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Liping Liu
School of Economics and Management, Nanjing University of Science and Technology, China

Yiliu Tu
Department of Mechanical and Manufacturing Engineering, University of Calgary, Calgary, Canada, paultu@ucalgary.ca

Yizhong Ma
School of Economics and Management, Nanjing University of Science and Technology, China

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Liping Liu[1], *Yiliu Tu*[2*], *Yizhong Ma*[1]
[1]School of Economics and Management, Nanjing University of Science and Technology, China
[2]Department of Mechanical and Manufacturing Engineering, University of Calgary, Calgary, Canada

Abstract: Variation reduction in multistage assembly processes is an important but challenging issue for quality control. It is desirable to minimize the final product variance from a system level. Fruitful research has been conducted on this issue based on the fixed assembly order. However, the variability of parts can be affected by different assembly order. In this paper, we propose a quality control strategy that takes into account the assembly order in two stage assembly processes. Specifically, we analyzed the relationship between the final product variation targets and the assembly order. A case study in conducted on a two stage assembly process of vessel diaphragm to illustrate the developed methodology.disastrous.

Keywords: quality control, assembly processes, assembly order, variation reduction

1. INTRODUCTION

Variation reduction is an important issue for the final product quality of multistage assembly processes. In multistage assembly processes, each assembly stage introduces variation that propagates through the process and influence the final product quality. Therefore, the final product quality is a result of the interaction of variation caused by all the stage of the assembly process. Understanding such kind of processes is critical for reduction of process variation and subsequent product quality improvement.

Fruitful researches can be found in the literature in order to improve the assembly process stability and reduce the final product variation. Considerable efforts have been made to establish a connection between the final product quality and the assembly parts quality, such as variation transition model [1]-[3]. Recently, so-called stream of variation methodology [4]-[7], which models the flow of the variation from one stage to another in the state space form with the stage index playing the role of the time index in the usual state space models used in control theory, provides the foundation for improving the final product quality of multistage assembly processes from different aspect. Izquierdo *et al*. use the feed-forward control strategy to improve the final product quality of multistage assembly processes by adjustment the locations of fixtures based on the stream of variation model [8]. Zhong *et al*. also propose a feed-forward control strategy for multistage assembly process by joint consider the model uncertainty based on the stream of variation model [9]. Zhou *et al*. describe the relationship between process faults and output quality by using the stream of variation model to formulate a linear fault quality model of multistage process and consequent identify the process parameter faults [10]. Other types of approaches are also adopted to improve the quality of multistage assembly processes, such as robust process design which aims to minimize the performance variability at the process design phase [11], statistical process control which monitoring the process by using the quality measurements [12], product tolerance allocation which aims to translate final product variation targets to tolerance specifications for subassemblies and parts [13].

Nevertheless, the aforementioned research did not pay attention to the relationship between the final product quality and the assembly order. Actually, the assembly order is not fixed for many multistage assembly processes. Furthermore, the quality characteristics of the parts, which will be assembled in the downstream subassembly stages, can be affected by the preceding subassembly stages. So, for different assembly scheme, the final product variation can be different.

* Corresponding author. paultu@ucalgary.ca (Yiliu Tu)

To mitigate problems faced in the previous research, a quality control method is proposed for reduction the final product variation with considering assembly order in this paper. The goal is to investigate the relationship between the final product quality and the assembly order based on the process model, and then determine the optimal assembly order so that the product variation at the end of the assembly process can be minimized.

In the following sections, we first introduce our process model, then the proposed methodology is presented. After that, an example that considers the assembly process of vessel diaphragm is used to illustrate the proposed methodology.

2. OPTIMAL ASSEMBLY ORDER FOR TWO STAGE PROCESSES

This section formulates the optimal assembly order problem for two stage assembly processes. First, the process model is presented, which is used to determine the relationship between the assembly order and the final product quality. Second, the determination of the optimal assembly order to minimize the variation of the final product is addressed.

For a two stage assembly process, all the parts are jointed at two stages to form the final product. Fig. 1 depicts a typical two stage assembly process of vessel diaphragm.

