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Variation propagation of bench vises in multi-stage machining processes

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Abstract

Variation propagation has been successfully modeled by the Stream of Variation (SoV) approach in multistage machining processes. However, the SoV model basically supports 3-2-1 fixtures based on punctual locators and other workholding systems such as conventional vises are not considered yet. In this paper, the SoV model is expanded to include the fixture- and datum-induced variations on workholding devices such as bench vises. The model derivation is validated through assembly and machining simulations on Computer Aided Design software. The case study analyzed shows an average error of part quality prediction between the SoV model and the CAD simulations of 0.26%.

Keywords: Stream of Variation; quality prediction; machining; multistage processes; fixturing errors.

1. Introduction

Nowadays, many manufacturing lines are based on several stations where sequential manufacturing operations take place. In these facilities, the final product quality depends not only on the quality of each manufacturing operation but also on the effect of previous operations on current stages. This type of processes, which are commonly named Multistage Manufacturing Processes (MMPs), are quite common in industry and the estimation of the final product quality is a challenging task due to the large number of factors and interactions that influence the

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final quality of the product. For illustrative purposes, Fig. 1 shows a MMP where N stations are sequentially placed to conduct different machining operations. At each station, three main source of variations are responsible of part quality error: i) datum-induced variations, which refer to deviations of the features that are used as locating features to hold and locate the part; ii) fixture-induced variations, which refer to the deviations of the fixture components that deviate the location of the part; and iii) machining-induced variations, which refer to deviations of the cutting-tools that produce an error when the feature is machined.

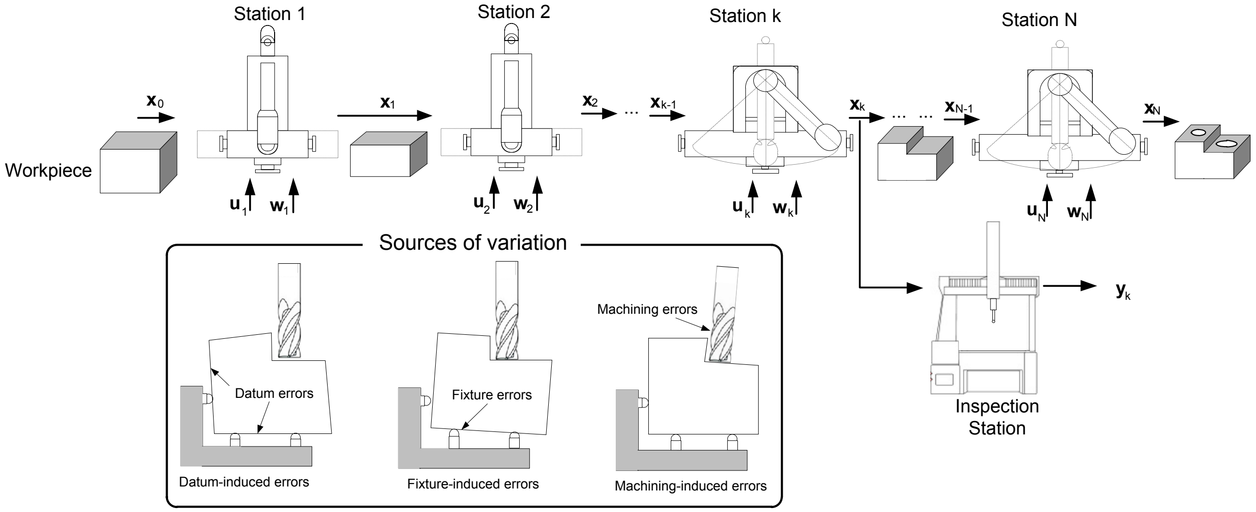


Fig. 1. Multistage Manufacturing Process (MMP) and induced variations that impact on final part quality.

