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Vibration analysis of moving machine tool axes based on phase information in video data

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Abstract

Vibrations of machine tools limit quality and productivity and therefore need to be analyzed. Video based vibration analysis using spatial phase information could in principle reduce measuring effort significantly. However, feasibility of these approaches for moving machine tool axes and relative movement between camera and object is yet to be shown. This paper investigates an approach for stabilizing linear axis movement to analyze vibration. It is shown that shaker induced vibration on a linearly moving clamping tower can be derived for low frequencies. However, influences of actual cutting processes as well as compensation of unwanted camera vibration needs further investigation.

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Keywords: vibration analysis; machine vision; video magnification; machine tools

1. Introduction

Vibrations of machine tools between workpiece and tool center point have an effect on many aspects such as workpiece quality, tool wear or achievable productivity [1, 2]. The sources of vibration can either be forces induced by the process itself or forces induced through peripheral components of the machine. The knowledge about the qualitative and quantitative characteristics of resulting vibration at machine tool components is key to identify the source of vibration and take effective countermeasures [1, 3].

Common methods to determine qualitative and quantitative aspects of vibration involve placing accelerometers at assumed points of interests and / or developing FEM simulation of the machine structure. In modal analysis, a model of the machine structure is coupled with experimental data of forces induced into the structure and the resulting reaction of the structure [1]. The process of modelling, applying sensors, conducting experiments and analyzing data is time consuming and knowledge-intensive.

Video-based approaches for vibration analysis show promising results regarding visualization and quantification of displacements [4, 5]. Approaches based on the algorithm presented by [5] use local phase variations in video data that correspond to object movements. By analyzing phase variations over time at defined areas of interest, small subpixel-movements can be evaluated in time domain and frequency domain [5, 6]. By amplifying those phase variations and reconstructing to video, small movements can be magnified in video. However, for the approach based on [5], the movement to be analyzed needs to be isolated from other interfering object or camera movement. Hence, large object movement or camera movement must not be present [7].

In accordance with Nyquist-Shannon sampling theorem, sampling rate of the video to be used for vibration analysis should be chosen to be at least twice as high as the highest frequency of interest. For example, in order to analyze frequencies of up to 500 Hz, a high speed video with more than 1000 frames per second is needed. Furthermore, appropriate signal to noise ratio in video data is needed to analyze small scale motion.

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If feasible, the analysis of video data could simplify traditional vibration analysis and the use of local accelerometers: video data not only covers single points of an object but large areas in view range of the lens and image sensor. Direct visualization of vibration could in some cases avoid time consuming modelling and experiments for modal analysis. Other advantages come from the contactless analysis with video data as no sensors have to be manually attached and vibration of the observed object is not influenced by sensor mass.

However, a main challenge for the application of video data for vibration analysis of production machines and machine tools is stiffness of object structure. Machine tools are designed to have high stiffness and favorable damping characteristics to have minimum deviations at the tool center point and reach high accuracy. This results in small amplitudes of the structure and therefore high, subpixel sensitivity and low noise needed for video based analysis.

Another challenge is relative movement of camera and object to be oberserved. Compared to a typical accelerometer where mass inertia is used as a reference to measure acceleration and displacement, video analysis relies on measuring relative movement of sensor and object. Relative movement of camera and object therefore interferes with analysis of the object of interest.

Firstly, this can be an unwanted relative movement of the camera induced by vibration. Experiments with a running water pump by [8] showed that vibration of the camera itself has a strong effect on the applicability of video data for vibration analysis. In a machine tool, forces induced by the cutting process or peripheral equipment also result in vibrations of the machine structure and surrounding area. When the camera itself is exposed to significant vibration, analysis of vibrating objects is affected.

Secondly, axis movements which are necessary for the machining process can cause large relative movement between camera and object of interest, e.g. the workpiece. Attaching the camera to the moving axes to avoid relative movement is not a favorable option as the camera would be exposed to acceleration of axes and strong vibration.

