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Paper:

Dynamic Interaction Between Precision Machine Tools and Their Foundations

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The manufacturing accuracy of modern machine tools strongly depends on the placement of the machine tool structure on the factory's foundation. Civil engineering knows a variety of foundation types and factory planners must carefully consider local circumstances such as the size and the properties of the regional subsoil as well as the individual requirements of machine tools. Two of the major reasons for the effect of the foundation onto the machining accuracy are the added stiffness and the increased mass from the installation site's foundation. A change of these characteristics greatly affects the dynamic characteristics of the overall machine tool and therefore also the machining dynamics. Although some general rules and guidelines exist for the design of foundations, their dynamic interaction with the supported precision machine tool structures is not well understood yet. This paper presents a series of measurements on two different types of machine tool foundations and highlights the characteristic differences in their dynamic interaction. It also proposes a novel approach to validate the conclusions with the use of foundation and machine tool scale models. These results can serve factory planners of precision targeting shop floors as a valuable guide for deciding on a suitable foundation for lowering the individual machine tool vibrations and/or reducing the dynamic interaction between closely located machine tools.

Keywords: dynamic interaction, machine tool foundation, scale model, operational deflection, machine tool dynamics

1. Introduction

Machine tools show the characteristics of rotating machinery and exhibit vibrations due to dynamic forces, e.g., from the cutting process, axes acceleration, or jerk [1]. Without proper damping, these vibrations can interfere with the cutting zone which leads to relative displacements between the tool center point (TCP) and the workpiece. This in turn can result in a decreased machining accuracy and surface quality [2].

Modern machine tool design aims at lightweight and resource-efficient solutions for new machine tools [3]. The demand for higher cutting feed and cutting speeds however leads to higher energetic excitations in these machine tools. Hence, nowadays vibration excitations can cause even more severe problems as the lightweight design with its high stiffness and low mass only yields a low inherent damping capability. As a result, the comparatively more compliant machine tool structures consider their underlying foundation as an integral part of their mechanical structure and rely on the added stiffness and mass properties [4].

The phenomenon of an insufficiently stiff support is called a soft foot which often leads to misalignments and bending in rotating parts of the machine tool [5]. It is clear that the foundation is an important contributor to the overall machine tool performance and precision and that it needs careful consideration as a whole during the acquisition of new machines or the planning of new factories [6].

A variety of four different foundation types are known to civil engineering and classified as follows [7].

- Block-type foundations: solid blocks of concrete support the machinery.
- Box-type foundations: hollow blocks of concrete support the machinery.
- Wall-type foundations: walls carry the machinery.
- Framed-type foundations: columns carry a framework which supports the machinery.

Figure 1 depicts these four types of machine tool foundations. The most commonly utilized foundation type for machine tools is the block-type foundation, which is suitable for rotating machinery with periodic forces and comparatively low induction of vibrational energy [7].

It is possible to further damp the transmission of vibrational energy with dedicated isolations. These isolations consist of gaps, also referred to as expanding joints, filled with springs of steel, rubber, or air bellows. They decrease the transmissibility of vibrational energy within the foundation [8].

A number of research aim at decreasing the transmissibility of vibrational energy between neighboring machine tools with active vibration isolations [9–11], to

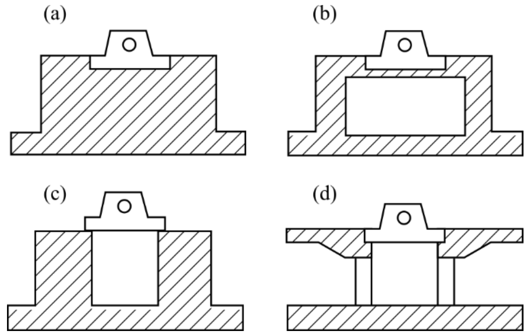

Fig. 1. Different types of machine foundations: block-type (a), box type (b), wall type (c), and framed type (d).

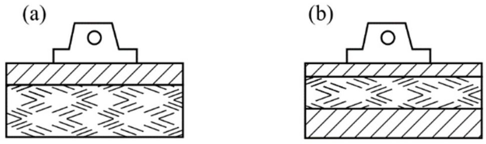

Fig. 2. Two different floor-type foundations: regular floor-type (a) and sacrifice floor-type (b).

name just a few. Usually, dedicated foundations are only slightly larger than the supported machine tools and tailored to their specific use-case. One example is the foundation for a high precision coordinate measurement machine (CMM), whose precise operation requires an extraordinary isolation of externally induced vibrational energy so that the targeted maximum acceleration of the structure does not exceed the range of several μg [12].

It is clear that, regardless of the presence of an isolation, dedicated machine tool foundations always hinder the rearrangement of machine tools and production lines within the shop floor [8]. This is one reason why modern volatile factory designs typically implement the less expensive alternative of using a common floor to support their machine tools.

Common factory floors divide into regular floors and so-called sacrifice floors (see **Fig. 2**). In contrast to a regular concrete floor, sacrifice floors have a layer of gravel between two concrete slabs. Therefore, the replacement of a top concrete slab is less complex and less financially expensive. Frequent reasons for the replacement of existing foundations are surface wear or the need to drill new holes for the anchorage of new machine tools or arrangements.

Although the modeling and simulation of machine tool foundations have been a vivid research topic already since the 1950s, a lack of experimental investigations of the different floor-type foundation characteristics is evident from the research [7, 13]. Many questions of the vibrational energy transmission from the foundation to the TCP remain unanswered.

This research paper presents the results of a comparative experimental study of two machine tools of the same type on an isolated block-type and regular floor-type foundation with focus on the TCP dynamics during operation. Results from a sacrifice floor-type foundation are included for references but do not use the same machine tool type or operation.

2. Theory

2.1. Foundation Mechanics

Foundations are usually modeled as rigid structures on elastic supports. Therefore, their dynamic behavior is governed by the basic equation of motion (see Eq. (1)).

$$m\ddot{x} + c\dot{x} + kx = F \quad (1)$$

The elasticity parameter k and damping parameter c result from the underlying subsoil, usually gravel. Eq. (2) gives the well-known fundamental frequency ratio of an undamped single-degree-of-freedom system with $c = 0$. Eq. (3) follows for the damped case with the damping ratio $\zeta = c/m \cdot 2\omega_0$.

$$\omega_0 = \sqrt{\frac{k}{m}} \quad (2)$$

$$\omega_d = \omega_0\sqrt{1-\zeta^2} \quad (3)$$

In this simplified understanding, the foundation stiffness equals the subsoil stiffness [14]. Various substitution methods exist to derive equivalent spring and damper parameters for the elastic subsoil. Interested readers are referred to the systematic review of Tian et al. [15] and the comprehensive handbook of Bhatia [13].

The reduced thickness h of floor-type foundations leads to a more plate-like dynamic behavior. Hence, in contrast to the block-type foundation, the stiffness of the floor is added to the subsoil stiffness. Especially out-of-plane or vertical vibrations are important for machine tool foundations [16, 17].