In the literature, two main approaches have been proposed to model the error propagation throughout MMPs. The first approach, the Stream of Variation (SoV), was firstly developed for multistage assembly processes [1] at the end of the nineties and was later adapted for multistage machining processes [2]. This model adopts the well-known state-space model from control theory to represent mathematically the relationship between the sources of variation of a MMP and the deviation of the machined surfaces at each station, including how the deviation of previous machined surfaces influences at current station when these surfaces are used as locating datums. The second approach, the Model of the Manufactured Part (MoMP), was derived for multistage machining systems [3] and it is based on 3D tolerance chains for mechanisms considering the machining set-up as a mechanism. A good comparison of both approaches and the main advantages and drawbacks can be found in [4]. Basically, the SoV model is more focused on process-oriented activities (fault diagnosis, process planning and quality control among others), whereas the MoMP is more focused on product-oriented activities, for instance product tolerance analysis and synthesis.

One of the main criticisms about the SoV model is that the fixtures included into the model are constraint to fixtures based on punctual locators distributed under the well-known 3-2-1 locating scheme. To overcome this limitation, the model was extended by Camelio et al [5] to include N-2-1 fixture schemes with punctual locators in order to hold complaint parts and Loose et al [6] improved the model to include general fixture configurations (not limited to 3-2-1 configurations) based on punctual locators. More recently, the derivation of the SoV model for multistage machining processes to include fixtures based on surfaces was proposed in [7], and the model has been improved and extended for turning operations in [8,9]. However, despite these efforts, it seems that there is no clear and straightforward way to include common workholding devices such as conventional bench vises into the SoV model.

This paper presents a methodology to include the errors of conventional bench vises as a workholding system within the SoV model. The mathematical derivation follows the standard derivation of the SoV model from previous researches [2,7] and thus it ensures the compatibility and the extension of the model. The validation of the model is conducted under Computer Aided Design (CAD) software. This paper is organized as follows. First, Section 2 overviews the methodology for the generation of the SoV model in order to identify the part of the model to be extended. Then, Section 3 and 4 show the mathematical derivation of the fixture-induced errors and the datum-induced errors for conventional bench vises as workholding systems, respectively. A case study is presented in Section 5 to validate the mathematical derivation. Finally, Section 6 concludes the paper.

2. Methodology Overview

In the SoV model, the dimensional deviations of part surfaces from nominal values are represented by a state vector $\mathbf{x}_k$ where k = 1 ;…, N and N is the number of stations in the MMP. Therefore, $\mathbf{x}_k$ refers to the deviations of all part surfaces from nominal values at station k. The state vector is composed of a stack of vectors as $\mathbf{x}_k = [\mathbf{x}^1_k, \mathbf{x}^2_k, \ldots, \mathbf{x}^M_k]^T$ where $\mathbf{x}^j_k$ with j=1,…,M is a differential motion vector (DMV) that defines the position and orientation error of the feature j, assuming that only small deviations apply. Noting the local coordinate system of a feature as LCS and the part coordinate system as RCS, the position and orientation of the LCS with respect to (w.r.t.) RCS is represented by a position and orientation vector $\mathbf{t}^R_{°L} = [t^R_{°Lx}, t^R_{°Ly}, t^R_{°Lz}]^T$ and $\boldsymbol{\omega}^R_L = [\omega^R_{°Lx}, \omega^R_{°Ly}, \omega^R_{°Lz}]^T$, respectively. The terms $\omega^R_{°Lx}$, $\omega^R_{°Ly}$ and $\omega^R_{°Lz}$ are the Euler rotating angles between RCS and LCS (rotation of RCS about Z axis, then a rotation about the new Y axis, and finally, a rotation about the new Z axis). Due to manufacturing errors, the LCS may be deviated from nominal values, and this deviation is defined by a DMV which is composed of a position deviation vector, defined by $\mathbf{d}^F_F = [d^{°L}_{Lx}, d^{°L}_{Ly}, d^{°L}_{Lz}]^T$, and an orientation deviation vector, defined by $\boldsymbol{\theta}^{°L}_L = [\alpha^{°L}_L, \beta^{°L}_L, \gamma^{°L}_L]^T$. Therefore, the DMV is defined as $\mathbf{x}^{°L}_L = [(\mathbf{d}^{°L}_L)^T, (\boldsymbol{\theta}^{°L}_L)^T]^T$. Note that the nominal and actual LCS is denoted as ºL and L, respectively. Fig. 2 shows and example of relationships between coordinate systems and DMVs.