The phase-based video motion processing approach presented by [5] laid the foundation for numerous publications focusing on the optimization and application of video data for vibration analysis. State of the art approaches either analyze vibrations in videos without large object motion [5, 8, 9] or magnify small motions in presence of large motion [10,11]. In [7] acceleration instead of displacement is magnified. This can improve the results of magnifying small motion in video but is not suitable to quantitatively analyze displacements in presence of large motion. Approaches presented by [5, 9] are also not directly suitable for analyzing vibration of moving objects. This is because pixels corresponding to edges of the vibrating object need to be selected for analysis. Since the object is moving over time, no defined pixels can be identified.

The feasibility of phase based video analysis for machine tool components and moving components in particular has not been investigated. Hence, the goal of this work is to investigate the feasibility of video data analysis based on the phase based approach shown by [5] for analysis of vibrations in moving machine tool components.

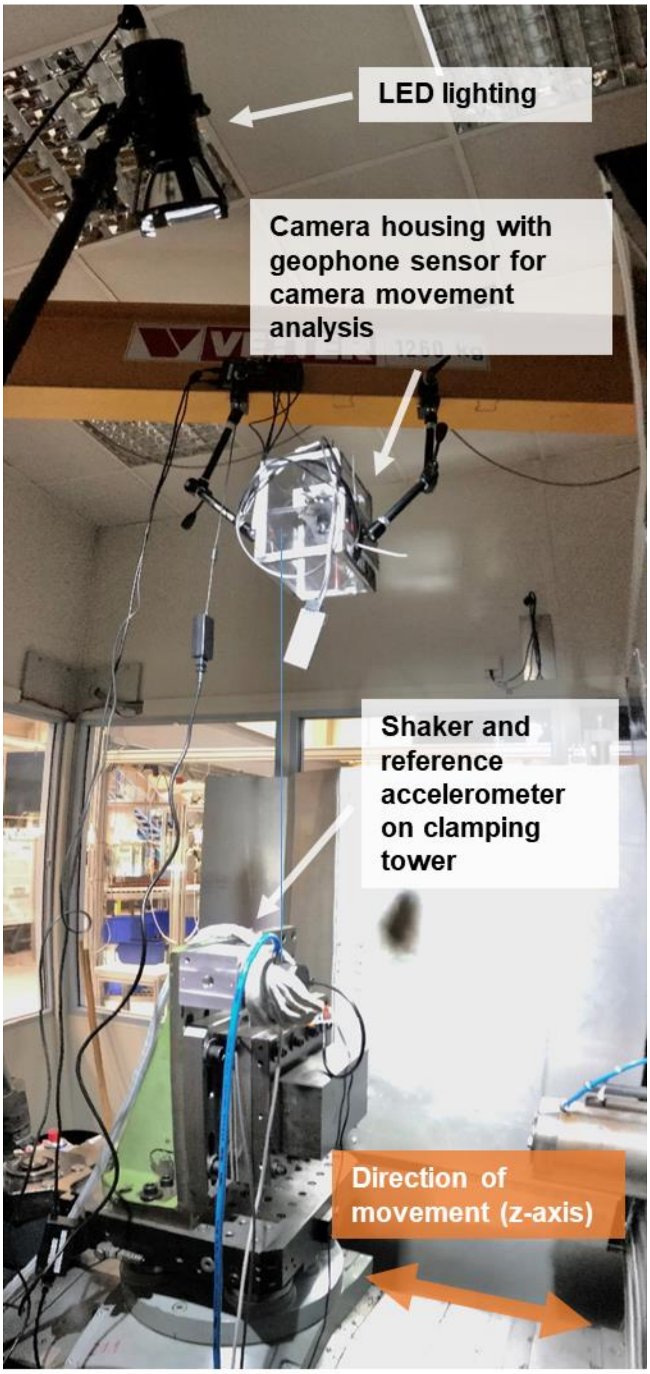

Fig. 1. Setup overview with camera filming moving clamping tower with attached shaker.

