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# Interactive data visualization of chatter conditions in a cold rolling mill

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ABSTRACT

Rolling of flat steel products is an industrial process in the field of metalworking where two or more pairs of rolls reduce the thickness of a steel strip to produce a uniform thickness material. Despite it has been studied for many years, there are still unpredictable problems that can affect the final quality of the product. One of them is the so-called *chatter*, that is a powerful self-excited vibration that appears suddenly and limits the productivity of the process. In this paper, a visual analytics approach is considered for exploratory analysis in order to discover and understand the factors and conditions under which chatter appears. An interactive web-based interface is presented here which allows the user to explore a map of dynamical conditions and visualize relevant details of each chatter onset. A validation case is performed using real data where normal/fault conditions have been identified automatically. By means of interactive exploration, the tool allows to refine an automatic chatter detection method. Moreover, it is shown to reveal correlations between variables, providing in some expected cases data-based confirmation, but also revealing less obvious relationships. Finally, it provides context, allowing to carry out comparative analysis, both qualitative and quantitative, for different subsets of coils (e.g. different years) as well as for different working conditions.

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## 1. Introduction

The rolling process transforms the shape of a steel material by means of a thickness reduction passing it between two or more pairs of rolls held by a mill stand. This process is different depending on the temperature of the rolled material. Precisely, a cold rolling mill [21] produces smoother finished products with a uniform exit thickness, commonly performed continuously through several stands in tandem mills. Despite it is an universal process in metalworking, there are still problems that cause economic losses in modern rolling mills. Moreover, the conditions under which these problems arise are not completely understood, making it difficult to prevent their occurrence.

One of the main problems is a self-excited vibration mode called *chatter*, that appears in rolling operations, provoking unacceptable gauge variations in the final surface of the strip, as it is explained in [26]. The removal of chatter is performed by means of a decrease in the rolling velocity. This involves a loss of productivity which makes chatter not only an industrial concern but also an economic one. The analysis of chatter requires understanding the conditions that lead to the instability of the process. The dynamic interactions between structural phenomena in the mill and the rolling process have been studied along years using theoretical models [18,1,30,19,31]. However, these models may be too complex with a large amount of parameters to be applied easily or have so many assumptions that excessively simplify the real problem. Tuning these models to suit a particular facility can be very costly requiring the availability of process data and calibration/optimization methods to estimate the model's parameters. On the other hand, rolling mills involve a large amount of interactions featuring coupled thermal, mechanical and computer systems for control. Besides being complex, their dynamics are constantly evolving as a result of changes in the mechanical properties of rolling elements, misadjustments, changes in the working point, etc. Also, the same model needs to be retuned if applied to other mill, even if it is of the same characteristics. All this poses the need for data-based approaches, that are based on the actual behavior of the process.

The current technologies facilitate data acquisition of many parts of a process, described by a large number of variables, and their massive storage in databases is a very common procedure. *Intelligent data analysis* (IDA) algorithms extract information automatically in order to discover new knowledge that may have stayed hidden. A proper visual presentation of the results from these algorithms is an excellent way for communication [27] and efficient interpretation which supports the decision. The so-called

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*visual analytics* (VA) methods exploit the combination of automatic computations with visualization techniques to support analytical reasoning through interactive interfaces [25,13]. In this way, the use of data visualization, machine learning and agile user-interaction mechanisms makes the analysis be supported by user's expert knowledge and empower intuition, while providing at the same time with solid quantitative information based on computations on the actual data.

In this paper, an approach to chatter analysis using the VA paradigm is proposed, allowing the user to explore the dynamical conditions of the process. This is done through an interactive web-based prototype, where automatic algorithms extract dynamic behaviors of normal operation and chatter fault from real data. These dynamic behaviors, characterized by high-dimensional feature vectors, are represented on an interactive interface where the user can explore them and get details on demand. This is performed by means of several views showing a spectrogram display, a 2D map of dynamic conditions and barcharts, including interactive mechanisms which provide coordinated links between all these views. The paper is organized as follows: in Section 2 previous works of analysis of the process and related data analysis methods are reviewed; in Section 3 data analysis methods for dealing with chatter fault are proposed; in Section 4 a real validation case is described and a web application design is presented; finally, Section 5 concludes the paper and suggests directions for future work.