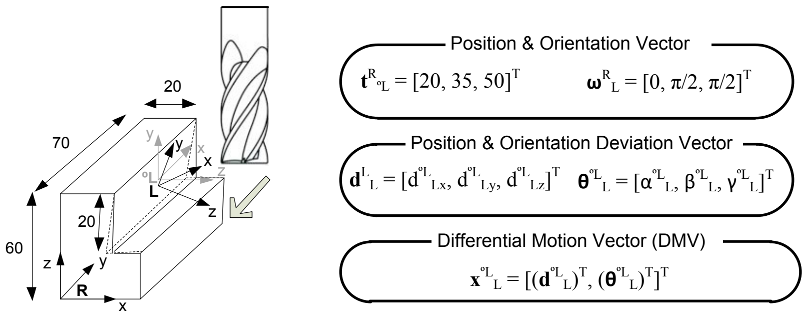


Fig. 2. Example of coordinate systems in a machined part and differential motion vector (DMV) for LCS.

The dimensional deviations of part surfaces machined in a MMP are mainly caused by fixture errors, machining errors and datum errors. According to the state space model adopted in the SoV model, the part surface deviations in a MMP of N-stations can be defined as [2,7]:

$$\mathbf{x}_k = \mathbf{A}_{k-1} \cdot \mathbf{x}_{k-1} + \mathbf{B}^f_k \cdot \mathbf{u}^f_k + \mathbf{B}^m_k \cdot \mathbf{u}^m_k + \mathbf{w}_k, \qquad k = 1,2,\ldots,N. \tag{1}$$

In this model, $\mathbf{A}_{k-1} \cdot \mathbf{x}_{k-1}$ represents the variations transmitted by datum features generated at upstream stations, $\mathbf{B}^f_k \cdot \mathbf{u}^f_k$ represents the fixture-induced variations within station k, where $\mathbf{u}^f_k$ denotes the fixture errors; $\mathbf{B}^m_k \cdot \mathbf{u}^m_k$ represents the machining-induced variations within station k, where the cutting-tool path deviation is denoted as $\mathbf{u}^m_k$; and $\mathbf{w}_k$ is the un-modelled system noise and linearisation errors. The general framework to build the state space model for a given N-station MMP is provided by [2], where it is presented the procedure of deriving the matrices $\mathbf{A}_{k-1}$, $\mathbf{B}^f_k$ and $\mathbf{B}^m_k$ at each station, according to given product and process information (part geometry and fixture layouts). The matrices $\mathbf{A}_{k-1}$, $\mathbf{B}^f_k$ and $\mathbf{B}^m_k$ are defined as

$$\mathbf{A}_{k-1} = [\mathbf{A}^1_{k-1} + \mathbf{A}^5_{k-1} \cdot \mathbf{A}^4_{k-1} \cdot \mathbf{A}^2_{k-1} \cdot \mathbf{A}^1_{k-1}], \tag{2}$$

$$\mathbf{B}^f_k = [\mathbf{A}^5_{k-1} \cdot \mathbf{A}^4_{k-1} \cdot \mathbf{A}^3_{k-1}], \tag{3}$$

$$\mathbf{B}_k^m = [\mathbf{A}_{k-1}^5], \quad (4)$$

where $\mathbf{A}^1_{k-1}$ is the relocating matrix, $\mathbf{A}^2_{k-1}$ is the datum-induced variation matrix, $\mathbf{A}^3_{k-1}$ is the fixture-induced variation matrix, $\mathbf{A}^4_{k-1}$ is an auxiliary matrix, and $\mathbf{A}^5_{k-1}$ is the selector matrix [2]. Matrices $\mathbf{A}^3_{k-1}$ and $\mathbf{A}^2_{k-1}$ are currently derived for 3-2-1 punctual schemes [2], the N-2-1 extension [5], general punctual fixture configurations [6] and surface based fixtures [7]. In this paper, these matrices are derived to model workholding devices such as conventional vises. Fig. 3 shows the methodology overview for the SoV model derivation according to [2] and the contribution of the paper within this framework. Please note that in this paper form errors are assumed to be negligible and only orientation and positional errors are considered.