The fundamental frequency of a plate depends on its stiffness and mass term. Ritz [18] gives the solutions for a free and undamped square plate with an edge length a (see Eq. (4)). The mode factor λ is known for various modes and can be found in the original source [18].

$$\omega = \frac{\lambda}{a^2} \cdot 2\pi \cdot \sqrt{\frac{D}{\rho h}} \quad (4)$$

Hereby, $D = (Eh^3)/12(1-\upsilon^2)$ is the flexural rigidity of the plate with the Young's modulus E, Poisson ratio υ, density ρ, and thickness h [19]. From Eq. (4), the fundamental frequency of a floor type foundation increases approximately with its floor thickness h and decreases with its edge length by $1/a^2$. Deriving from this simplified theory, the following statements are condensed.

- Higher stiffness of the floor-type foundation and/or its subsoil leads to an increase in the fundamental frequency.

- Higher mass of the foundation and/or machine leads to a decrease of the fundamental frequency.
- Damping has only a small influence on the foundation's fundamental frequency.
- The stiffness of a square floor-type foundation increases cubically with its floor thickness h.
- The fundamental frequency of a quadratic floor-type foundation increases linearly with its floor thickness h and decreases inverse quadratically with its edge length $1/a^2$.

2.2. Modal Analysis

Modal analyses examine the dynamic behavior of structures [20]. One goal is the extraction of modal parameters of models, e.g., as established in Eq. (1) [21]. The overall procedure subdivides into the experimental modal analysis (EMA) and operational modal analysis (OMA).

The EMA uses instruments to generate excitations and measure the input frequency spectrum $F_a(\omega)$. Sensors then measure the corresponding response or output $A_b(\omega)$. The ratio of both is called the transfer functions (TF) $H_{ab}(\omega) = A_b(\omega)/F_a(\omega)$ [22]. However, the process is more complicated with real measurements and modern analyzers commonly use the cross- and auto-spectra $H_{ab}(\omega)$ and $H_{aa}(\omega)$ to only estimate the real TFs [23].

In contrast, OMAs do not measure the input excitation but only the system's response that is transmitted through the structure to the sensor location [24]. The signal is attenuated on the structural path and partly amplified by the local structural resonances. Hence, the results represent the actual operating response of the system [25].

3. Experimental Investigations

3.1. Instrumentation

The most used sensor for vibrational analysis is the accelerometer. It senses surface vibrations with an internal seismic mass clamped onto a pressure sensitive piezoelectric cell [26]. Impact hammers are used for the excitations of the structure. The excitation signal aims at approximating a theoretically infinitely short Dirac impulse, as this translates into a uniform input force spectrum [22]. In practice however, this impulse is non-ideal and consists of a compression and relaxation phase of the hammer tip. Hence, the input spectrum continuously falls towards higher input frequencies and limits the usable bandwidth of the measurement.

The frequencies of the interaction of foundation and machine tools are typically very low. To accommodate for that, soft hammer tips allow for the excitation of the lower frequency bandwidth. This leads to a higher signal-to-noise ratio at lower frequencies and an improved coherence of the respective TFs.

Table 1. Utilized measurement equipment hardware.

Item	Manufacturer	Model
Accelerometer	Bruël & Kjær	8318
Impact hammer	PCB	210B50
Charge amplifier	Bruël & Kjær	2635
Data acquisition	Siemens PLM	LMS

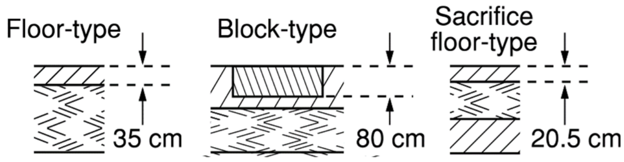

Fig. 3. Section cut through the three different types of investigated foundations.

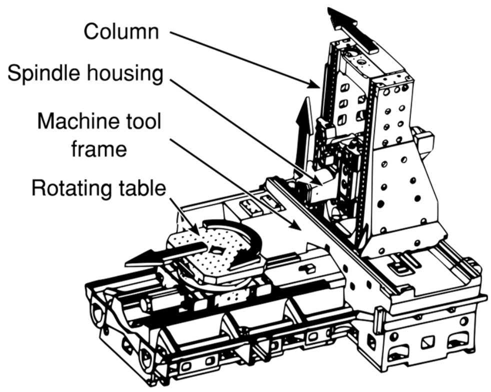

Fig. 4. Design of the analyzed machine tool.

Table 1 lists the measurement hardware. Post-processing of the results is done in the LMS Test.Lab REV10B software suite by company Siemens PLM Software, Plano, Texas, United States of America. The selected measurement sample rate is 12,800 kHz.

3.2. Measurements

To reveal the differences between floor-type and block-type foundations and how they interact with the supported precision machine tool, the experiments are performed at different factories and locations [27]. These locations implement a regular isolated block-type foundation with thickness $h = 80$ cm, a regular floor with thickness $h = 35$ cm, and a sacrifice floor-type foundation with thickness $h = 20.5$ cm (see **Fig. 3**).

In the experiments, the regular floor and isolated block-type foundations support the same machine tool type. It is a four-axes milling machine tool with horizontal spindle (see **Fig. 4**). The machine consists of the following components.

- Machine tool frame: core structure of the machine tool locating all components and auxiliary units. The

Table 2. Performed EMAs and OMAs with excitation sources.

Experiment	Excitation sources	Type	
		EMA	*OMA*
Transfer from an operational machine tool to the foundation	External operations and hammer	×	×
Transfer from a stationary machine tool to an operating machine tool	External operations and hammer	×	×
Transfer from the foundation to a stationary machine tool's frame	External operations and hammer	×	–
Transfer from the foundation to the spindle housing	External operations	–	×
Transfer of hydraulic pump vibration to the spindle	External operations and auxiliaries	–	×
Vibration transmission in the foundation	External operations	×	×

machine tool frame is anchored to the machine tool foundation.

- Column: two pillars that move horizontally. The column is running on guideways that are attached to the machine tool frame.
- Spindle housing: locates the main drive of the milling machine tool, i.e., the spindle. It is attached to the column and moves vertically.
- Rotating table: supports the workpiece. The table rotates and moves horizontally.

The analyzed machine tools are anchored onto the foundation with BW Fixatoren series RK 3-GA.b anchors of the company Fixatorenbau Bertuch & Co. GmbH, Leverkusen, Germany. The sacrifice floor measurements do not include a machine tool and are listed for comparative reference.

Several points of interest are defined, and each measurement is repeated five times, partially during regular shop floor operations. The TF measurements are accompanied by measurements of the externally induced vibrations. Various TFs are recorded with an impact hammer including the transfer from an operational machine tool to a stationary machine tool, the effects of the foundation vibrations on the machine tool spindle, and vibrational transfer within the open floor. **Table 2** gives a summary of the performed measurements.

