of the system can be shifted actively and so, the high dynamic during machining remains preserved.

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