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PVDF sensor based on-line mode coupling chatter detection in the boring process

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ABSTRACT

Dynamic instability in the form of chatter vibrations during boring is detrimental to machining process. Therefore, an on-line chatter detection system is required to detect chatter before damage occurs. This paper evaluates a Polyvinylidene Fluoride (PVDF) piezoelectric thin-film based strain sensing system to detect mode coupling chatter in the boring process. In addition, this paper compares the performance of time domain based (autocorrelation), time–frequency based (wavelet transform), and frequency based (Fast Fourier Transform) methods for detecting mode coupling chatter. The PVDF sensor system is demonstrated to be a low-cost solution for detecting chatter in the boring process.

1. Introduction

During machining of gas turbine parts, dynamic instabilities such as chatter vibrations can negatively impact part quality, especially during boring. Therefore, an appropriate sensor-based process monitoring system is required to compensate for process modelling limitations. The majority of literature on chatter detection and suppression in machining is focused on the regenerative chatter mechanism [1–6], which occurs commonly in turning and milling operations performed on relatively rigid machine tools. However, the chatter mechanism in the boring process is primarily due to the difference in orientation between the two principal axes of stiffness and the resultant force vector [7,8]. This chatter mechanism, known as mode coupling chatter, occurs in symmetric low stiffness machining systems including long boring bars and serial link-based robotic milling [9]. While some work on mode coupling chatter modeling and ways to suppress it have been reported [10,11], methods for real-time detection of chatter in boring operations are lacking.

This paper seeks to evaluate a low-cost Polyvinylidene Fluoride (PVDF) thin film wireless sensor system in detecting mode coupling chatter in the boring process. In addition, various chatter detection algorithms suitable for implementation in an embedded system are evaluated for monitoring of mode coupling chatter in boring operations. The embedded chatter algorithms developed for detection of regenerative chatter in turning presented in [12] are extended to the boring process in this paper. Note that due to the differences between the underlying chatter mechanisms, the performance of the chatter detection system is expected to differ, thus contributing to the novel findings discussed in this paper.

2. Methodology

This section describes the mechanism of chatter in boring. In addition, an overview of the PVDF thin film sensor-based chatter monitoring system hardware used to implement and evaluate the boring chatter algorithms is presented.

2.1. Mode coupling chatter mechanism

For mode coupling stability analysis, a schematic of the boring process, as viewed from the feed direction, is shown in Fig. 1. Note that the cutting force is decomposed in the X and Y directions of a rotating frame via the angle α attached to the workpiece.

The corresponding two degree of freedom dynamic system equation without considering damping is:

$$[M]\begin{bmatrix}\ddot{x}\\ \ddot{y}\end{bmatrix} + [K]\begin{bmatrix}x\\ y\end{bmatrix} = \begin{bmatrix}K_{px}\cos\alpha & K_{py}\cos\alpha\\ K_{px}\sin\alpha & K_{py}\sin\alpha\end{bmatrix}\begin{bmatrix}x\\ y\end{bmatrix} \quad (1)$$

where $[M]$ is the effective dynamic mass, $[K]$ is the dynamic stiffness of the boring bar, and K_{px} and K_{py} are defined as the linear

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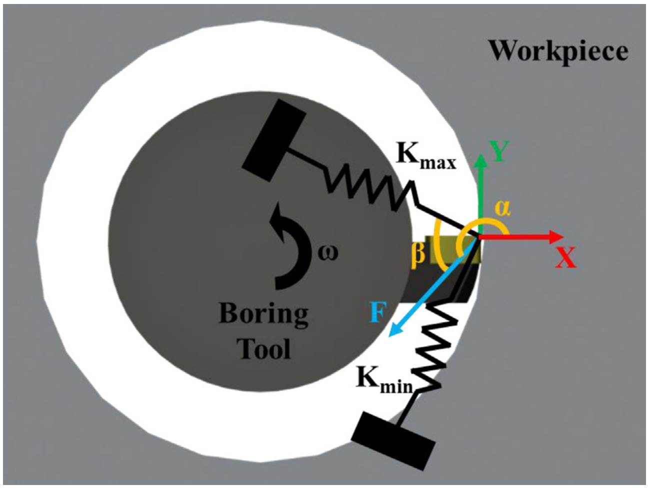

Fig. 1. Schematic of the boring process dynamic model.