In the present case, it is not possible to shut down the factory operation during the measurements. Hence, a certain amount of background noise is present in the TF measurements. This noise couples into the output signal $A_b(\omega)$. In this scenario, it is beneficial to utilize the so-called H_1 estimator to minimize the TF estimation error. The H_1 estimator calculates the TF by dividing the signals cross-spectrum by the inputs auto-spectrum (see Eq. (5)).

$$H_1 = \frac{H_{ab}(\omega)}{H_{aa}(\omega)} \quad \quad (5)$$

3.2.1. Transfer from an Operating Machine Tool to the Foundation

The operating machine tool measurements use an accelerometer about 50 cm apart from the machine foot under the machine tool (see **Fig. 5**). Four different impact points are defined. The machine tool performs face-milling operations during the acceleration measurements.

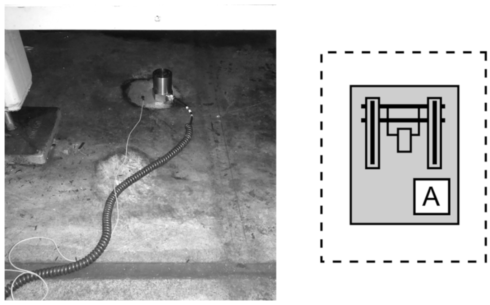

Fig. 5. Photograph of the placement of the accelerometer close to the machine tool foot on the foundation (left) and sketch of the experimental setup (right).

Figure 6 shows the recorded data. The coherence function of the measurements is used as a criterion to judge the validity of the impact test's extracted TFs. The drop of coherence in the floor-type measurement below 100 Hz indicates that the external operations couple into the TF measurements and reduce the correlation between input and output signals.

Figure 7 displays the externally induced vibrations and the signal's power spectral density. The acceleration amplitudes at the isolated block-type and the regular floor-type foundation are of the same order of magnitude (see **Fig. 7**). In case of the machining process on the regular floor-type foundation, the main vibration occurs around 87 Hz. A series of harmonics, i.e., peaks at multiples of that frequency, are observable in the higher frequency bandwidth (see **Fig. 7**).

The cutting process on the floor excites vibrations at 133 Hz which are also accompanied by a series of harmonics. The difference in the magnitude of the overtones is notable in particular. At the block-type foundation, the magnitude of the overtones appears to decay much more rapidly than at the floor-type foundation. One reason for this may be that the thick and heavy block-type foundations tend to move as a rigid body in lower frequencies rather than higher frequencies (see Section 2.1). In turn, the more lightweight but stiffer floor-type foundation shows the opposite properties, i.e., a tendency to

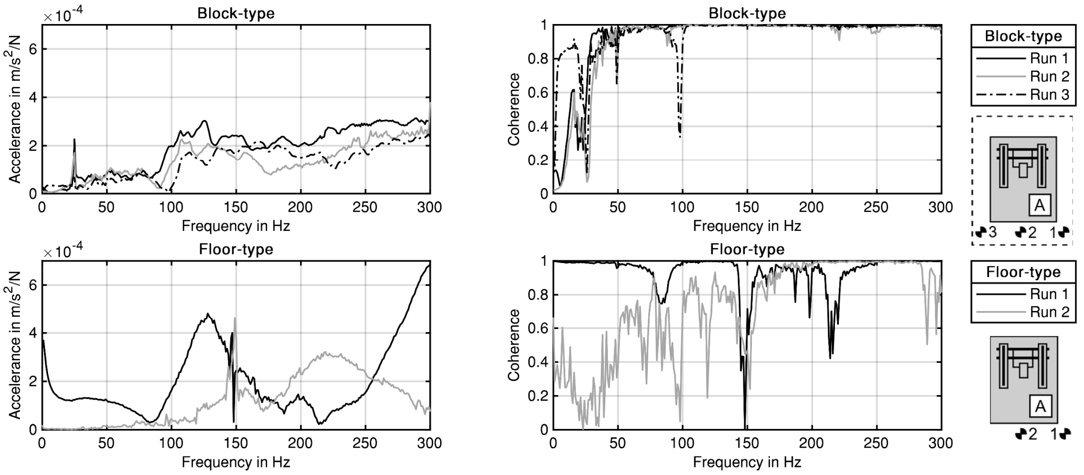

Fig. 6. Transfer functions from an operational machine tool to the foundation close to the machine tool foot.

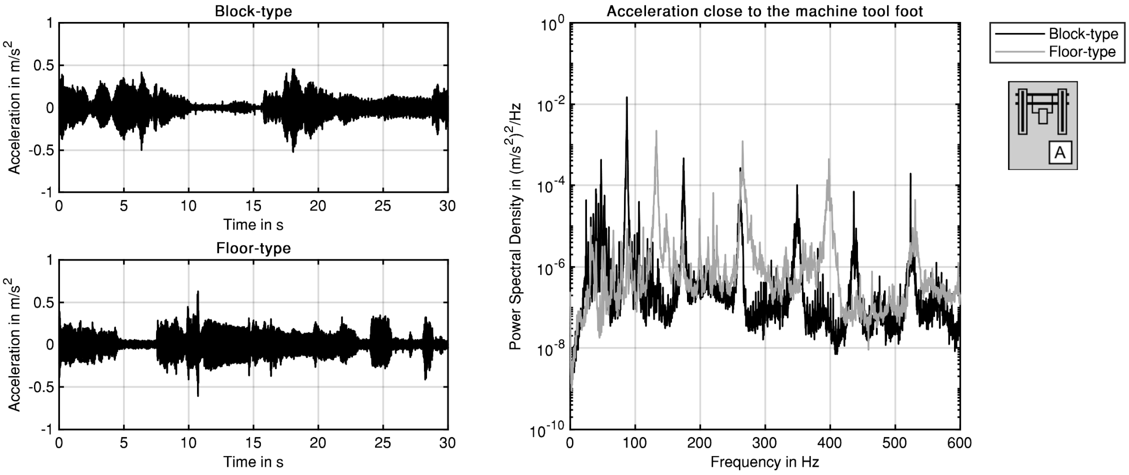

Fig. 7. Externally induced vibrations and their power spectral density at the foundation close to the machine tool foot.

vibrate more easily at higher frequencies. This is also evident when comparing the accelerance of both foundations above 150 Hz (see **Fig. 6**).

3.2.2. Transfer from a Stationary Machine Tool to an Operational Machine Tool

One accelerometer measures the vibrations close to the machine foot of an operational machine tool which performs face-milling operations. Several impact points are defined along the path to a non-operational machine tool in 3.5 m distance. That way, the vibrational energy transmission between neighboring machines is investigated. **Fig. 8** shows a photograph of the space between the two machines (left) and the related sketch (right). **Fig. 9** shows the measurement data of the TF measurements and **Fig. 10** gives the recorded background vibration signals.

The externally induced acceleration amplitudes are similar in both cases and lay around 0.1 m/s^2. Two significant peaks are evident in their power spectral density at 25 Hz and 87 Hz. One explanation for the 25 Hz vibration is a hydraulic unit of a neighboring machine tool.

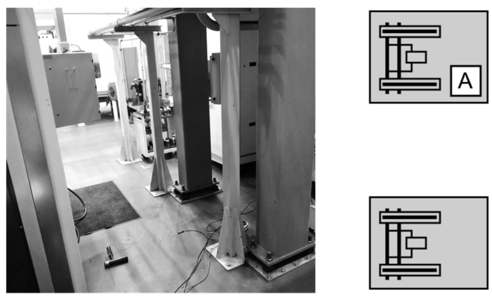

Fig. 8. Photograph of the space between the two machines at the floor-type foundation (left) and sketch of the experimental setup (right).