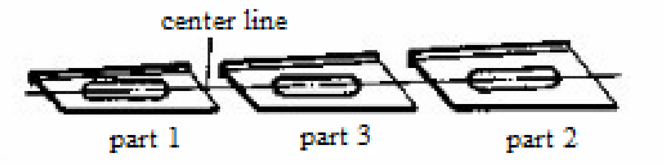

Figure 1 an example of assembly process

We separate the parts into two kinds: i) key part(s), which should be assembled at more than one stage, such as the part 3 in Fig.1; ii) common part(s), which just should be assembled at one stage, such as the part 1 and 2 in Fig.1. For the common part(s), its/their affection on the final product quality is fixed and unrelated to the assembly order. But, the quality characteristics of key part(s) can be affected by the first assembly stage, and consequently will affect the quality of the second assemble stage. So, the final product quality can be affected by assembly order though the key part(s).

For the two stage assembly process, there are two candidate assembly order strategy: the one (a_1) is the key part, e.g. part 3, is jointed to the part 1 at the first stage, then assemble the part 2 at the second stage; the alternative one (a_2) is the part 3 is jointed to the part 2 at the first stage, and then assemble the part 1 at the second stage. We assume that the effect of first assembly stage on the input and output quality characteristics of each part is linear. Let X_{ij}, $i=1,2,3$, $j=1,2$ denotes the state vector of each part i before the jth assembly stage. Then, we have

$$X_{i2} = B_i X_{i1} + \varepsilon_i, \quad i=1,2 \tag{1}$$

$$X_{32} = B_{a_k} X_{31} + \varepsilon_3, \quad k=1,2 \tag{2}$$

Where matrix $B_i \in \Re^{p_i \times p_i}$, $i=1,2$ represents the transit matrix for part i and unrelated to assembly order strategy, and p_i is the dimensional number of the quality characteristics of part i; matrix $B_{a_k} \in \Re^{p_3 \times p_3}$,

$k = 1, 2$ represents the transit matrix for key part, e.g. part 3, corresponding to assembly order strategy ak; $\varepsilon_i \sim N_{p_i}(0, \sum_i)$, $i = 1, 2, 3$ represents the random noise vectors. We can rewrite equation (1) and (2) as the matrix form:

$$X_2 = BX_1 + \varepsilon \tag{3}$$

Where $X_i = (x_{1i}, x_{2i}, x_{3i})^T$, i=1,2, $\varepsilon = (\varepsilon_1, \varepsilon_2, \varepsilon_3)^T$,"T" denotes the transposition of vector (matrix); and

$$B = \begin{pmatrix} B_1 & 0 & 0 \\ 0 & B_2 & 0 \\ 0 & 0 & B_{a_k} \end{pmatrix} \tag{4}$$

Where 0 is zero matrix with appropriate dimension. For different assembly order, the matrix B can be different. To establish the process model, we also assume that the relationship between the quality characteristics of the final product and the parts is linear. Let Y denotes the quality characteristics of the final product, we have

$$Y = AX_2 + v \tag{5}$$

Where matrix A represents the variation relationship between inputs of the second assembly stage and measured the quality characteristics of the final product, vector v is the measurement error with mean of and covariance of Σ_v.

According to equation (4) and (5), we can obtain the relationship between the quality characteristics of the final product and the state vectors of all parts before the first assembly stage, e.g. the initial states of the parts for assembly. This relationship can be described as follow:

$$Y = ABX_1 + A\varepsilon + v \tag{6}$$

The variation of the final product is given as follow:

$$\Sigma_Y = Var(Y) = AB \cdot Var(X) \cdot (AB)^T + A\Sigma_\varepsilon A^T + \Sigma_v \tag{7}$$

with the variation model equation (7), to minimize the variation of the final product, the optimal assembly order problem's object function can be formulated as:

$$\begin{gathered} Minimize\ M(\Sigma_Y) \\ subject\ to\ a_k, k = 1, 2 \end{gathered} \tag{8}$$

Where $M(\Sigma_Y)$ is the measurement of the variation of the final product. For example, the determinant or the trace of Σ_Y is common used single-number quantity for measuring the variation of a multivariate process in quality control field [14]. The optimal assembly order is:

$$a^* = \begin{cases} a_1 & if\ M_{a_1}(\Sigma_Y) < M_{a_2}(\Sigma_Y) \\ a_2 & o.w. \end{cases} \tag{9}$$

