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EXECUTIVE SUMMARY OF THE THESIS

Extracting periodic signals from machine direction product quality variation

LAUREA MAGISTRALE IN MECHANICAL ENGINEERING - INGEGNERIA MECCANICA

Author: Carlotta Massotti
Advisor: Prof. Marco Tarabini
Co-advisor: Assistant Prof. Raine Viitala
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1. Introduction

In many production processes, rotating rolls are used to form the final product. This is the case for papermaking, steel and non-ferrous metal manufacturing, and plastic film production. Imperfections in the roll geometry, caused by the manufacturing process, and errors in the mounting procedure generate vibrations in the machines. These vibrations affect the quality of the end product. In particular, the final quality is subjected to periodic variations, with a periodicity that depends on the rotational frequency of the rolls [2]. The extent of the variation imposed by a single roll is related to its run-out, which is the sum of the central axis movement and the surface roundness profile.

To reduce production waste and, therefore, increase production efficiency, it is fundamental to measure and control quality variation. Different quality parameters can be measured on the final product and their variation can be categorized in terms of amplitude, frequency, and direction. The main directions in which the paper is examined are machine direction (MD), the direction of the flow of material in the machine, and cross direction (CD), the direction perpendicular to MD.

Nowadays, sensors placed on the machine, measuring, for example, vibrations or acoustic emissions, are used for conditioning monitoring purposes. Moreover, different paper parameters are continuously measured in the end product but, currently, there is no procedure to directly relate quality variation to a specific component of the machine. This study analyzes a method to separate the effect of machine components, particularly rolls, on paper parameter variations in MD.

It was already demonstrated through several past studies (for example [3] and [2]) that defects in machine rotating components manifest themselves in the signals acquired by the sensors measuring product quality parameters as harmonics with a frequency that is equal to or a multiple of their rotational frequency. As an example, roll unbalance manifests in parameter variation occurring one time per revolution while bending stiffness variation two times per revolution.

This means that the frequency of occurrence of a defect remains constant from when it is generated until when it is measured. When the product passes through the rolls the material stretches and the distance between defects increases (Figure 1). However, the thickness of the

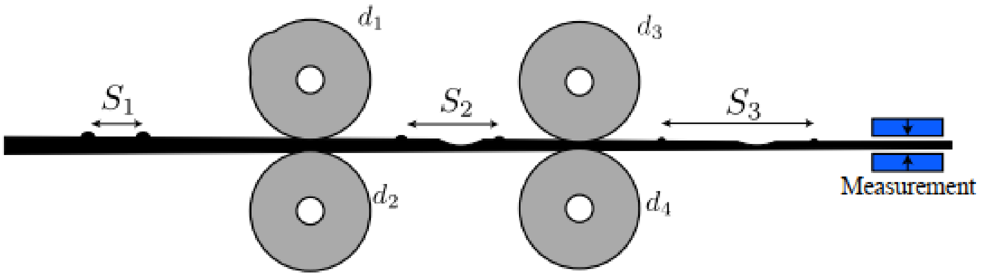

Figure 1: Distance between defects along the machine. When the product passes through the rolls the material stretches and the distance between defects increases.

paper decreases as well, and if no volume of material is lost, the velocity increases. In this way, the temporal frequencies of the phenomena remain constant through the production line even though the spatial frequencies change.

In theory, the Discrete Fourier Transform (DFT) can be applied to estimate the signal spectrum and to extract the harmonic components. Although it is a very light method from the computational point of view, it presents some limitations. The DFT, indeed, has a frequency resolution limited by the sampling frequency and the length of the signal, i.e., $\Delta f = f_s/N$, and it is not efficient in presence of a high level of noise. In paper machine manufacturing many rotating machine elements have almost identical sizes and rotational speeds and the measurement environment is quite noisy. The proposed method, which is an optimal filter inspired by the principle used in the Amplitude and Phase Estimation (APES) method, overcomes some of the limits of the DFT, having as its main advantage the possibility to arbitrarily choose the frequency to be extracted, regardless of sampling frequency and DFT bin spacing.

2. Materials and Method

The method is first applied to different artificially generated signals to test its effectiveness and limitations and then to data measured on a strip of paperboard. A comparison with existing software able to extract the periodic patterns from signals measured offline is also performed. Two sets of data from a paper production line are available. One is acquired online, on the running machine, and the other offline, through laboratory instruments.