According to its data sheet, the hydraulic unit operates with 1440 rpm or roughly 24 Hz.

At both setups, the main peaks correlate to the neighboring machine tool's cutting processes. These are found at 87 Hz and 149 Hz, respectively. However, one notable difference is evident in the TFs of the acceleration

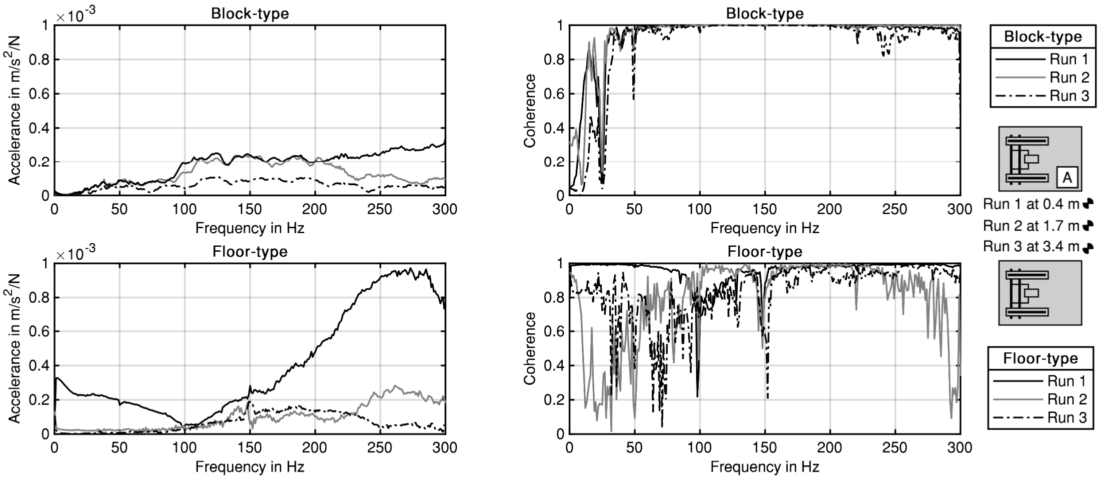

Fig. 9. Transfer functions from a stationary machine tool to an operational machine tool.

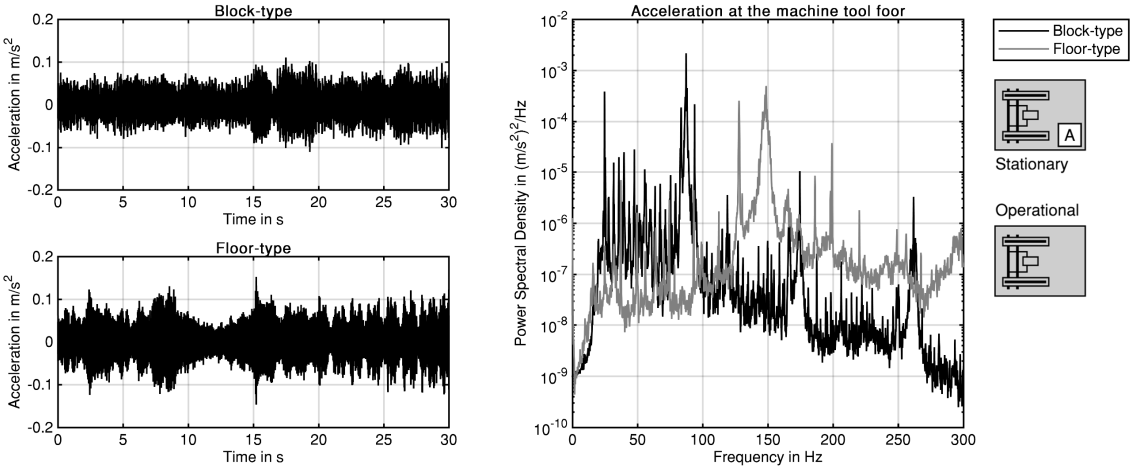

Fig. 10. Externally induced vibrations and their power spectral density at the machine tool floor below a stationary machine tool.

at the block- and floor-type foundation. At the block-type foundation, almost all transmitted external vibrations occur under 100 Hz and rapidly decrease towards higher frequencies. At the floor-type foundation, the situation is the opposite, as low frequency vibrations below 150 Hz are significantly reduced. This indicates that the floor-type foundation tends to transfer more vibrational energy in the higher frequency range.

The TFs in **Fig. 9** demonstrate the damping effectiveness of the vibration isolation at the block-type foundation. It is notable from the black and gray lines that they only separate after 200 Hz. This means that the damping between two points close to each other on the foundation is highly frequency-dependent. The measurement data also indicates that frequencies above 200 Hz are damped very effectively. In contrast to that, the floor-type shows a significantly higher transmissibility of the vibrations also at greater distances to the machine.

The previously discovered pattern of low energetic vibrations below 100 Hz is again observable. It is denoted that the data's coherence is low below 100 Hz for two of the three measurements. This is an indicator for the transmission of uncorrelated vibrational energy through the floor-type foundation into the stationary machine tool.

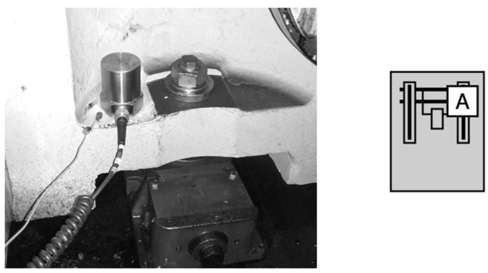

Fig. 11. Photograph of the accelerometer on the machine tool's frame (left) and the experimental setup (right).

3.2.3. Transfer from the Foundation to a Stationary Machine Tool's Frame

The accelerometer is located on the machine tool frame above the machine tool foot (the left side of **Fig. 11**).

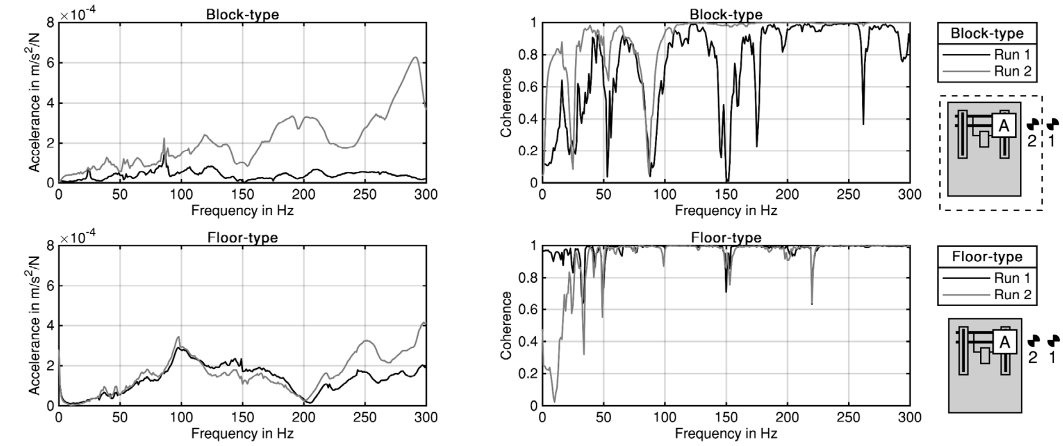

Fig. 12. Transfer functions from the foundation to a stationary machine tool's frame.