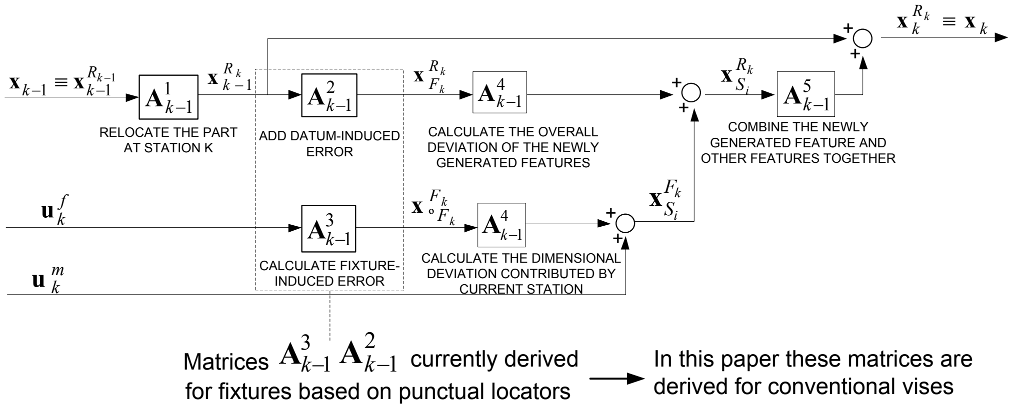


Fig. 3. Methodology for deriving the SoV model and contribution of the paper.

3. Modeling fixture-induced errors

A fixture defines de location of a part (position and orientation) that is held during machining. The fixture defines a fixture coordinate system (FCS) according to the position of the workholding components. The deviation of the FCS w.r.t. nominal values produce a final deviation of the machined feature since the nominal cutting-tool path trajectory is set-up w.r.t. the nominal FCS (ºFCS). In [2], the deviation of the FCS due to the locator deviations in a 3-2-1 fixture based on punctual locators is studied. The deviation is defined by the matrix $\mathbf{A}^3_{k-1}$ as

$$\mathbf{x}_{{}^{\circ}F_k}^{F_k} = \mathbf{A}_{k-1}^3 \cdot \mathbf{u}_k^F = -\mathbf{T}_3 \cdot \mathbf{u}_k^F \quad (5)$$

where $\mathbf{u}^F_k = [\Delta l_1, \ldots, \Delta l_6]^T$ are the deviation of the 6 locators that defined the 3-2-1 fixture scheme in [2]. If the fixture used is a conventional vise as shown in Fig. 4, the fixture errors are defined by the errors of the jaw vise, the support errors and the locating pin error. To understand which errors influence the location of the FCS, let us explain the clamping process in a vise. First, the workpiece is placed over the support which makes the support surface (surface 2) and secondary datum (surface B) to be coplanar. Then, the workpiece is moved over the support to touch primery datum (surface A) with the jaw vise (fixture surface 1). Afterwards the workpiece is moved over both the primary and secondary datum until the tertiary datum (surface C) touches the pin of the vise (surface 3). Finally, the movable vise jaw moves until it touches the lateral surface of the workpiece and moves the part until the primery datum and the jaw vise surface are coplanar, since the jaw vise blocks three degrees of freedom (d.o.f.) in this workholding system, 2 rotations and one translation. Due to the sequence of locating and the gravity, the support blocks other two d.o.f, one rotation and one translation, and the pin block the remaining d.o.f.