Specially, if the dimension number of the quality characteristics of the final product Y equals the dimension number of input vector X, we can use the determinant of the covariance matrix, $|\Sigma_Y|$, for measuring the variation of the final output quality characteristics. Then equation (8) can be rewritten as

$$Minimize\ |\Sigma_Y| = |A||B||\Sigma_X||B^T||A^T| + |A||\Sigma_\varepsilon||A^T| + |\Sigma_v| \tag{10}$$

$$subject\ to\ a_k, k = 1, 2$$

Since B is a diagonal partitioned matrix, we can rewrite $|B|$ as $|B_1||B_2||B_{a_k}|$. In addition, both $|A||\Sigma_\varepsilon||A^T|$ and $|\Sigma_v|$ are unrelated with assembly order. So, the object function (10) can be replaced by

$$Minimize\ |A|^2 |B_1|^2 |B_2|^2 |B_{a_k}|^2 |\Sigma_X| \tag{12}$$

$$subject\ to\ a_k, k = 1, 2$$

Then, we can obtain the optimal assembly order strategy for this situation as follow:

$$a^* = \begin{cases} a_1 & if\ |B_{a_1}| < |B_{a_2}| \\ a_2 & o.w. \end{cases} \tag{13}$$

3. A CASE STUDY

After the development of optimal assembly order strategy, a case study is conducted to illustrate the effectiveness of this strategy. As illustrated by Fig. 1, the assembly process of vessel diaphragm which is formed by three parts, and this assembly is performed in two stages with final measurement of product quality taken after the second stage. The locations of each part, as the quality variables, are the input vector for this case. The center line's deviation and the assembly tolerance are used to define the final product quality. For simplicity, we use two locators to describe the quality of each part, i.e. $p_i = 2$, $i = 1, 2, 3$; and six variables are set to describe the final product quality, i.e. the dimension number of Y is six, two of them are used to measure the center line's deviation and each two of the rest are used to measure the assembly tolerance of each assembly stage.

The proposed strategy performance is presented through calculating the determinant of Σ_Y for two candidate assembly order strategy. And then reduction variation for the proposed strategy is calculated. The parameters used in this section are $\Sigma_X = 1.6I$, $\Sigma_\varepsilon = 0.2I$, $\Sigma_v = 0.4I$, $B_1 = B_2 = I$, where I stands for the identity matrix with appropriate dimensions. In addition,

$$A = \begin{pmatrix} 0.982 & 0.126 & 0.015 & 0.320 & 0.135 & 0.020 \\ 0.060 & 0.242 & 0.017 & 0.230 & 0.189 & 0.018 \\ 0.017 & 0.018 & 0.720 & 0.020 & 0.164 & 0.296 \\ 0.009 & 0.027 & 0.27 & 0.71 & 0.050 & 0.310 \\ 0.390 & 0.260 & 0.018 & 0.530 & 0.782 & 0.281 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix} \tag{14}$$

$$B_{a_1} = \begin{pmatrix} 0.707 & 0.380 \\ 0.140 & 0.530 \end{pmatrix} \tag{15}$$

$$B_{a_2} = \begin{pmatrix} 0.530 & 0.029 \\ 0.017 & 0.320 \end{pmatrix} \tag{16}$$

Then, the determinants of A, B_{a_1} and B_{a_2} are 0.065, 0.3215, 0.1691 respectively.

Since $0.3215 > 0.1691$, according to equation (13) the optimal assembly order strategy is a_2, i.e. the part 3 is jointed to the part 2 at the first stage, and then assemble the part 1 at the second stage. Furthermore, the variations associate with assembly order strategy a_1 and a_2 are 0.0114, 0.0061 respectively. The effect of considering assembly order significantly improves quality, the reduced variation of the final product reaches to 46.54% by the optimal assembly order strategy compared with the alternative one.

4. CONCLUSIONS

This paper considered the quality control problem for two stage assembly process with unfixed assembly order. The optimal assembly order strategy is proposed to minimize variation of the final product. A case study that considers the assembly of a boat frame is presented. The result proved that the proposed method reduces the variation of the final product significantly.

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