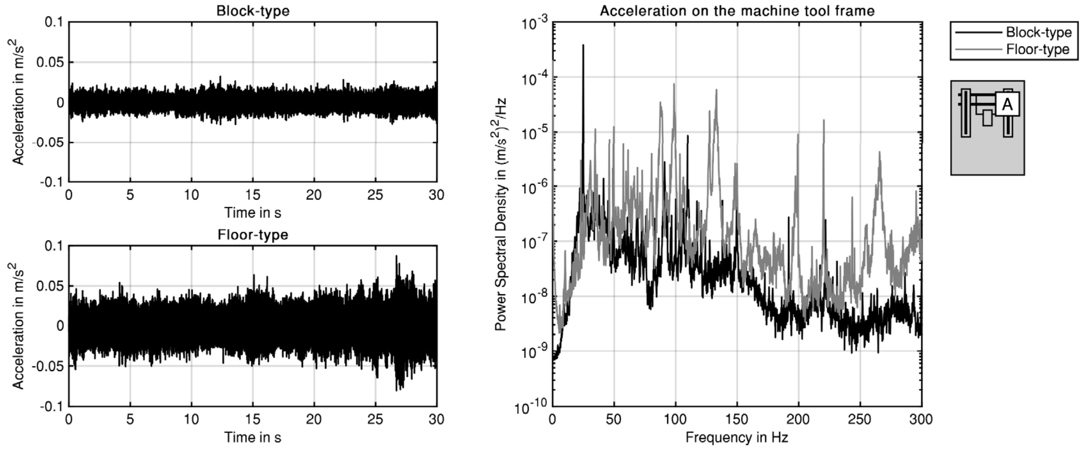

Fig. 13. Externally induced vibrations and their power spectral densities measured at a stationary machine tool's frame.

The machine tool is not operational and its auxiliary units such as the hydraulic pumps and the chip conveyor are turned off. However, the surrounding manufacturing line remains operational during the measurements. **Fig. 12** displays the TF measurement results, **Fig. 13** shows the recorded background noise and its power spectral density.

The time signal data shows amplitudes around two times larger at the floor-type foundation than at the regular block-type foundation. In the frequency spectra, a peak at 24 Hz is present, which is likely originating in a yet undiscovered internal aggregate. The power spectral density amplitudes are of similar magnitudes as in Section 3.2.2. This shows the reduced damping capabilities of the rigid anchored machine tool foot.

The TFs again reveal that the vibration isolation of the block-type foundation is more effective at frequencies above 100 Hz. The TF has a lower magnitude on the machine tool support directly below the machine in case of the floor-type foundation. The data also indicates a high effectiveness of the vibration isolation of the investigated foundation.

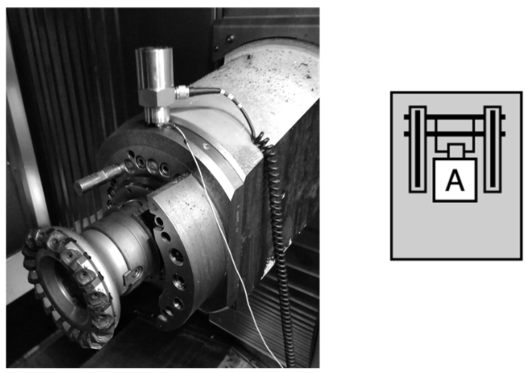

Fig. 14. Photograph of the accelerometer on the spindle housing (left) and the experimental setup (right).

3.2.4. Transfer from the Foundation to the Spindle

To assess the TF from the foundation to the spindle, the accelerometer is placed on the spindle housing in close proximity to the TCP (see **Fig. 14**). During the measurements, the machine tools are not operational but the neighboring manufacturing lines continue working.

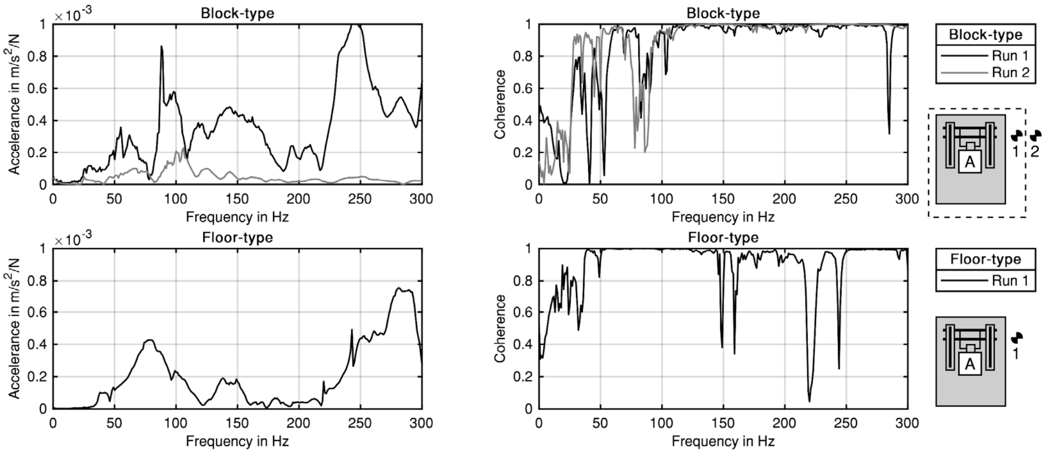

Fig. 15. Transfer functions from the foundation to the spindle housing.

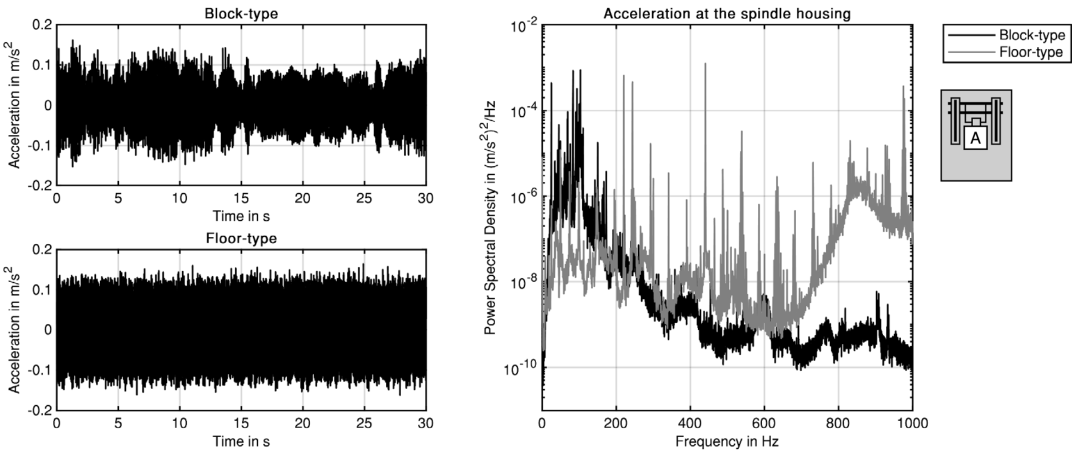

Fig. 16. Externally induced vibrations and their power spectral density at the spindle housing.