2.1. Optimal APES filter

As previously stated, the selected method is an optimal filter based on the principle of the APES method. The selected type of filter is optimal in a mathematical sense since it minimizes the mean square error between the filter output (y_k) and the desired output ($\hat{y}_k$) under the constraint that the filter should pass the content at specific frequencies undistorted. It is therefore formulated as a convex optimization problem with equality constraints (Equation 1).

$$
\begin{aligned}
P = \frac{1}{G} \sum_{n=M-1}^{N-1} |y_k(n) - \hat{y}_k(n)|^2 \quad s.t. \\
\mathbf{h}_k \mathbf{z}(\omega_k l) = 1, \quad \text{for} \quad l = 1, \dots, L_k.
\end{aligned}
\tag{1}
$$

The chosen filter is specifically designed for periodic signals, and this makes it suitable for this application. The desired output, in fact, is defined as a sum of sinusoids with frequencies multiple of a fundamental frequency. Moreover, the method is efficient for different values of signal-to-noise ratio (SNR) and signal-to-interference ratio (SIR) [1].

One of the filter hypotheses is to have as input a stationary periodic signal of N samples, affected by white Gaussian noise and composed of a limited number of harmonics, L_k. Additionally, the filter length M must be lower than N/2+1.

In this case, it is reasonable to model the signal produced by the machine elements as a periodic multi-pitch harmonic signal consisting of sinusoids with different amplitudes and frequencies that are integer multiples of the fundamental frequencies. The fundamental frequencies of the signal should correspond to the rotational frequencies of the rolls. The length of the signal, N, and of the filter, M, should be chosen to ensure stationarity and as a trade-off between accuracy and computational complexity.

2.2. Tests on synthetic and measured data

In an industrial application, the hypotheses of the method are not entirely satisfied. Therefore, a synthetic signal is built, and the filter is applied in non-ideal conditions, to verify its applicability. The synthetic signal is generated based on the analysis of measured data. It is composed of 9 harmonic series, having different fundamental frequencies. The base frequencies are chosen from the list of roll frequencies of a paper production plant. Each harmonic series is composed of 30 harmonic components with exponentially decreasing amplitude values. It is impossible to exactly define the type and the amplitude of the noise in the production environment, which is caused by the structure vibration, electrical noise, and measurement noise. For this reason, different types of noise, white and pink, and RMS values are analyzed.

The filter requires as input the frequency to be extracted. One possible problem can arise when the frequency of occurrence of defects does not perfectly correspond to the set point of the rotational frequency. This can be due to some loss of material or a commonly used control strategy that consists in adjusting the rotational frequency, making it oscillates around the set point. A frequency detection is proposed as a solution to this problem. A range of frequencies containing the set point is defined. The filter is applied for the frequencies of the interval chosen, starting from the lowest one, and the RMS of the extracted signal is computed. The algorithm stops when a maximum of the RMS is found, and the corresponding frequency is selected and used to extract the final result.

Tests are conducted to evaluate the effect of different signal lengths and non-stationarity in the signal. The ability of the filter to reject noise and distinguish two similar frequencies is also analyzed. In all the cases, performances are evaluated by computing the signal-to-distortion ratio (SDR). The parameter is calculated as the inverse of the RMS of the difference between the extracted signal and the generated one. The closest the signals are, the lower the RMS value of their difference and the higher the SDR.

After performing tests on the synthetic signal, the filter is also applied to the measured data. Generally, different parameters can be measured to evaluate paper quality, such as thickness, gloss, moisture, or basis weight. The relevant parameters depend on the grade and end use of the produced paper or cardboard. Quality parameters can be measured online with a quality control system (QCS) placed at the end of the machine or offline in laboratories. In this case, caliper and basis weight measurements acquired online and offline on the same strip of paperboard are available. The online data are acquired with a sampling frequency of 25 Hz, while offline data have a resolution 40 times higher.

The filter is applied to the signals to derive the impact of each roll on the quality parameters and list the rolls according to how much they affect the quality. The influence of each roll on the quality variation is estimated by computing the RMS of the signal obtained by applying the filter to the original signal, considering an input frequency equal to the rotational frequency of the roll under investigation.

A final comparison with a software currently used in the laboratory analysis of paper quality is performed. This software can extract from the signal acquired offline by an analyzer the effect of the machine components with the highest impact on quality.

3. Results

One of the tests performed on the synthetic signal is done by varying the signal length and computing the SDR for all 9 fundamental frequencies of the signal. The result is shown in figure 2. As expected, the performance increases by increasing the number of samples, especially for the lower numbers of samples, at the expense of the computational time. To clarify the meaning of the SDR parameter, an example is reported in figure 3. In this figure, the amplitude values of the harmonic components obtained by extracting one of the harmonic series of the signal are reported and compared with the ones of the corresponding series in the generated signal. In this case, the SDR is equal to 4.48 µm. To this SDR value corresponds an average error of 0.014 µm in the amplitude values. The other results obtained on the generated signal are commented on in the *Section 4* of this article.