2. Approach

In phase based motion analysis, image changes at fixed image locations are analyzed over time. However, continuous relative movement of the object of interest, such as a workpiece moving with a machine axis, results in large movement of the object location in video.

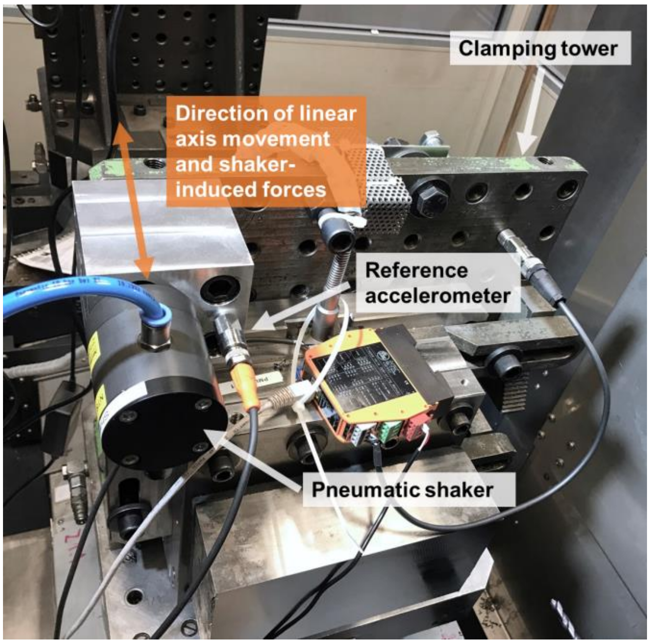

Fig. 2. Detail view of machine clamping tower with attached shaker and reference accelerometer.

In order to compensate for the constant movement of machine axes, an approach for stabilization is implemented. As in [10, 11], the approach is based on the idea of stabilizing the moving object as a pre-processing step before analysis.

First, the approach uses user-guided Sobel Operator edge detection to identify the same object edge on the first and last frame of the video to be analyzed. Linear, non-accelerated movement of this edge between the selected frames is assumed. By comparing the edge position and direction of movement between the first and last frame, object movement in every frame is then assumed. Second, to stabilize the movement, an approach based on the Fourier Shift theorem comparable to [12] is used. By manipulating the video in frequency instead of spatial domain, the shifting of video frames can be achieved with sub-pixel accuracy. Hence, an interference of inaccurate shifting with the small scale underlying vibration is avoided.

As the resulting video is stabilized only regarding the selected linear movement, an analysis of the spatial phase changes can now be carried out at fixed image locations comparable to [9]. Unlike approaches for magnifying small movements in video by manipulating phase variations and reconstructing to a video with magnified motion, only local phase variations at the points of interest are extracted and transferred to time and frequency domain. This way, a qualitative comparison of frequencies analyzed with reference measurements is possible.

To create video data in a machine tool scenario and evaluate the approach, a high speed camera type Krontech Chronos 1.4 with Ricoh lens FL-CC3516-2M is mounted to an overhead crane in 85 cm distance to the clamping tower of a 4-axis machine tool type DMC 60H. In order to reduce camera movement induced by the vibration to be measured, the camera is attached to an overhead crane which is mounted to a floor baseplate. The recorded machine tool has no housing to