The results of the TF measurements are depicted in **Fig. 15**. **Fig. 16** shows the externally induced vibrations and their power spectral density.

The time series data of the floor-type foundation in **Fig. 16** are very even. One reason might be the closer packaging of machines at the floor-type factory site. That way, the multitude of different neighboring processes produces widely spread vibrational energy. In contrast, the differences in the block-type foundation time signal might root in fewer operating machines in closer proximity.

Again, the TFs of the block-type foundation clearly show higher magnitudes in the low frequency range until 100 Hz, but the floor-type foundation's damping appears not as effective at the higher frequencies above 100 Hz. One reason might be the tuning of the isolated block-type foundation. As seen earlier, the shift appears around 100–200 Hz.

Both machines largely respond at the spindle in low frequencies under 100 Hz. Experience shows that these frequencies likely belong to one of the fundamental frequencies of the machine tool structure. There is an additional peak distinguishable on the floor-type foundation around 250 Hz which is not evident at the block-type foundation. Additionally, a heavily damped peak appears around 850 Hz. One possible reason might be a mode shape of the spindle housing and tool close to this frequency.

The coherence belonging to the block-type foundation under 100 Hz is low so that these values should be taken with care. Besides the externally induced vibrations, reasons might be undiscovered non-linearities, an unfortunately placed accelerometer, or hammer impacts on structural nodes.

Nevertheless, the results demonstrate the impact of the foundation not only on the machine tool structure but also on the spindle housing and therefore the TCP. It is evident that the vibration isolation is more effective in the higher frequency range. However, the difference at the TCP is less prominent since the machine tool itself induces a considerable amount of damping.

3.2.5. Transfer of Hydraulic Pump Vibration to the Spindle

The machine tool requires a hydraulic unit for operation. This hydraulic unit is a pump located next to the machine tool structure. Because of differences in the organi-

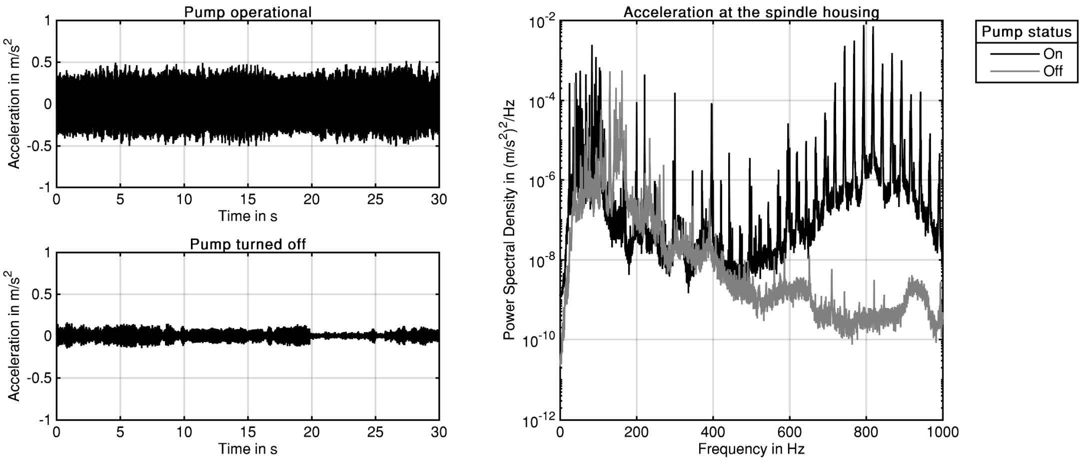

Fig. 17. Externally induced vibrations at the spindle housing on the floor-type foundation with operational and switched-off hydraulic unit as well as its power spectral density.

zational structure of the two factories, it is only possible to measure the hydraulic pump influence on the floor-type foundation.

The accelerometer again is located on the spindle housing (see **Fig. 14**), and the machine tool is not operational. After measuring the vibrations with an operating pump, the pump is switched off. **Fig. 17** presents a comparison of the changing time series data and the respective power spectral densities.

The hydraulic pump clearly induces vibrations into the foundation and the amplitudes are higher than expected. Clusters of frequency peaks lay around 800 Hz, ranging from about 600 Hz up to 950 Hz. The nominal speed of the pump translates to roughly 24 Hz, but apparently mechanisms such as gears, valves, and bearings generate a broader frequency spectrum of excitation so that higher frequencies are also excited at the machine.

Around 850 Hz, a likely structural frequency response is clearly visible again. It is noted that the cluster of overtone peaks spaces with 24 Hz which is a strong indicator for forced vibrations due to the pump.

The results are interesting, since they indicate that most vibrations originate from the machine itself. This in turn questions the necessity of an isolated block-type foundation in the first place. The generated vibrations are of higher magnitude than the transferred vibrations of the surrounding machines of the floor-type foundation. However, it is denoted that the surrounding manufacturing lines on both foundations differ and that the results are at this point only of sample size one.

3.2.6. Vibration Transmission in the Foundation

Three measurements are conducted to measure the transmission of vibrational energy on the isolated block-type, regular floor-type, and sacrifice floor-type foundation (see **Fig. 3**). **Fig. 18** shows a photograph of the placement of the accelerometer (left) and the impact hammer points (right).

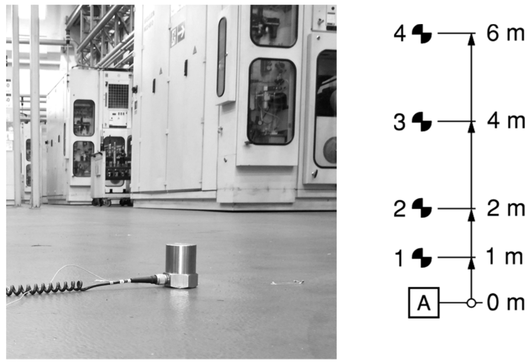

Fig. 18. Photograph of the accelerometer on the open foundation (left) and the experimental setup (right).

Figure 19 displays the TF measurement results. The analyzed sacrifice floor is significantly thinner, as it is designed to carry smaller machine tools, i.e., $h = 20.5$ cm in comparison to $h = 35$ cm directly on the subsoil gravel. Hence, the results are only an indication of how differently the vibrations transmit in the different types of foundations.

It is denoted that the measurement's coherence is checked and ensured for all reported measurements. Hence, the various rather undistinguishable peaks appearing in the block-type foundation are traced back to the fact that the foundation is only roughly representing a uniform plate as it has various cutouts, pillars for the conveyor and other auxiliary equipment for the machine tools.

An interesting comparison arises from the comparison of the vibration transmission on the regular and the sacrifice floor type foundation. The thinner sacrifice floor type foundation has lower response levels than the thicker regular floor. The responses at different distances however are of comparable magnitudes.

