APPLICATION OF AN ACTIVE CLAMPING SYSTEM IN WOOD MACHINING
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INTRODUCTION
The productivity demands put on wood-working machines are continuously increasing. Generally, this resulting increase in productivity also leads to greater dynamic and in-process forces, which may cause higher structural vibration amplitudes during machining and thus negatively affect the production quality [1]. Therefore, technological advancements are made to improve the performance and machining speeds of these machines.

Vacuum clamping systems are predominantly used on stationary wood-working machines during machining of particle boards and fiberboards. Using these systems, the workpieces are neither damaged nor deformed during milling, drilling or sawing processes. These clamping systems also allow an arbitrary positioning of each suction block and good accessibility to workpiece edges. However, they have the disadvantage that the workpieces have free, overhanging ends. These ends are perturbed during the machining over a wide frequency range, thereby inducing forced vibrations. Moreover, these vibrations increase the risk of flaws along the edges of the workpiece. The quality of the workpiece edges, however, is an important quality criterion for the final product.

Furthermore, Figure 1 shows that the forced vibrations through the workpiece during milling process bring about higher overall noise levels, both direct and indirect sounds, which lead to elevated noise exposure to the production environment. The direct sound radiates originally from the milling tool alone, while the indirect sound comes from the workpiece through impulse interaction of the milling tool.

Generally, local encapsulation and passive noise damping methods are used to counteract this problem, but they do not reduce the noise level as desired. Besides, particularly for the stationary wood-working machines, such solutions are constructively limited. Thus, an improved performance can only be realized through innovative fundamental system analysis. This kind of improvement may be achieved by the integration of active or adaptronic (a.k.a. smart structure) systems into the mechanical components of machine tools [2]. Therefore, the idea was to design and employ an active clamping system on stationary wood-working machines.

Thus, the goal of the research project presented in this paper is to achieve an active vibration and noise level reduction during machining of particle- and fiberboards on stationary wood-working machines.

MODELING AND DESIGN
Initially, an adaptronical clamping system, which is composed of sensors, a workpiece clamped on four suction blocks and actuators within each of those suction blocks, was modeled into a multi-body-simulation (MBS) environment (Figure 2). The simulation aims to analyze its fundamental behavior. The workpiece was modeled as a finite-element-model and imported into MSC.ADAMS over an interface. Subsequently, an excitation force and actuator’s reactions applied to the workpiece were also modeled. The excitation force was implemented in the MBS-model as an input vector. This vector was modeled on a workpiece edge and defined...
as a sine signal. The piezoelectric actuators were likewise modeled to react in the sine signals with the same amplitude, however in the different phase from the amplitude and phase from the input vector, respectively.

In the following, the structure behavior was simulated in the MBS-environment. The simulation result in Figure 3 shows that the vibration amplitudes of the workpiece can be reduced about 14 times [3].

Each control signal from a single actuator, which propagates through the ‘physical’ system $S(z)$, is modified by the response characteristics of the control source and the error sensor. The influence of all of these can be lumped into a single ‘secondary path transfer function’ $S'(z)$, which is constructed through system identification [4].

CONTROL ALGORITHM

By using an active vibration control system, an external voltage signal is applied to the actuators to produce forces and accordingly displacements in the opposite direction of those produced by the tool at a particular workpiece position. The simple idea behind is the destructive wave interference and thus reduces vibrations. To achieve a wider amplitude vibration reduction area on the workpiece, several sensors and actuators are employed by implementing a Multi-Input Multi-Output (MIMO) system. Using a Filtered-X algorithm in the control strategy with adaptive filters Least Mean Square (LMS) and/or Recursive Least Square (RLS), the control system is intended to be adaptive in order to cope with various machining parameters and workpiece dimensions.

As illustrated in Figure 5, the error signal $e(n)$ measured by the error sensor is a mixture of signals both from $P(z)$ and $S(z)$. $P(z)$ is the primary path from the reference signal depending on the rotating frequency of the
milling tool to the error sensor, whereas $S(z)$ is the single secondary path between each piezoelectric actuator and each error sensor.

Due to the higher stability and less computation of the LMS, it is chosen to be used in the control process and the identification process is left to the RLS algorithm. Regarding the RLS performance, it is possible to identify the secondary path faster and more precisely. This combination leads to the Filtered-X LMS controller with the RLS identification, shortened to the FXLMS-RLS.

Assuming that $W(z)$ is a FIR- (finite impulse response-) filter of tap-weight length $N$, the control signal $y(n)$ is computed as

$$y(n) = w^T(n)x(n)$$  \hspace{1cm} (1)$$

where $w = [w_0(n), w_1(n), \ldots, w_{N-1}(n)]^T$ is a tap-weight vector and $x(n) = [x(n), x(n-1), \ldots, x(n-N+1)]^T$ is an $N$-sample reference signal vector.