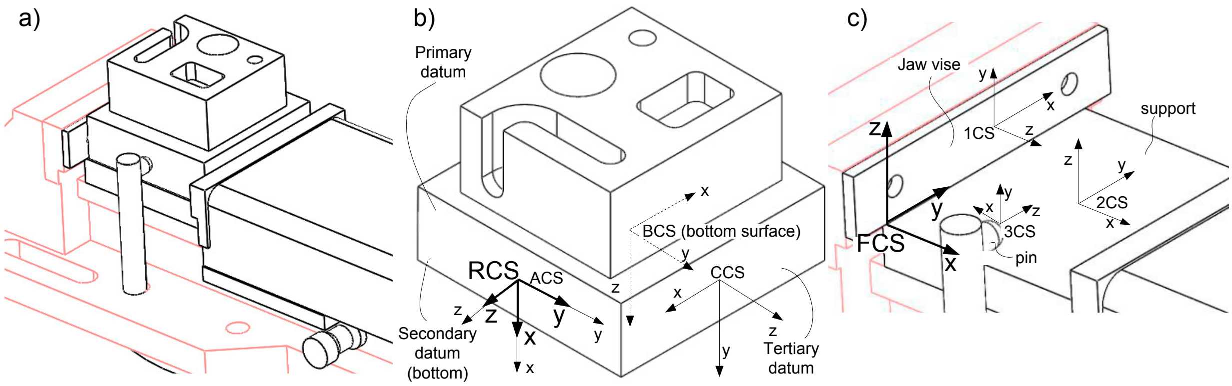


Fig. 4. a) Example of part and conventional vise assembly. Notation of surfaces used in model derivation: b) workpiece; c) fixture.

According to these locating / clamping scheme, it can be seen that the matrix $\mathbf{T}_3$ will have the following structure:

$$\mathbf{T}_3 = \begin{bmatrix} 1 & & & & & 0 & 0 \\ 0 & \mathbf{p} & \mathbf{q} & \mathbf{r} & \mathbf{s} & 0 & 1 \\ 0 & & & & & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 \end{bmatrix}, \tag{6}$$

and the fixture errors are defined as

$$\mathbf{u}_k^F = [\Delta z_1, \Delta\alpha_1, \Delta\beta_1, \Delta z_2, \Delta\alpha_2, \Delta\beta_2, \Delta z_3]^T \tag{7}$$

which are the components of the DMV of fixture surfaces that influence the deviation of the FCS at the station k. In Eq. (6), the terms with ones refer to the direct transmission of surfaces deviation onto the FCS. For instance, the number one placed at (1,1) means that the deviation Δz_1 (Z-axis deviation of the jaw vise) will produce the same deviation at the X-axis of FCS; or the orientation deviation of $\Delta\alpha_2$ (rotation on X-axis of the support) will produce the same orienation deviation at the FCS. Vectors **p**, **q**, **r** and **s** relate the deviation of X, Y and Z coordinates of the FCS due to orientation errors of fixture surfaces that locate the primary and secondary datums. These vectors can be derived analyzing the orientation effects individually and considering the simplification commonly applied when small displacements are present, i.e., cos $\varphi \approx \varphi$ and sen $\varphi \approx 1$ when φ is very small.

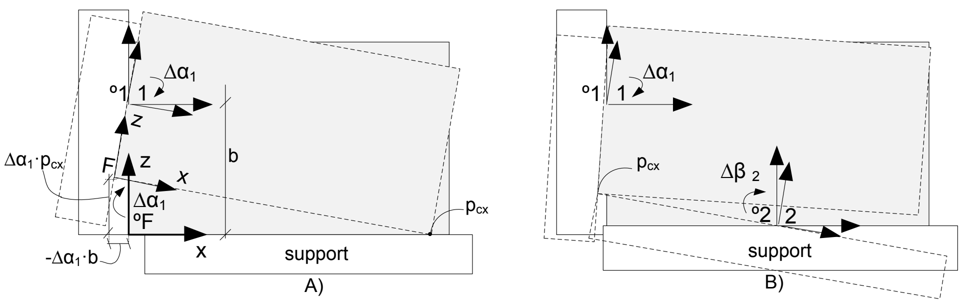


Fig. 5. Examples of FCS deviation due to orientation errors of a) jaw vise surface and b) support surface.