There is a distinct peak at about 250 Hz at the floor-type foundation which is also observable at 6 m distance. Below 150 Hz, the floor appears to be very rigid. The

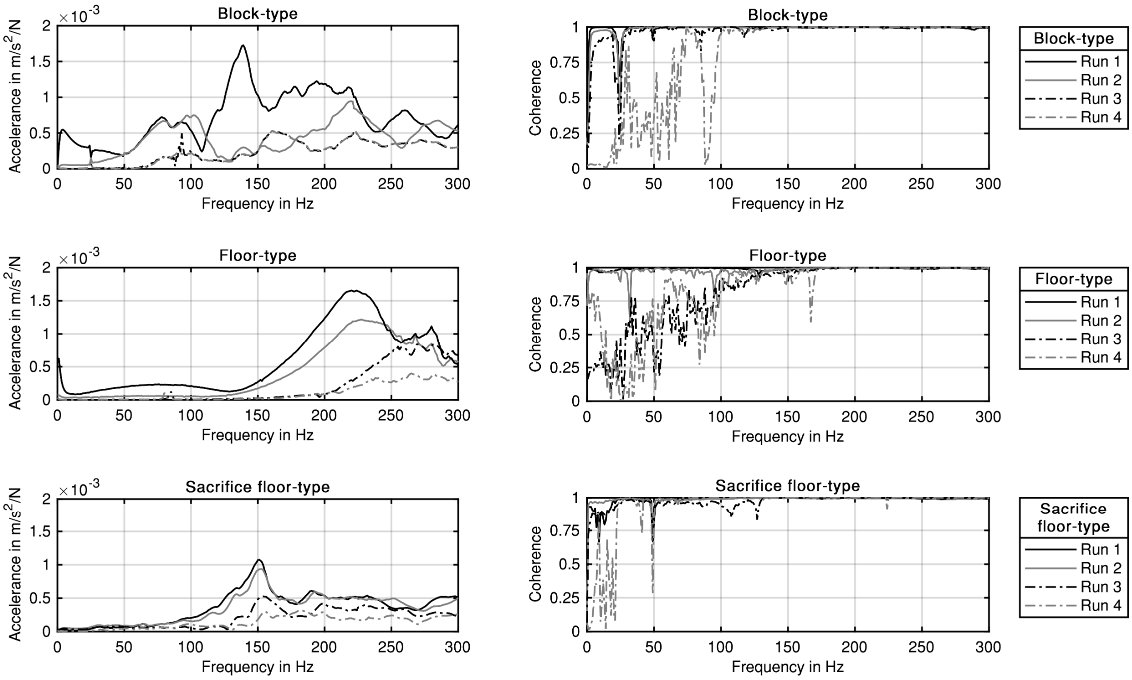

Fig. 19. Results of the transfer measurements along the open foundations at various distances according to the right side of **Fig. 18**.

response of the sacrifice floor-type foundation has a more even response with low magnitude TFs under 100 Hz and only one distinct peak at 150 Hz.

3.3. Scale Models of Machine Tool Foundations

It is generally challenging to induce a sufficient amount of energy into the machine tool foundation for the performance of a full EMA with good signal-to-noise ratio. Tests with a drop weight did not yield useful results, as they mostly cause a double impact without a dedicated apparatus. A rubber tip impact hammer was used instead to increase the spectral force input at lower frequencies.

Another challenge are the externally induced vibrations. In an industrial manufacturing line, the shutdown of several machine tools is not an option. Hence, a certain amount of unmeasured background noise is inevitable and might be a significant source of errors.

A possible solution to this issue is the measurement of machine tools and foundations in a dedicated laboratory environment. Hereby, spatial limitations call for the design of scaled experiments, similar to the ones in wind tunnels and water tanks.

3.3.1. Model Design

The design of the scale models should orientate at real full-size foundations. Hence, the dimensions of the foundations are chosen to have the same thickness ratio as the investigated block-type and floor-type foundations of the industrial shop floors. Weiner [8] recommends a foundation mass of approximately 2.5 times the machine tool mass. **Table 3** lists the dimension of the two scale foundation models and the utilized machine tool model.

Figure 20 presents two design concepts for the laboratory sized foundation scale models and their realization.

Table 3. Dimension of the foundation scale model and the milling machine tool model.

	Foundation type		**Machine tool model**
	Block	***Floor***	
Length [mm]	400	1,200	350
Width [mm]	300	800	130
Height [mm]	150	28	600
Mass [kg]	42	–	19

Both models are cast concrete and use the same gravel material to approximate the subsoil.

As a substitute to a real machine tool, the authors suggest using a small desktop machine tool as common among hobbyists and often used for teaching purposes. In the present case, a three axes milling machine tool with a weight of 19 kg is selected as a substitute model. It is installed on four aluminum feet to avoid excessive stiffening of the model's base (the left side of **Fig. 21**). The right side of **Fig. 21** displays the aluminum foot. It is an aluminum cylinder with a diameter of 25 mm and an M5 thread.

3.3.2. Validation Experiments

Three experiments are performed on the scale models to validate the subsequent conclusions in Section 4. The experiments include the measurements of the free machine tool model supported only by weak springs, measurements with the foundations on weak springs and measurements with the full foundations supported by the underlying gravel.

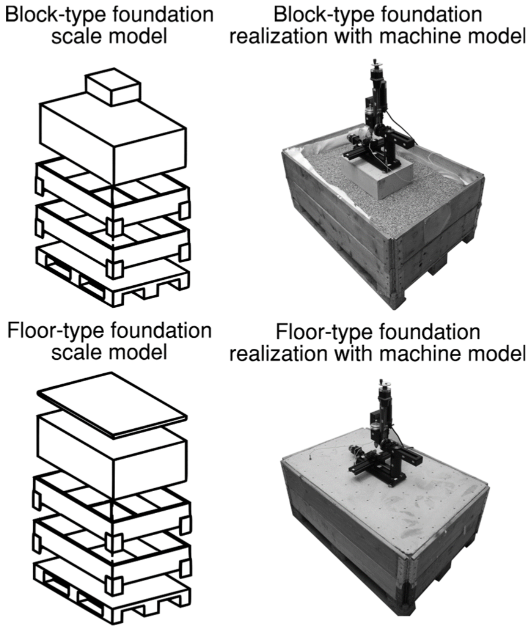

Fig. 20. Concept and realization of the scale models.

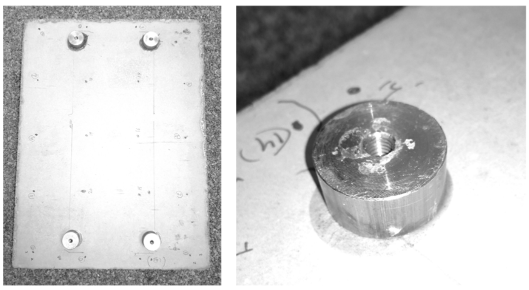

Fig. 21. Photograph of the four aluminum feet pattern (left) and close-up of one aluminum foot (right).