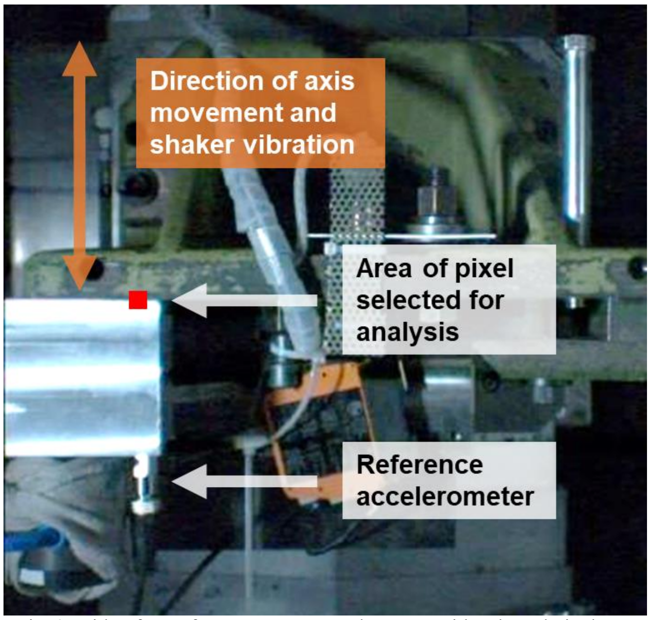

Fig. 3. Video frame from crane-mounted camera with selected pixel to be analyzed.

achieve high accessibility and visibility of components. An overview of the setup is shown in fig. 1.

For an analysis of interfering camera movements, high sensitivity geophone sensors type SM-24 are attached to the camera body. In order to analyze the main effect of camera movement, direction of the geophone is chosen to be in the same direction as direction of analyzed vibration. LED lighting of type WASP 100C is used to illuminate the clamping tower of the machine with constant intensity.

To simulate process induced vibration on the clamping tower, a pneumatic shaker of type Netter Vibration NTS 100/01 is used. With maximum force of ~420 N at ~72.5 Hz, the shaker excites the clamping tower with forces and frequencies in range of measurements from actual cutting processes. For reference analysis of excited frequencies, an accelerometer type IFM VSA001 is attached to the structure. To achieve a worst case scenario for the stabilization approach, forces are induced in the direction of axis movement. This way, stabilization of the axis movement has a direct effect on the vibration to be analyzed. However, by using a shaker instead of an actual machining process, disturbing factors of an actual cutting process such as flying chips and coolant flow are avoided.

The video is shot with 1000 frames per second and 1024x608 pixel resolution. During the video, the z-axis of the machine with clamping tower, attached shaker and accelerometer is moved with a velocity of 600 mm/min. It is filmed for a corresponding linear movement of 2 cm or 2000 frames with 1/60 pixel linear movement per frame.

To evaluate the feasibility and limiting factors of the approach and developed algorithm, data from accelerometer, data from video and geophone data of camera movement is then compared regarding frequencies. Figure 3 shows a frame of the recorded video with the area of analyzed pixel.

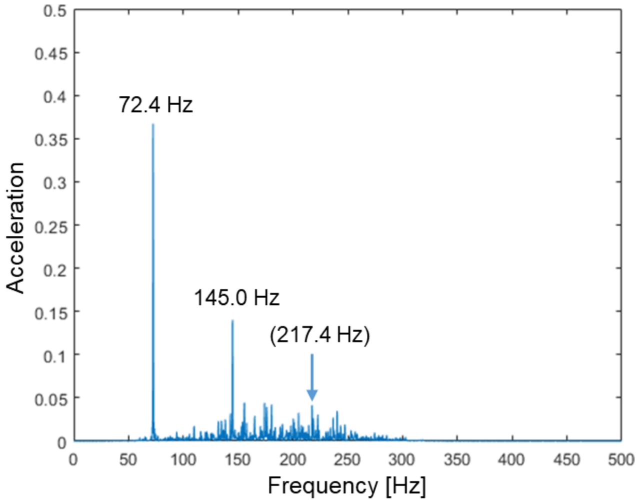

Fig. 4. Spectrum of acceleration from video; distinct peaks at 72.4 Hz and 145.0 Hz.