Let us consider and orientation deviation of the jaw surface in X- axis (i.e., $\Delta\alpha_1 \neq 0$) and no additional deviations in fixture and datums surfaces. As shown in Figure 5 a), this deviation produces the same rotation in Y-axis and two small displacements in X and Z axis. Considering small displacements, the value of these displacements are

$$\begin{aligned} d_{Fx}^{\circ F} &= -\Delta\alpha_1 \cdot b \\ d_{Fz}^{\circ F} &= \Delta\alpha_1 \cdot p_{cx} \end{aligned} \tag{8}$$

It should be noted that the contact point p_{cx} depends on the relationship between the orientation deviation of the jaw vise in X-axis ($\Delta\alpha_1$) and the orientation deviation in Y-axis ($\Delta\beta_2$). Remind that datum errors are not considered in this part, only fixture errors; datum errors are considered in the next subsection. According to Figure 5 b), it can be seen that the contact point is defined as

$$\begin{aligned} p_{cx}^F &= L_x \text{ } if \text{ } \Delta\alpha_1 > \Delta\beta_2 \\ p_{cx}^F &= 0 \text{ } otherwise \end{aligned} \tag{9}$$

Similar procedure can be conducted in the rest of orientation deviations for the jaw vise and support surfaces in order to obtain each component of vectors **p**, **q**, **r** and **s**. Therefore, the final matrix $\mathbf{T}_3$ is defined as:

$$\mathbf{T}_3 = \begin{bmatrix} 1 & -b & a & 0 & 0 & 0 & 0 \\ 0 & 0 & -p_{3x}^F & 0 & p_{3z}^F & 0 & 1 \\ 0 & p_{cx}^F & 0 & 1 & -c & (L_x - p_{cx}^F)/2 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 \end{bmatrix}, \tag{10}$$

4. Modeling datum-induced errors

Datum surfaces used for locating the workpiece may always present some degree of geometric imperfection due to manufacturing variability in previous stations. Due to this imperfection, the part reference coordinate system (RCS) of the workpiece in the fixture setup will deviate from its nominal location, denoted as ºRCS, and thus a dimensional variation of the machined part will present. According to [2], the influence of datum-induced errors on the deviation of the reference coordinate system (RCS) w.r.t. FCS is modeled as

$$\mathbf{x}_F^R = \mathbf{T}_1 \cdot \mathbf{x}_2^R + \mathbf{T}_2 \cdot \mathbf{x}_3^R \tag{11}$$

where $\mathbf{x}^R_2$ and $\mathbf{x}^R_3$ are the DMV that define the deviations of the secondary and tertiary datums of the workpiece in the 3-2-1 locating. Unlike the 3-2-1 locating scheme, the clamping procedure when using vises requires to determine the sequence of clamping and the contact points between the secondary datum and the fixture support, as explained above. Thus, secondary surface will touch only on two points or one line in the support surface since, due to the square errors of the workpiece, planes defined by secondary datum and the support are rarely coplanar.

Following the procedure in [2] but adapted for vises, the DMV $\mathbf{x}^R_F$ can be obtained solving the following equation

$$\begin{aligned} \mathbf{H}_R^B \cdot \mathbf{H}_F^R \cdot \tilde{\mathbf{p}}_1^F &= \tilde{\mathbf{p}}_1^B \\ \mathbf{H}_R^B \cdot \mathbf{H}_F^R \cdot \tilde{\mathbf{p}}_2^F &= \tilde{\mathbf{p}}_2^B \\ \mathbf{H}_R^C \cdot \mathbf{H}_F^R \cdot \tilde{\mathbf{p}}_3^F &= \tilde{\mathbf{p}}_3^C \end{aligned} \tag{12}$$

where $\widetilde{\mathbf{p}} = [\mathbf{p}^T, 1]^T$, p is a point defined by its three coordinates $[p_x, p_y, p_z]^T$, and $\mathbf{H}_i^j$ is the homogeneous transformation matrix (HTM) of the CS i w.r.t the CS j. Since the contact points between datums and fixture surfaces have a coordinate of 0 in Z axis w.r.t. the each datum coordinate system (note that all datum CS have a Z-axis pointing out to the surface), the coordinate Z of points $\mathbf{p}^B{}_1$, $\mathbf{p}^B{}_2$ and $\mathbf{p}^C{}_3$ are equal to 0. Therefore, previous equation can be simplified to (please, refer to [2] for details)

