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Audio signal analysis for tool wear monitoring in sheet metal stamping

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ABSTRACT

Stamping tool wear can significantly degrade product quality, and hence, online tool condition monitoring is a timely need in many manufacturing industries. Even though a large amount of research has been conducted employing different sensor signals, there is still an unmet demand for a low-cost easy to set up condition monitoring system. Audio signal analysis is a simple method that has the potential to meet this demand, but has not been previously used for stamping process monitoring. Hence, this paper studies the existence and the significance of the correlation between emitted sound signals and the wear state of sheet metal stamping tools. The corrupting sources generated by the tooling of the stamping press and surrounding machinery have higher amplitudes compared to that of the sound emitted by the stamping operation itself. Therefore, a newly developed semi-blind signal extraction technique was employed as a pre-processing technique to mitigate the contribution of these corrupting sources. The spectral analysis results of the raw and extracted signals demonstrate a significant qualitative relationship between wear progression and the emitted sound signature. This study lays the basis for employing low-cost audio signal analysis in the development of a real-time industrial tool condition monitoring system.

1. Introduction

Sheet metal stamping is the most frequently used primary manufacturing method for mass-production of automotive body and structural components. Since, global automotive production exceeds 60 million vehicles per year, and there are over one hundred sheet metal components on average in each car, this potentially has a very significant number of applications even for just the automotive industry alone. Hence, even a small improvement could be highly influential to the product quality and cost efficiency. The increasing trends towards advanced- and ultra-high strength steels (AHSS and UHSS) in the automotive industry for continued vehicle light-weighting has increased forming forces, die wear and galling and, therefore, has resulted in premature die failures. These faults are difficult to predict at the design stage and may lead to expensive tool replacements and additional costs due to poor part quality, machine downtime and unscheduled maintenance [1]. Hence, stamping tool condition monitoring is a timely need. The aim of implementing a monitoring system is to achieve uninterrupted production and prevent the adverse consequences described. However, current techniques for assessing tool wear and part quality rely on manual visual inspection of formed part surface quality or the tool surface condition. These methods only provide information about the state of the tooling after the wear has become severe and, therefore, can be too late to prevent production downfall. Hence, it is a non-trivial requirement to have a system for online

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monitoring of tool condition that can provide the early detection of tool wear and identification of the current tool state.

Du et al. [2] presented a comprehensive review on the sensing and online monitoring techniques for sheet metal stamping processes. Other earlier reviews and research articles [3–6] provide evidence of progress in this area, but still demonstrate the current need for a high-performance condition monitoring system. Tonnage or force monitoring has been the most popular [7,8] while other commonly used sensors include acceleration [9], proximity, optical [5,6], and acoustic emission [10,11]. Du. et al. [2] reviewed strain, acceleration, force and proximity sensors and argued that force and proximity sensors could be effective, but the sensor cost is too high. Acceleration sensors are cost effective, but very high computational power is necessary to convert the signal into useful information. Strain and acoustic emission sensor signals are rich in wear information, but can be difficult to install, since they must be mounted on the tool or sheet surfaces [12]. Despite this research, there is still an unmet demand from manufacturing industries for a low-cost easy to set up condition monitoring system which is capable of detecting the onset of wear.

Audible acoustic sensors (microphones) have a higher potential to meet this demand compared to other acoustic sensor types - such as vibration (acceleration) and acoustic emission sensors - due to their low-cost, non-disruption to the ongoing operation and simplicity in sensor placement and setup. However, the high sensitivity to background noise has hindered the employment of microphones in real applications. Audio has been employed in many other manufacturing applications, except stamping, such as diesel engine injection monitoring [13], rolling element bearing defect detection [14] and monitoring of machining/cutting operations such as turning [15–17], micro milling [18,19], and drilling [20,21]. Downey et al. [22] conducted audio analysis to study a single point machining operation in an environment where no other machine operations occurred at the same time. Unfortunately, this will not be the case in a real production environment. Additionally, this study and other research works [12,23] were founded on the characteristic that experienced operators can differentiate the good quality and degraded process conditions by hearing changes in the emitted sound. Depending on the manufacturing process and application examined, the emitted audio signal characteristics in both time and frequency domains can significantly vary as evidenced by the wide range of literature findings. For example, Eneyew et al. [20] observed a decreasing trend of sound amplitude with the number of holes drilled, while Downey et al. [22] detected an increasing trend in amplitude with the number of machining cycles. A shift in signal energy from a lower frequency range to a higher frequency range is observed with wear formation in micro-milling operations [12] and in turning operations [15]. However, in metal cutting it has been shown that higher amplitude signal peaks appear in the upper frequency range for sharp tools and in the lower frequency range for worn tools [24].