## 2. Related work

Vibration phenomena appear in rolling processes as a result of dynamic interactions [26] between the mill stand structure and the strip material. There are two main different vertical vibration modes, third-octave-mode chatter (120–250 Hz) and fifth-octave-mode chatter (500–700 Hz), being the former one more harmful, that occurs suddenly, accumulating a large quantity of energy within a few seconds, so that chatter is referred here as this third-octave-mode vibration. Several works have studied this phenomenon along many years, the earliest studies are [30,19], or [24] that define chatter as self-excited vibration and they study possible causes through models.

In [31] several models for the structure of the mill and the rolling process are reviewed and then combined to obtain chatter models. For the case of the structural model, the classical ones are based on the mass-spring system, where forces are represented in terms of stiffness and damping. Since some of these models assume symmetry with respect to the roll gap, only the top part of the mill is considered in the analysis.

The models for the rolling process are mathematical expressions related to rolling parameters that help in determining, for example, roll force, torque, neutral point, strain, etc. They involve coefficients such as yield stress and friction, which can vary during the process [18,1].

Later, more works were made considering not only a static analysis but also a dynamic one in order to obtain a better understanding of the problem [10,11]. In [29] a single-stand chatter model in state-space is proposed coupling models for the dynamic rolling process, the stand structure and the hydraulic servo system and it is simplified to perform a robust thickness control. A multiple-modal-coupling dynamic model is proposed in [32] to characterize the coupling relationship between mill structure and the rolling process. The optimization of rolling parameters and their influence on the system stability are studied in [6]. Also the use of multistand models in tandem mills explained in [12] increases the complexity of the study. However, there still remain issues to fully understand the conditions which lead the system to this instability.

Recently, more models related to chatter have been proposed. For instance, a rolling force fluctuation model is proposed in [28] to identify chatter marks. Furthermore, time delay effect in tandem mills is analysed in [15] showing its influence in the change of the optimal parameters. Besides, wave propagation theory is studied in [17]. Simulation and experimental data of two stand rolling mill are compared and predicted values for chatter frequency and critical speed present low error values. Other models introduce friction, which is an important factor in mill vibration. Examples include a numerical model based on friction models in [8] where it is shown that friction coefficients of a two stand rolling mill are dependent, or models based on unsteady lubrication whose results show a direct correlation between critical rolling speed and limiting shear stress in [7], and the replication of chatter conditions in [9]. Many existing chatter models are valuable in providing insight into the problem. Also, they can be very effective, provided a proper parameter adjustment is done.

Data analysis algorithms extract information that can be used to understand and support decisions. A particularly well-known approach in this field are *dimensionality reduction* (DR) techniques. These methods allow to project high-dimensional data points on a low-dimensional latent space – typically 2D or 3D –, which can be visualized. A detailed revision of these techniques can be found in the book of [14]. Some of these data-based methods were applied to study dynamical conditions in real scenarios previously. For

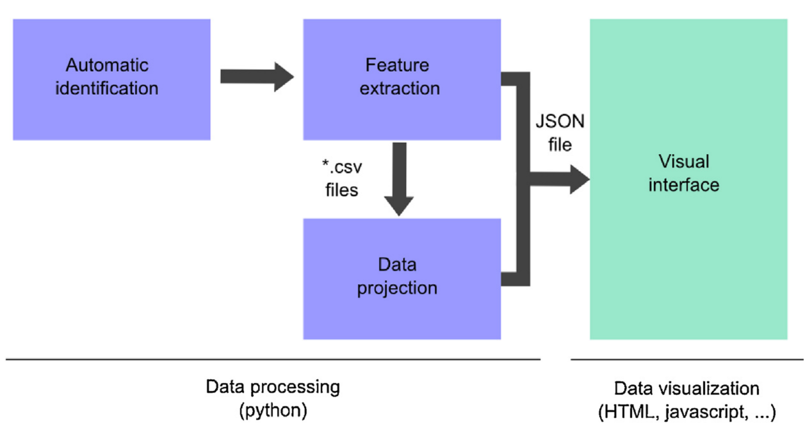


**Fig. 1.** Scheme for the method where dynamic features are projected on a visualization space for data exploration.

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