$$\begin{bmatrix} [{}^o\mathbf{a}_B^F]^T & [\mathbf{p}_1^F \times {}^o\mathbf{a}_B^F]^T \\ [{}^o\mathbf{a}_B^F]^T & [\mathbf{p}_2^F \times {}^o\mathbf{a}_B^F]^T \\ [{}^o\mathbf{a}_C^F]^T & [\mathbf{p}_3^F \times {}^o\mathbf{a}_C^F]^T \end{bmatrix} \cdot \mathbf{x}_F^R = \begin{bmatrix} [[\boldsymbol{\theta}_B^R \times {}^o\mathbf{n}_F^B]_{(3)} & [\boldsymbol{\theta}_B^R \times {}^o\mathbf{o}_F^B]_{(3)} & [\boldsymbol{\theta}_B^R \times {}^o\mathbf{a}_F^B]_{(3)} & [\boldsymbol{\theta}_B^R \times {}^o t_F^B + \mathbf{d}_B^R]_{(3)}] \cdot \widetilde{\mathbf{p}}_1^F \\ [[\boldsymbol{\theta}_B^R \times {}^o\mathbf{n}_F^B]_{(3)} & [\boldsymbol{\theta}_B^R \times {}^o\mathbf{o}_F^B]_{(3)} & [\boldsymbol{\theta}_B^R \times {}^o\mathbf{a}_F^B]_{(3)} & [\boldsymbol{\theta}_B^R \times {}^o t_F^B + \mathbf{d}_B^R]_{(3)}] \cdot \widetilde{\mathbf{p}}_2^F \\ [[\boldsymbol{\theta}_C^R \times {}^o\mathbf{n}_F^C]_{(3)} & [\boldsymbol{\theta}_C^R \times {}^o\mathbf{o}_F^C]_{(3)} & [\boldsymbol{\theta}_C^R \times {}^o\mathbf{a}_F^C]_{(3)} & [\boldsymbol{\theta}_C^R \times {}^o t_F^C + \mathbf{d}_C^R]_{(3)}] \cdot \widetilde{\mathbf{p}}_3^F \end{bmatrix} \quad (13)$$

where $\mathbf{d}^R{}_B$ and $\boldsymbol{\theta}^R{}_B$ define the $\mathbf{x}^R{}_B$ DMV, and vectors $\mathbf{n}^i{}_j$, $\mathbf{o}^i{}_j$, $\mathbf{a}^i{}_j$ and $\mathbf{t}^i{}_j$ are defined for an HTM as

$${}^o\mathbf{H}_j^i = \begin{bmatrix} {}^o\mathbf{n}_j^i & {}^o\mathbf{o}_j^i & {}^o\mathbf{a}_j^i & {}^o\mathbf{t}_j^i \\ 0 & 0 & 0 & 1 \end{bmatrix}, \quad (14)$$

For the workpiece-vise system considered in Figure 4 and the corresponding CS for secondary and tertiary datums, the resolution of Eq. (13) is

$$\mathbf{T}_1 = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -p_{3z}^F & 0 & 0 \\ 0 & 0 & -1 & -t_{Fy}^B & (t_{Fx}^B + p_{2x}^F) & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}, \quad \mathbf{T}_2 = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & -1 & (-t_{Fy}^C + p_{3z}^F) & (-p_{3x}^F + t_{Fx}^C) & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}, \quad (15)$$

where $p^F{}_{3z}$ and $p^F{}_{3x}$ are the Z and X-coordinates of the pin used in the vise for blocking the Y movement of the part, and $p^F{}_{2x}$ is the contact point between secondary datum and the vise support . The contact point depends on datum errors of primary (ACS) and secondary (BCS) datums as follows:

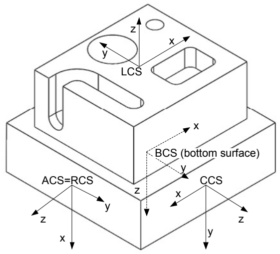
$$p_{2x}^F = L_x \ \mathit{if} \ \Delta\beta_A > \Delta\beta_B; \ \mathit{otherwise} \ p_{2x}^F = 0 \quad (16)$$