However, these existing techniques focus on identifying few distinct wear levels or faults such as slug, misfeed, or tool breakage. Furthermore, to the authors' best knowledge, no work in the literature has examined the use of audio sensors for progressive wear monitoring in sheet metal stamping. One of the reasons for this may be that even an experienced stamping process operator cannot distinguish the wear state of the tools by relying on his/her hearing. Hence, it is still unknown if emitted audio carries any information about wear progression of the stamping tools. To ensure this, it is necessary to obtain the audio emitted by stamping. However, it is not straightforward to isolate the stamping signal since most of the industrial production lines use mechanical presses with progressive die sets or transfer press systems, which integrate several operations – such as piercing, trimming, feeding, clamping, restrike, etc. –within a single stamping press stroke. Our recent work [25] has shown that these additional operations may emit higher intensity sound signals compared to stamping, making it difficult for the human ear to recover the stamping signal.

Therefore, it is particularly useful to determine firstly if the emitted sound from the stamping operation contains any useful information related to wear progression. If this is the case, sound-based condition monitoring systems would be highly preferred by manufacturing industries due to the advantages discussed earlier. In the studies discussed above, several techniques have been developed/employed for data processing based on fast fourier transform (FFT) analysis, cepstrum, wavelet analysis [26], singular spectrum analysis (SSA) [16,17], and Hilbert Huang transform (HHT) [27,28]. Speech recognition systems [23], pattern recognition systems [24], neural network systems [29], and support vector machines [16] have been used in the decision making phase. Nevertheless, there is a lack of robust methods which consider the disturbances by other processes/components of the machine and background signals. This point is a key impediment for application to the real production environment, and therefore, there is a need for techniques to recover information from corrupted sensor signals.

Blind signal separation (BSS) is an effective technique capable of recovering unobserved source signals from observed mixtures without any information of the mixing system [30–33]. BSS first emerged as a biological problem in 1982 and then evolved to successful usage in several applications such as communication, audio processing (speech and music) and image processing [34]. BSS also has been employed in mechanical applications, including rotating machinery condition monitoring [35,36], fault detection [37] and condition monitoring of manufacturing processes like milling [38–40]. Among the BSS techniques for manufacturing process monitoring, Shao et al. [38] and Shi et al. [39] focused on single channel source separation, using power signals and audio signals respectively. Both of these studies face computational complexity due to the selection of a single sensor to deal with higher sensor cost and installation inconveniences. As initial studies, they have conducted experimental analysis on the extreme conditions (i.e. sharp tool condition against severe tool breakage) and have noted the need for future investigations into minor tool breakages or tool wear. The direct usage of above techniques for our application is hindered because the BSS algorithm development depends on original source characteristics, which differ from application to application.

Hence, a blind signal separation technique, appropriate for the application, should be developed. Since the knowledge of original signal characteristics and the mixture model is unavailable, system parameterization was necessary and was previously conducted by Ubhayaratne et al. [25]. In this analysis, the audio signals generated by the stamping operation were modeled as a BSS system and a simple semi-blind signal extraction technique was developed. This is not a final signal separation solution. However, it served the purpose of recovering the stamping signal so that it could be employed in studying the correlation between wear progression and audio emissions. However, in [25] this signal extraction technique was tested only on four distinct tool/operation conditions: (i)