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Diagnosibility and sensitivity analysis for multi-station machining processes

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Abstract

Dimensional variation is a major problem affecting product quality in discrete-part manufacturing. The stream of variation (SoV) methodology has been proposed as one of the systematic approaches to identify the root causes of process variation based on part measurements. This paper presents the results of the diagnosibility and sensitivity analysis study of the SoV methodology in a multi-station V8 cylinder head machining process used by a major domestic automotive manufacturer. The SoV model of dimensional machining errors has been derived based on the CAD description of the part and CAPP description of the process. Variation patterns of the final product were assessed based on the measurements of 20 automotive cylinder heads machined under normal process conditions, and the relative contributions of each machining station were assessed. In addition, one faulty product was observed and SoV model was used to identify the machining station that caused this quality problem. A *station-level error decomposition* method has been introduced and the SoV model correctly identified the culprit station. Furthermore, the sensitivities of dimensional features of the cylinder head to departures in fixture parameters away from their nominal values are evaluated based on the SoV model. Finally, four major issues arising from this implementation study of SoV in industry have been identified. Those are: non-diagnosibility of available measurements, vectorial representation of features, random sampling of parts at inspection and inadequate level of details in modeling of the process faults.

Keywords: Stream of variation; Multi-station machining process; Diagnosibility; Sensitivity

1. Introduction

Dimensional quality problems due to the process variation are amongst the most critical issues for multi-station discrete part manufacturing, especially for precision parts such as engine blocks, heads or transmission components. Each manufacturing station in one such system introduces errors that propagate through the system and influence the final product quality. As indicated in Fig. 1, product quality errors $x(k-1)$ accumulated in manufacturing stations 1, 2, 3,..., $k-1$ influence the product quality errors $x(k)$ that are present after operations at manufacturing station k. In addition, at any manufacturing station k new errors $u(k)$ are introduced which influence the outgoing product quality $x(k)$. Measurements $y(k)$ of the part quality can potentially be taken after operations at any station in order to depict the outgoing part quality. One should note that the inherent natural process variations $W(k)$ also contribute to the product quality errors $x(k)$ and thus also appear in the measured quality characteristics $y(k)$. Reduction and elimination of the root-causes $u(k)$ of quality problems that are introduced and accumulated in each manufacturing station $k = 1,2,\ldots,N$ would lead to a reduction and elimination of the quality problems in the finished workpiece.

Considerable efforts have been made to establish a mathematical connection between the root causes with the measured part quality characteristics [1–3]. More recently, the so-called stream of variation (SoV) methodology [4,5] was introduced, which explicitly models the flow of dimensional errors from one station to another in the state-space form with the ordering index of the manufacturing

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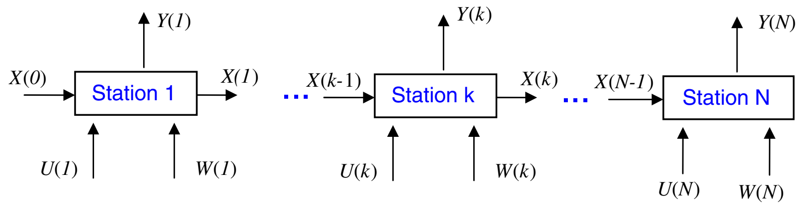

Fig. 1. Dimensional errors flow in a multi-station manufacturing processes.

station playing the role of the time index in the usual state-space models used in control theory. The reported research work in SoV methodology development includes four main aspects:

(1) State-space modeling that links the product quality measurements with process faults [5–8].
(2) Algorithms for extracting fault information [9–11].
(3) Design evaluation for product quality and process parameters [9,12].
(4) Evalutation and optimal selection of measurements and sensor locations [4,13,14].

The aforementioned work pertaining to the SoV-based modeling and applications is mainly theoretical work and all the experimental results have been obtained from a controlled, laboratory environment. In [15], the authors reported a successful industrial implementation of the SoV idea in an automotive assembly plant. However, it utilized the knowledge-based product and process representation and pattern recognition rather than the explicit, analytical modeling of the process. There is currently no research that has been conducted on the application of the linear state-space model based SoV methodology in an uncontrolled, real factory environment.

This paper reports the results of the diagnosibility and sensitivity analysis of the SoV methodology in a real industrial plant, where automotive cylinder heads are machined for one of the major domestic car manufacturers. It also discusses the issues raised from the application of the linear state-space SoV model in industrial environment. The remainder of this paper is organized as follows: Section 2 briefly reviews the SoV linear state-space modeling method for machining systems and describes the applications of this model in the industrial environment. Section 3 shows the SoV modeling results and the application results of this model in the V8 cylinder head machining process. The issues encountered during implementation of the SoV methodology in industry will be discussed in Section 4. Finally, Section 5 offers conclusions of the work presented in this paper and guidelines for possible future work.

2. Linear state-space model of errors in machining and its applications

This section gives a brief review of the linear state-space modeling procedure for a multi-station machining process. In addition, methods for the application of this model in variation analysis and sensitivity analysis are presented.

2.1. Review of the linear state-space modeling for dimensional errors

In this paper, we will follow the procedure for linear state-space modeling of the error flow in machining processes reported in [6]. One must first define the *part coordinate system* (PCS) using a set of ideal workpiece. The PCS is fixed to the workpiece and moves with it through different machine setups. The features describing the PCS can be chosen as features with respect to which most of the workpiece measurements are expressed, or as features with respect to which the dimensions in the part drawing are expressed. In addition, the *machine coordinate system* (MCS) also needs to be defined for each machining station. It is fixed to the machine itself and is not moving as the part progresses through the system. The motion of the cutting tool and parameters of the fixtures in each machining operation can then be described in the MCS. For analytical tractability purposes, the MCS for a given machining station can be defined by the nominal fixture parameters in that station, as was done in [6]. The character and mutual relationship between the PCS and the MCS are schematically shown in Fig. 2.

According to [6,16], each of the n part dimensional features i, $i = 1,2,\ldots,n$ was described after operations in machining station k, $k = 1,2,\ldots,N$ (N is the total number of machining stations in the process) as

$$X_i(k) = [[\vec{n}_i(k)]_p^{\mathrm{T}}[\vec{p}_i(k)]_p^{\mathrm{T}}[\vec{d}_i(k)]_p^{\mathrm{T}}]^{\mathrm{T}}, \quad (1)$$

where $\vec{n}_i$ denotes the feature orientation vector, $\vec{p}_i$ is the feature position vector, $\vec{d}_i$ denotes the vector of scalar parameters corresponding to that feature (e.g., diameter of a cylinder, radius of a curve, depth of a hole) and $[\vec{v}]_P$ denotes the representation of a vector $\vec{v}$ in the PCS (in this case, vector $\vec{v}$ could be the feature orientation vector $\vec{n}_i$ or the feature position vector $\vec{p}_i$).

Errors of each feature after machining in station k were represented as

$$\Delta X_i(k) = X_i(k) - X_i^{\mathrm{nom}}(k)$$

where $X_i^{\mathrm{nom}}(k)$ denotes nominal vectorial CAD description of the feature in the PCS. Stacking up feature errors $\Delta X_{\mathrm{i}}(k)$ for $i = 1,2,\ldots,n$ gives a vector

$$\Delta X(k) = \left[\Delta X_1^{\mathrm{T}}(k)\ \ \Delta X_2^{\mathrm{T}}(k)\ldots\Delta X_n^{\mathrm{T}}(k)\right]^T,$$