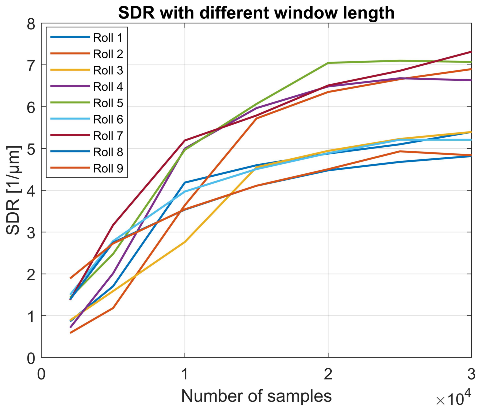

Figure 2: Performance evaluation for different numbers of samples when the signal is built with a sampling frequency of 1000 Hz. The outcome is shown for all 9 fundamental frequencies of the signal.

In the followings, the results obtained by applying the filter on the set of data measured offline are reported. Indeed, after some experiments on the online measurements, it is concluded that the results obtained with these data are not reliable due to the low sampling frequency. As an example, the rolls with the highest impact on caliper variation are reported in Table 1. The higher the RMS of the output signal, the higher the impact of the roll. Figure 4, instead, shows the effect of the thermo roll in the calender section on the caliper. Only the first 10 harmonic components are extracted, being the most significant. The high amplitude of the first harmonic component indicates that the caliper variation is mainly caused by defects occurring once per revolution, e.g., a roll deflection.
Regarding the comparison with the software cited before, the result is shown in Figure 5. The frequency extracted by the software is 3.64 Hz. This frequency is close to 3.566 Hz, the frequency of a component in the machine. The optimal filter is applied with a frequency detection in the range $\pm 0.5\%\omega_0$ where ω_0 is equal to the frequency of the machine component, 3.566 Hz. The fundamental frequency detected by the optimal filter is 3.560 Hz.

4. Discussion

From the tests done on the synthetic signal, it can be stated that, as expected, the performance improves by increasing the number of samples.

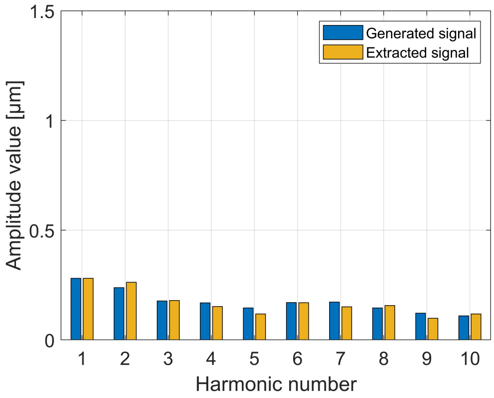

Figure 3: Bar plot of the amplitude values when the extracted frequency is 8.585 Hz. SDR: 4.48 1/µm. Average error in the amplitude values: 0.014 µm.

On the other hand, the computational time increases with $\mathcal{O}(N^3)$. The calculation can be parallelized to decrease the overall computational time. Thanks to parallelization, the effect of all rolls can be extracted together instead of in sequence. The window length must be chosen according to the minimum acceptable level of performance, and therefore it depends on the specific application. For example, for a signal with white noise characterized by an SNR almost equal to 1.5 and a window length of 20000 samples, an average error in the amplitude values of the harmonic components of 0.014 µm is obtained in the worst case. However, the performance is not only connected to the number of samples but also the sampling frequency. Lowering the sampling frequency, the maximum detectable frequency decreases, but a higher performance is obtained using the same number of samples. Moreover, the signal length should be chosen to reduce as much as possible non-stationarity. The filter is found to have a bad performance when the signal to be extracted presents a base frequency variation.
The filter shows quite robust behavior when pink noise is added to the signal, even though this disagrees with the hypothesis. With pink noise, the filter can still extract the periodic signal of interest but with lower performance, especially for the lowest frequencies, which are more affected by the noise.
The filter is not able to completely reject the noise. Indeed, when the filter input frequency is absent from the signal, the amplitude of the

Roll	Rotational freq. [Hz]	RMS [µm]
Thermo roll in valzone calender	2.352	1.328
Deflection-compensated calender roll	4.539	1.084
Forming roll in the body wire	2.439	0.833
Press 1 pick-up driving roll	3.730	0.819
Back wire driving/pulling roll	3.094	0.777

Table 1: Rolls with the highest impact on caliper variation.