sensitivities of cutting forces due to deflections in the X and Y directions (cutting coefficient), which depend on the cutting conditions and the workpiece material. Note that the machining force in the feed direction was not considered because the stiffness in the feed direction is much higher than the stiffness of the coupled modes in the X and Y directions. Also note that since the presence of damping generally increases the system stability, the undamped model in Eq. (1) yields a conservative solution for system stability. Because $[M]$ and $[K]$ are symmetric and semi-positive definite matrices they can be diagonalized by a transformation matrix $[V]$, which results in the following after solving for the acceleration vector [9]:

$$\begin{bmatrix} \ddot{x} \\ \ddot{y} \end{bmatrix} = [A] \begin{bmatrix} x \\ y \end{bmatrix} \tag{2}$$

$$[A] = [V]^T \begin{bmatrix} K_{px} \cos\alpha & K_{py} \cos\alpha \\ K_{px} \sin\alpha & K_{py} \sin\alpha \end{bmatrix} [V] - \begin{bmatrix} K_{max} & 0 \\ 0 & K_{min} \end{bmatrix} \tag{3}$$

where the stability and oscillation frequencies depend on the eigenvalues of $[A]$. Note that the eigenvalues, and therefore their oscillatory terms, do not depend on spindle rotational velocity. The oscillatory frequency for mode coupling chatter has been shown to be near the system's lowest natural frequency mode [10,11]. Hence, the hardware and algorithm for detecting mode coupling chatter must be capable of discerning the natural frequencies of mode coupling susceptible systems including boring bars, which are lower than frequencies encountered in regenerative chatter. Therefore, the robustness requirements of the chatter detection sensors and algorithms differ between chatter mechanisms.

2.2. PVDF based chatter monitoring system

A schematic of the PVDF sensor based chatter monitoring system for boring is shown in Fig. 2. Specifically, the sensing and monitoring system components utilized in this work are as follows:

- A PVDF-based sensor rosette capable of measuring the dynamic shear strains produced in the host structure (boring bar) during boring is used. The PVDF polymer can be laminated onto a sheet of polyester, resulting in a very thin sensor film (~40 μm) thus minimizing its impact on the host structure's dynamics [13]. The sensitivity and capability of the PVDF sensor rosette to measure the dynamic cutting torque signal in boring and its comparison to a quartz-based cutting force dynamometer was demonstrated in earlier work [14]. Two PVDF thin film sensors are mounted 45° from the vertical axis of the boring bar to isolate the dynamic torsional strains (from the bending and axial strains), from which the dynamic cutting torque signal

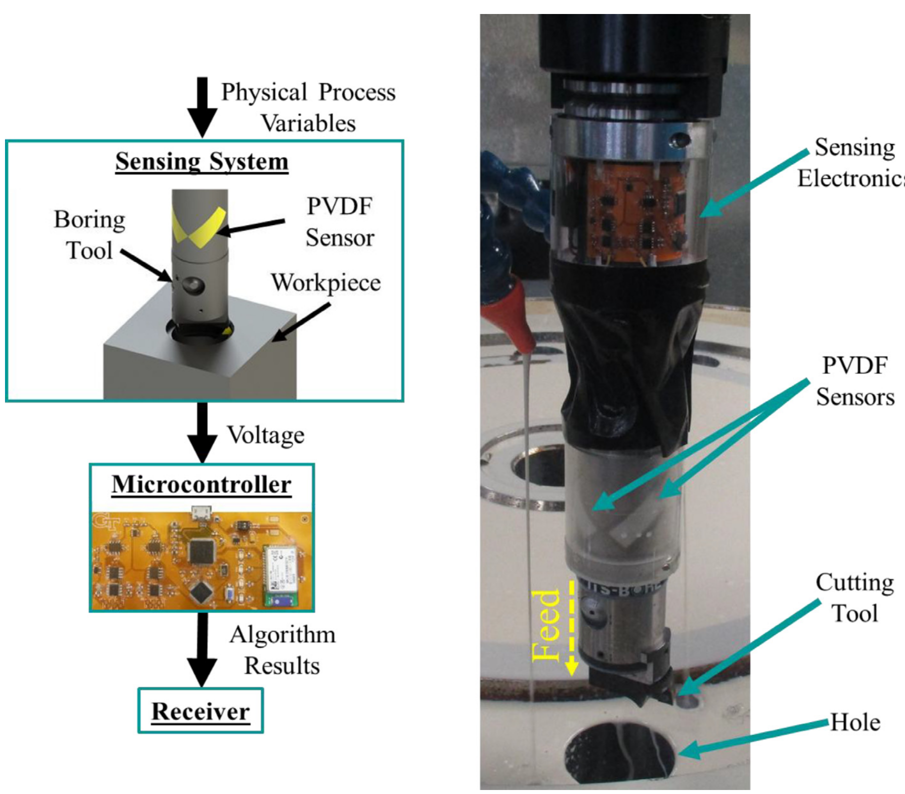

Fig. 2. Schematic (left) and tool path for boring experiment (right).