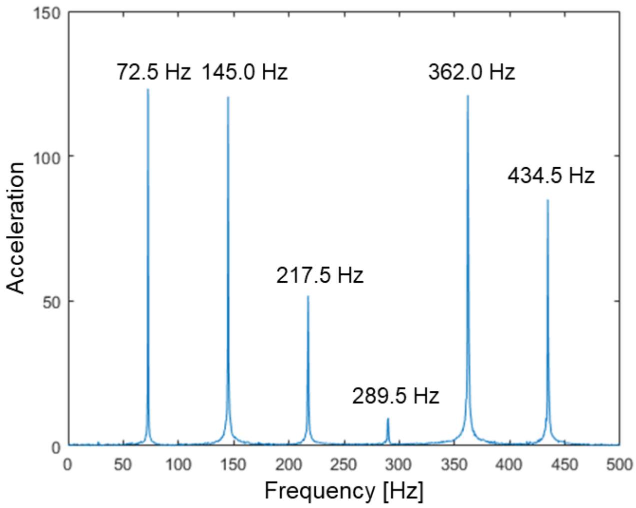

Fig. 5. Spectrum of acceleration from accelerometer at shaker; distinct frequencies at 72.5 Hz, 145 Hz and harmonics.

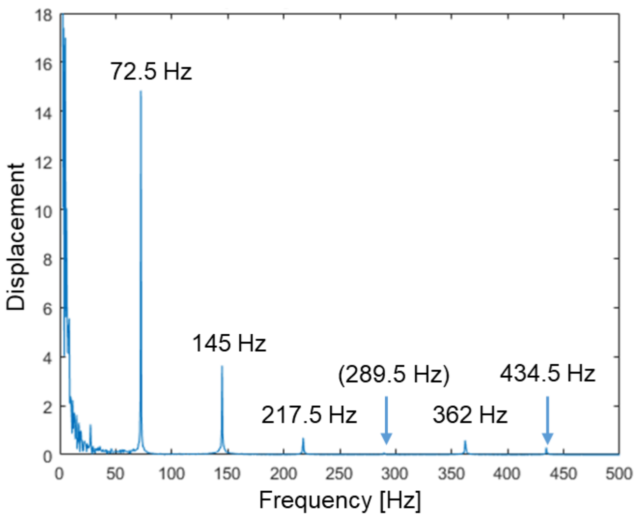

Fig. 6. Estimated spectrum of displacement integrated from accelerometer at shaker.

3. Results

Fast Fourier Transform derived from video of the axis moving with 1 cm/s shows distinct peaks at frequencies of 72.4 Hz and harmonic frequency of 145.0 Hz. Fig. 4 shows the frequency spectrum of acceleration. For frequencies higher than 145.0 Hz, peaks cannot be clearly distinguished from noise.

The spectrum of the reference accelerometer shows matching peaks at 72.5 Hz and 145.0 Hz. Further harmonics of the shaker frequency are shown up to 434.5 Hz, see fig. 5.

To estimate the relation of displacement for the frequencies seen in accelerometer data, the acceleration signal was integrated. The estimated displacement and its spectrum show that higher frequencies have significantly decreasing amplitude, see fig. 6.

The acceleration spectrum of camera movement in direction of the vibration to be analyzed is derived from geophone data. It shows distinct peaks at 72.5 Hz and 105.1 Hz, see fig. 7. At higher frequencies, a broader spectrum of frequencies is excited. As the geophone sensor is rated to have extended error over 240 Hz, analysis of higher frequencies can be affected.

4. Discussion

The results show that vibration on moving machine tool axes can be analyzed with the stabilized phase based video motion processing approach in principle. For lower frequencies of up to 145 Hz, the vibration frequencies derived from video data match the frequencies from reference accelerometer with good accuracy. With the induced forces, frequencies and structures being comparable to actual cutting processes, the approach shows good potential for further investigation in actual machining processes.

