Modern paper machines have building-like dimensions of more than 100 m in length and up to 12 m in width and impressive production speeds of up to 120 km/h. A mixture of cellulose fibers and water (the main ingredients for paper making) is fed onto a moving screen, which in paper technology is called “wire.” In the wire section, a large portion of the water drains through the wire, but the fiber web is still wet with very little consistency. Then, revolving felts carry the web through the nip of two press rollers that squeeze more water out of the paper. In the following drying section, heat removes the remaining water. Many product parameters such as thickness, grammage (mass per unit area), ratio of fibers to other ingredients, fiber orientation, and surface texture must be kept within tight limits. Because the manufacturing process is complex, high product quality can only be achieved with advanced control techniques.

One of Sulzer Innotec’s customers had trouble with a newly commissioned paper machine. Cross stripes occurred in the paper at irregular intervals and limited the printability of the product. In the affected paper areas, the stripes occurred at intervals of 0.2 to 0.5 m, and the paper density was reduced. Several conventional approaches for reducing the cross stripes were unsuccessful. A comprehensive vibration analysis revealed that the variations in paper density were caused by a superposition of many discrete frequencies and that they were correlated to vibrations of the headbox. It was presumed that the vibrations were excited when variations in felt thickness passed through the press section.

Active vibration control for paper machines

Controlling complex vibrations

Although paper is a low-cost everyday commodity, it requires a high-tech precision manufacturing process. In paper machines, complex vibration problems can occur which substantially affect the paper quality. Sulzer Innotec has developed an innovative approach to control the vibrations.

Vibration control ensures high product quality.
These vibrations were then transferred through the structure of the building as indicated in Fig. 1 and amplified by structural resonances of the headbox. This resulted in variations of the headbox opening (slice lip, Fig. 2), which consequently affected the paper density. Overall, five different sources of vibrations were found:

- Three felts within the press section of the machine (period of circulation ≈2 s)
- The drive mechanism of a particular roll (frequency ≈23 Hz)
- Residual reaction forces of the shake mechanism that drives the breast roll (frequency ≈8 Hz)

**Innovative feed-forward concept**

Sulzer Innotec developed and implemented an active vibration control system to cancel the vibrations at the headbox. In contrast to passive damping concepts, this system actively applies forces to the vibrating machine component. The Machinery Dynamics and Acoustics group of Sulzer Innotec has broad expertise in this technology from earlier fundamental research projects. Nevertheless, the scale-up of the technology from lab demonstrators to an industrial application required a considerable engineering effort. An innovative feed-forward approach was used to...
How does the feed-forward active control work?

- Vibrations due to felts, rollers, and shake mechanism are superimposed and reach the headbox. The resulting vibrations of the headbox are to be canceled.
- Sensors measure the timing of the revolutions of the vibration sources and deliver trigger signals to the controller. This method is called feed-forward control. In contrast, conventional feedback concepts only measure the vibrations at the headbox and use them as input signal as well as for the adaptation algorithm.
- The controller calculates the necessary forces to be exerted by the electrodynamic actuators. These are mounted on the headbox front wall and cancel the vibrations.
- A residual vibration sensor measures the remaining vibrations of the headbox. This feedback is used to optimize the parameters of the control algorithm.

More details of the control algorithm can be found in the publication listed below1.

![Diagram of vibration control system]

Simultaneously cancel the vibrations caused by five different periodic sources with fundamental frequencies between 0.4 Hz and 25 Hz. The applied feed-forward concept has fundamental advantages over feedback configurations. In feedback systems, the level of cancellation is limited because the residual vibration signal becomes very weak and noisy when the cancellation approaches the optimum level. Furthermore, feed-forward control typically provides superior stability and adaptation performance, so that the additional complexity of the trigger sensors is worthwhile. The basic approach is explained in the infobox.

**Successful industrial implementation**

The sensors for the felt triggers are optical detectors. A black mark, which must not be bleached by the process, is applied to each felt. For illumination, a long-life LED is used. Soiling of the optics is prevented by continuous flushing with clean air. Even with these provisions, a reliable trigger signal cannot be guaranteed under all circumstances. Therefore, the algorithm monitors the consistency of the trigger signals and, in the case of a fault, disables the cancellation of the corresponding vibration source and displays a warning on the process control system.

Two actuators are attached at two spanwise positions on the headbox. They are based on the inertial mass principle, where the mass is moved linearly by an electrodynamic voice coil drive mechanism. The resulting vertical reaction force, which is proportional to the current, acts on the base of the actuator and, thus, also on the front wall of the headbox. The power required to drive the actuators is only around 30 W.

The algorithm, which represents the core technology in active vibration control, is programmed with MATLAB and runs on a standard National Instruments PXI controller. The performance can be monitored by remote access over the Internet, which also allows software updates to be implemented. All raw signals, harmonic coefficients, and other control parameters are continuously stored for several days, so they can be analyzed in detail if performance issues arise.

**Convincing performance**

When the active vibration control system is started, the controller begins to optimize the parameters for the cancellation signal. This procedure requires some time for the exponential averaging to reach the optimum. Figure 3 shows a typical trend of the residual vibration signal as displayed by the process control system. The RMS (root-mean-square value) of the residual vibration signal follows an exponential descent with a time constant of $\approx 400$ s. A significant reduction can be observed when cancellation is active.

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1. [Publication link]
Figure 4 shows a comparison of the frequency spectra of the residual vibration signal with and without active control. All harmonic components of trigger frequencies (marked with a colored circle) are substantially reduced with active control.

**High potential of active control**

The active control system reduces vibrations due to the known periodic excitation at the residual vibration sensor on the headbox very effectively. Some periodic variations in grammage remain due to residual vibrations of the bottom lip. In the future, a more advanced system could measure the variations of grammage online and use them as a residual vibration signal to further optimize the adaptation procedure.

The implemented system has now been in operation for several years, and has substantially improved the product quality of the paper produced. The system functions autonomously, is very robust, and can be operated without expert knowledge. After a few initial modifications, the system has required hardly any maintenance. The experience gained with this customized implementation of active vibration control is useful for solving other vibration problems with the same basic concept.

![Without control](image1)

**With active vibration control**

![With active vibration control](image2)

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**Active control has various possible applications**

Active control is particularly suited for problems where conventional approaches are not effective enough or are not applicable due to weight or size limitations. Active control can be designed to operate very selectively. E.g., it will not affect system dynamics at frequencies outside the specified range. Possible applications are:

- Vibration isolation of sensitive measuring instruments such as electron microscopes
- Active suspension of cars and elevators
- Active damping of high-rise buildings and bridges
- Active noise control in pipes
- Active noise control in passenger compartments of cars and aircraft
- Active noise control headsets
- Active control of instabilities such as flow, combustion, rotordynamic instabilities

Typically, the control algorithm must be adapted and fine-tuned to the particular applications. This requires some expert knowledge and a considerable engineering effort, which is justified by the good performance. Also, the robustness of the sensors and actuators can be critical, depending on the application. The computing power of low-cost digital signal processors is ample and is generally not a limiting issue.

More information: [www.sulzer.com/machinery-dynamics](http://www.sulzer.com/machinery-dynamics)

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**References**