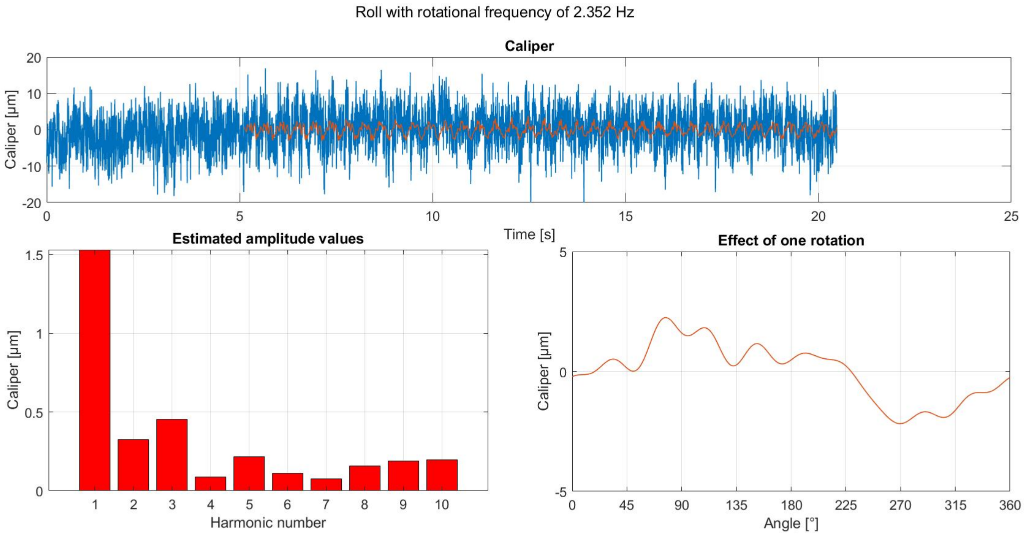

Figure 4: Impact of the thermo roll in the calender section on caliper variation. The top figure shows the caliper signal (blue) together with the signal extracted by the filter (red). The bottom figures show the amplitude values of the extracted harmonic series and the effect on the caliper of one revolution of the roll.

Figure 5: Comparison between the signal extracted by the SOS tool and the one extracted by the optimal filter.

harmonic components extracted by the filter is not null. However, the noise is attenuated by passing through the filter, especially for lower noise levels.

In case of a wrong input frequency, frequency detection brings an improvement in the results. When this procedure is applied, the method is almost insensible to errors in the input frequency.

Lastly, the capability of the filter to separate the effect of similar frequencies is limited. The filter performance strongly decreases when the difference between two frequencies is around 0.02 Hz. Particular caution should be exercised in the presence of such similar frequencies.

Without additional information from the production environment, it is impossible to evaluate the correctness of the results when dealing with measured data. However, the frequencies of the peaks visible in the signal spectrum correspond to the fundamental frequencies of the extracted signals with the highest RMS.

Furthermore, the filter leads to a better result than the existing software. Indeed, the frequency found by the filter is closer to that of the machine component than that found by the software. Additionally, the current software is not suitable as a condition monitoring tool since it can only be used offline.

In general, the number of harmonics to extract should be chosen according to the application. The target is to reproduce the most significant part of the signal. For high harmonic numbers, the amplitude value is generally small and can be confused with noise.

5. Conclusions

This work analyzes a procedure for separating repeating patterns from machine direction quality variation. This can be used to monitor the condition of the machine and act on the component or machine section that causes the highest variations.

The filter was first applied to a signal generated to reproduce realistic situations that deviate from the ideal condition. The aim was to test the robustness of the method when some of the hypotheses are not satisfied. Subsequently, the filter was applied to available measured data from a production plant. Satisfying results were obtained in both cases, and the filter was finally validated through a comparison with a currently used software, showing an even better result.

This work represents an initial study of the method. It does not provide a ready-to-use tool for industries.

As a first improvement, better understanding the type and amplitude of the noise in the machine environment can help generate an artificial signal that more closely reproduces the real one.

To complete the study, further tests should be performed on the data acquired on the running machine. The sampling frequency of the available set of data was, in fact, too low to provide good results.

Another interesting analysis might be to collect signals related to different quality parameters to understand which sections or components impact a particular parameter the most. For example, the press section can have, in general, a higher impact on basis weight.

Additionally, simulations in the production environment should be carried out to have practical feedback on the results and to modify the choice of filter parameters according to the outcome.

A further possible investigation is to compare the extracted harmonic series with known roll run-out data to determine if they are correctly related.

Finally, to improve the accuracy of the result, data should be acquired on different CD positions, deriving the outcome as an average of the results obtained for each point. In the present case, the probe of the sensor was held stationary in a single position.

References

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