The tap-weights of the adaptive filter $W(z)$ are updated using the LMS algorithm [4], [5], [6].

$$w(n+1) = w(n) - \mu x^\top(n) e(n)$$  \hspace{1cm} (4)$$

where $\mu$ is the corresponding step-size parameter and $x'(n)$ is an $N$-sample filtered reference signal. The filtered reference signal $x'(n)$ is an approximation result after the influence factors of the cancellation path described as follows

$$x'(n) = \hat{S}'(z)x(n)$$  \hspace{1cm} (5)$$

where $\hat{S}'(z)$ is copied from the cancellation path modeling $S'(z)$.

The tap-weights of the adaptive filter $S'(z)$ are updated using the RLS algorithm [6].

$$k(n) = \frac{\hat{\lambda}^\top \mathbf{P}(n-1) v(n)}{1 + \hat{\lambda}^\top \mathbf{v}'(n) \mathbf{P}(n-1) v(n)}$$  \hspace{1cm} (6)$$

$$v'(n) = s'(n)v(n)$$  \hspace{1cm} (7)$$

$$f(n) = e(n) - v'(n)$$  \hspace{1cm} (8)$$

$$s(n) = s(n-1) + k(n)f(n)$$  \hspace{1cm} (9)$$

$$\mathbf{P}(n) = \hat{\lambda}^\top \mathbf{P}(n-1) - k(n) v'(n) \mathbf{P}(n-1) \mathbf{v}'(n)$$  \hspace{1cm} (10)$$

where $k(n)$ is the Kalman gain vector, $s(n)$ is the filter coefficients of $S'(z)$ and $\mathbf{P}(n)$ is the inverse of the auto-correlation matrix of $v(n)$.

Since the designed control system is composed by four actuators and four error sensors, there are 16 secondary paths from each actuator as secondary source to each error sensor (Figure 6).

![VeryFigure 6: Multiple channel secondary path identification procedure](image)

**EXPERIMENTAL RESULTS**

In order to examine the practical issues associated with the MIMO-FXLMS-RLS controller, several experiments during machining were done. Figure 7 shows the experimental setup with the MIMO-FXLMS-RLS structure using four LASER triangulation sensors (LTSs) as error sensors. The actuators and the sensors were located relatively close to the disturbance source at the milling position, yet the machining shall not be disturbed. The workpiece, a medium density fiberboard (MDF) in $600 \times 600 \times 18$ mm$^3$, was clamped on the active suction blocks. It was milled at a workpiece edge with a depth of cut of 2 mm and a tool’s rotation speed of 18000 rpm.

![Figure 7: Experimental setup](image)

During the milling process, the vibration amplitude of the workpiece was dominated at the tool’s rotation frequency of $300$ Hz. Therefore, the error signals were filtered by a narrow band-pass filter in the corresponding frequency. Each secondary path from each actuator to each error sensor was identified at the frequency of $300$ Hz as well. The experimental result in Figure 8 shows an amplitude reduction in all error signals after the control was activated.
The filtered error signals taken from error sensors LTS 1, LTS 2 and LTS 3 - which were relative nearby to the disturbance source - had greater amplitudes as expected than one from error signal LTS 4. Since an improved workpiece quality is the primary research goal, the vibration amplitudes of the workpiece at the milling position (LTS 1 and LTS 2) became a priority to be reduced. A maximum vibration reduction was achieved by 25 dB. At the same time, the vibration amplitude at sensors LTS 3 and LTS 4 were reduced as well.

![Error signals at milling process](image)

**FIGURE 8: Error signals at milling process**

Furthermore, in order to capture the noise radiation particularly from the workpiece during the machining, a microphone was subsequently positioned over the workpiece surface. The dominant sound pressure levels were measured likewise at the tool’s rotation frequency of 300 Hz and its five harmonics at 600 Hz, 900 Hz, 1200 Hz, 1500 Hz and 1800 Hz.

By employing an accelerometer right in the middle of the workpiece surface as an error sensor, the active clamping system was also investigated in aim to reduce the noise levels at the tool’s rotation frequency of 300 Hz and its three harmonics at 600 Hz, 900 Hz and 1200 Hz. Actuator 1 and 2 controlled the frequencies of 300 Hz and 600 Hz, whereas actuator 3 and 4 handled the frequencies of 900 Hz and 1200 Hz, respectively. The experimental result in Figure 9 shows an overall noise level reduction of 4 dB(A), in which a maximal noise level reduction at 300 Hz was achieved by 20 dB(A).

![Noise levels at milling process](image)

**FIGURE 9: Noise levels at milling process**

**CONCLUSIONS**

In this paper, it has been proved that with the developed adaptronical/active clamping system and the implemented MIMO-FXLMS-RLS controller the vibration amplitudes on the workpiece surface and the noise levels during machining are reduced by maximal 25 dB and 20 dB(A), respectively. The designed controller has provided a good convergence and a superior stability behavior.

**REFERENCES**