The excitation point remains the same throughout the measurements and is located at one of the machine tool feet. The accelerometer is placed at the spindle to allow for a judgement of the foundation's impact on the TCP dynamics (see **Fig. 22**).

Due to the smaller physical scale, a different set of instruments is used to measure the TFs of the scale models (**Table 4**). Again, the H_1 estimator of the modal analysis software suite LMS Test.Lab Rev 10B from the company Siemens PLM Software, Plano, Texas, United States of America, is used for the extraction of the presented TFs. The measurement sample rate is fixed at 12,800 kHz.

The current setup does not permit to recreate the measurements of vibrational energy transfer between machines since only one scaled foundation model of each type is available.

Figure 23 shows the foundation impact on the overall machine tool damping when comparing the freely suspended machine tool and the machine tool placed on the foundation. This is in alignment with the theory, as the foundation adds stiffness and mass to the system.

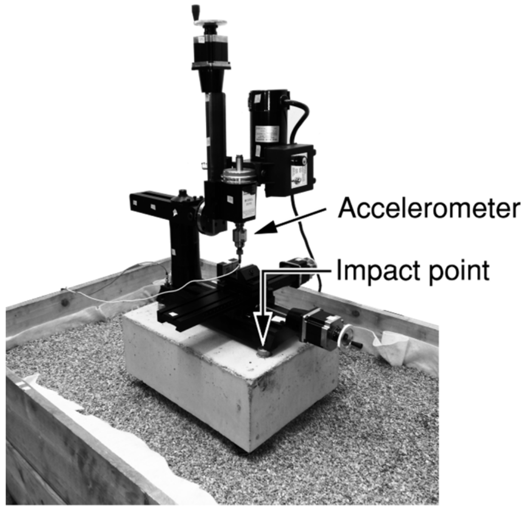

Fig. 22. Impact point and placement of the accelerometer for the scale model experiments.

Table 4. Utilized measurement equipment hardware for the validation experiments on the scale models.

Item	Manufacturer	Model
Accelerometer	Bruël & Kjær	4508 B 002
Impact hammer	Ziegler	IXYS
Charge amplifier	Bruël & Kjær	2635
Data acquisition	Siemens PLM	LMS

The effect of the gravel is not as notable as the one from the foundation. However, the effect of the gravel under the foundation is clearly seen in the damping of the two peaks around 100 Hz. When comparing these results, a good correspondence to the previous findings is denoted.

4. Conclusions

This paper presents the result of an extensive testing campaign at different shop floors with different types of machine tool foundations. The overall goal was to establish a comparative database for the deduction of proper design guidelines for precision targeting machine tools. The premise is the investigation of vibrational transmission and to find indications for low vibrational disturbance to decrease the vibration amplitudes of the accuracy determining TCP.

The database indicates that floor- and block-type foundations offer a similar performance. Despite the comprehensive measurements, it remains challenging to judge which foundation type is superior in which case. A peculiar difference is the significantly higher noise level at the floor-type foundation which will be investigated further in future research.

The following general conclusions are drawn from the investigations.

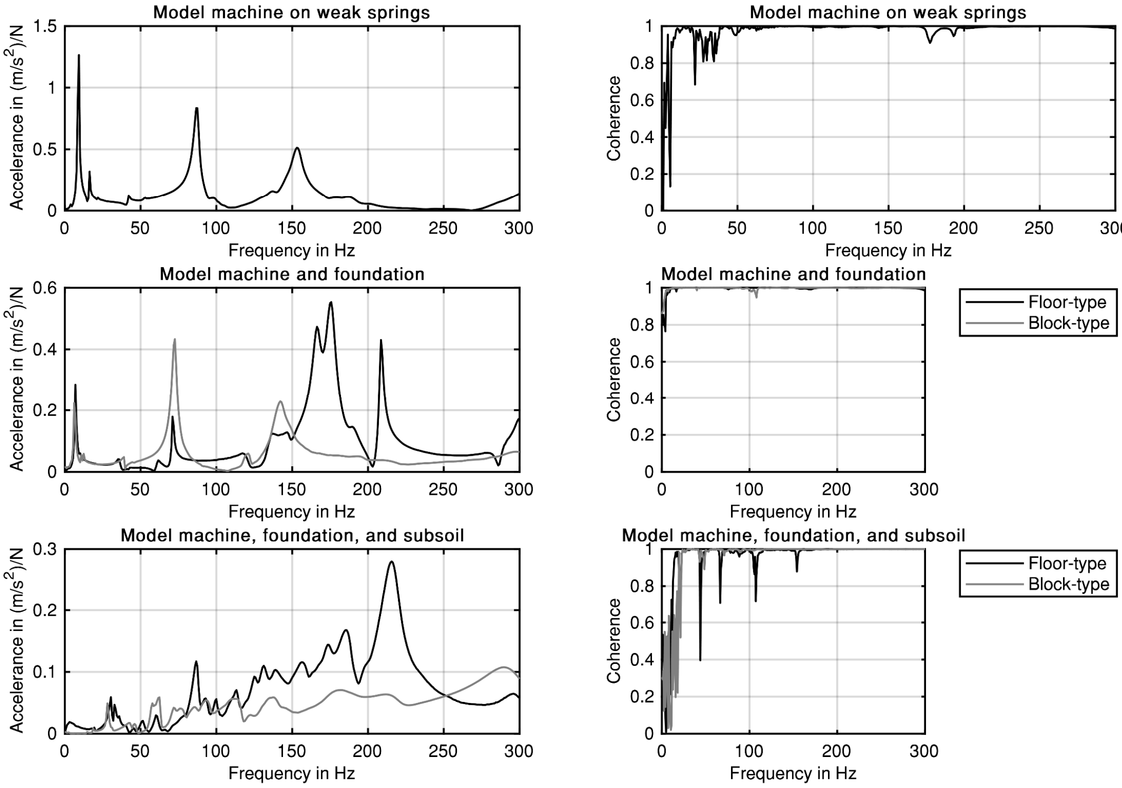

Fig. 23. Transfer functions from the machine tool model foot to the spindle housing on various configurations of the scale models.

- The investigated block-type foundation shows mainly vibrations at lower frequencies due to its tendency for rigid body movement.
- The investigated isolated floor-type foundation exhibits vibrations mainly at higher frequencies and behaves as a stiff floor.
- At a stiff floor, vibrational energy transfer between machines appears mainly at higher frequencies. This implication leads to a significantly reduced level of audible noise in the factory.
- The investigated block-type foundation vibration isolation is most efficient at higher frequencies.
- Below 150–200 Hz, the vibration isolation of the block-type foundation is not as efficient as in the regular floor. However, it still exhibits damping effects.
- Vibrations of auxiliary units such as hydraulic pumps couple significantly into the foundation and may affect neighboring machines.

For validation of these findings, scale models of machine tools and their respective foundations are presented. They exhibit similar tendencies and allow for further investigations.

In conclusion, the measurements turned out well and the data are of good quality. However, no single measurement gives a clear answer. The results are also only comparable on a broader scale, as only the investigated machine tools are of the same type but the neighboring manufacturing lines and performed operations obviously differ. Despite that, patterns are recognized and relevant conclusions are drawn.

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