For frequencies higher than the first harmonic of the excited frequency, peaks shown by the accelerometer cannot be clearly distinguished in the video data anymore. It is assumed that with the higher frequencies and smaller

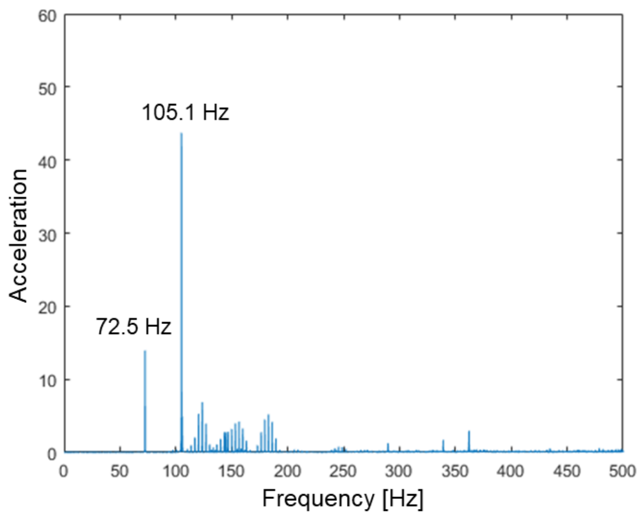

Fig. 7. Acceleration spectrum of camera movement from geophone attached to camera; geophone in direction of vibration and movement to be analyzed.

amplitudes estimated in figure 6, noise induced by unwanted camera movement as well as pixel noise overlay the signal of actual object motion. As the camera sampling rate was chosen to be 1000 FPS, it is not considered the limiting factor when analyzing frequencies of up to 500 Hz.

The frequency spectrum of camera movement recorded with the geophone shows that the camera is also excited with frequencies that match the first frequency derived from video and accelerometer. However, as the most significant peak from the geophone spectrum at 105.1 Hz cannot to be seen in accelerometer or video data, peaks at 72.5 Hz and 145 Hz seen in video data are not considered to be caused by camera movement. For higher frequencies and accordingly smaller amplitudes however, camera movement seen in the geophone spectrum is considered to have a large impact on signal to noise ratio of video analysis.

Hence, to achieve more robustness and improved signal to noise ratio especially in noisy production environments, a rigid and well dampened camera mount as well as further steps for filtering unwanted camera movement are needed.

A further limitation of the current approach is the Sobel Operator used for edge detection in the first and last frame of the video to be stabilized. It does not achieve subpixel accuracy and therefore creates an error regarding assumed displacement between frames. Therefore, the accuracy of the necessary shift in each frame for stabilization has limited accuracy. This is especially true for short videos with small velocity of movement to be stabilized. Furthermore, linear movement without acceleration for the moving axis is assumed. Hence, the effect of video length, movement velocity and acceleration needs to be further investigated.

For non-linear movements of the object of interest, e.g. a combined 2-axis non-linear movement of the workpiece or spindle, the stabilization approach needs to be modified. This could be achieved by modeling the non-linear movement as segments of higher order functions.

As the forces on the machine tool were induced by a shaker instead of an actual machining process, the influence of cutting chips or coolant was excluded. Their effect on video analysis needs to be investigated.

5. Summary and outlook

The conducted experiments show that phase based video data analysis for machine tools with moving objects of interest is feasible in principle. Experiments with a pneumatic shaker exciting a linearly moving clamping tower of a machine tool show that lower frequencies can be analyzed with video data. However, with higher frequencies and smaller amplitudes, frequencies cannot be derived from video data, yet. Evaluation of a geophone sensor attached to the camera reveal camera movements interfering with the small scale object vibration to be analyzed.

For application in noisy production environments and for enabling analysis of vibration with higher frequencies and smaller amplitudes, further work will have to focus on dampening or compensating interfering vibration. In this regard, approaches for stabilizing moving objects in video could also be adapted to stabilize camera vibration.

Furthermore, the effect of other factors typical for machine tools needs further investigation. The presence of cutting fluid, flying chips and non-linear axis movement needs to be taken into account.

As visualization of small movements would be a key advantage of video analysis, the motion magnification aspect should also be investigated for production environments and machine components.

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