5. Case study

In order to validate the model derivation, a CAD software is used to simulate the deviation of the part due to fixture and datum errors when using conventional vises as workholding systems. The coordinate systems of fixture surfaces and datum surfaces are shown in Table 1. The table also includes the coordinate system of the machined feature (LCS) under this setup l. This workpiece-fixture system is setup in Solidworks and the deviation of the LCS w.r.t. to its nominal value is measured. This procedure is conducted under four scenarios: i) only datum-induced errors, ii) only fixture-induced errors and iii-iv) under both datum- and fixture-induced errors.
The results from the SoV model using the matrices derived in this paper for conventional vises and the measurements from Solidworks are shown in Table 2. The table shows the fixture and datum errors added in the system for the four scenarios. It can be seen that the error of the SoV model is minimum, with an average of 0.26% considering all results which validates the formulation presented in this paper. Note that the average error is due to the linealization errors required in the mathematical formulation when considering small displacements. Furthermore, this approach neglects form errors and assumes no deformations during the clamping process.

Table 1. Coordinate Systems for fixture and part surfaces.

Part Coordinate Systems



CS	$\mathbf{t}^R$	$\boldsymbol{\omega}^R$	CS	$\mathbf{t}^F$	$\boldsymbol{\omega}^F$
ACS	$[0,0,0]^T$	$[0,0,0]^T$	1CS	$[0,47.5,15]^T$	$[0, \pi/2, \pi/2]^T$
BCS	$[15,0,-47.5]^T$	$[0, \pi/2,0]^T$	2CS	$[47.5,47.5,0]^T$	$[0,0,0]^T$
CCS	$[0,47.5,-47.5]^T$	$[\pi/2, \pi/2, \pi]^T$	3CS	$[56,0,10]^T$	$[\pi/2, \pi/2, \pi/2]^T$
LCS	$[-50,0,-47.5]^T$	$[\pi, \pi/2,0]^T$			

Fixture Coordinate Systems

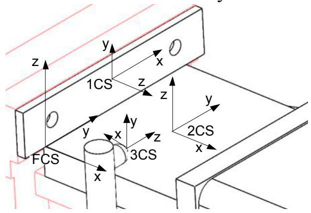


Table 2. Comparison of the estimated errors from SoV model and CAD simulations.

	Fixture errors							Datum errors						SoV			CAD		
#	Δz_1	$\Delta\alpha_1$	$\Delta\beta_1$	Δz_2	$\Delta\alpha_2$	$\Delta\beta_2$	Δz_3	Δz_B	$\Delta\alpha_B$	$\Delta\beta_B$	Δz_C	$\Delta\alpha_C$	$\Delta\beta_C$	Δx_L	Δy_L	Δz_L	Δx_L	Δy_L	Δz_L
1	-0.08	0.0017	0	-0.1	0.0021	0	0.15	-0.15	0.0032	0	-0.1	0.0067	0	0.080	-0.359	0.250	0.080	-0.358	0.251
2	-0.15	0	0.0016	-0.13	0	-0.0027	0.2	-0.1	0	0.0011	-0.1	0.0067	0	0.150	-0.160	0.200	0.149	-0.159	0.200
3	0	0	0	0	0	0		-0.15	0.0032	0	-0.1	0.0067	0	0	-0.107	0.150	0	-0.107	0.150
4	-0.08	0	0.0017	-0.1	0.0021	0	0.15	0	0	0	0	0	0	0.080	-0.252	0.100	0.079	-0.251	0.100

6. Conclusions

This paper has shown the steps for modeling workholding systems such as vises within the Stream of Variation approach. Under this approach, the fixture- and datum-induced errors propagated in multistage manufacturing processes when using bench vises can be estimated. The proposed methodology was validated under simulations based on CAD software and the results showed an average error of 0.26%. The application of this methodology can lead to potential process improvements such as process planning, process control, fault process identification and so on when vises are used as a workholding system.

Acknowledgements

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