

# Deviation Diagnosis and Analysis of Hull Flat Block Assembly Based on a State Space Model

Zhiying Zhang<sup>1\*</sup>, Yinfang Dai<sup>1</sup> and Zhen Li<sup>2</sup>

1. School of Mechanical Engineering, Tongji University, Shanghai 200092, China

2. State Key Laboratory of Estuarine and Coastal Research, East China Normal University, Shanghai 200062, China

**Abstract:** Dimensional control is one of the most important challenges in the shipbuilding industry. In order to predict assembly dimensional variation in hull flat block construction, a variation stream model based on state space was presented in this paper which can be further applied to accuracy control in shipbuilding. Part accumulative error, locating error, and welding deformation were taken into consideration in this model, and variation propagation mechanisms and the accumulative rule in the assembly process were analyzed. Then, a model was developed to describe the variation propagation throughout the assembly process. Finally, an example of flat block construction from an actual shipyard was given. The result shows that this method is effective and useful.

**Keywords:** hull flat block; state space model; deviation source diagnosis

**Article ID:** 1671-9433(2012)03-0311-10

## 1 Introduction

Recently, with the application of new shipbuilding technologies, China's shipbuilding industry has developed rapidly. Many shipbuilding indicators, such as total tonnage and on-hand orders, have reached the top rank worldwide. However, there is still a large gap in terms of the quality and efficiency of the shipbuilding industry between China and countries such as Japan and South Korea. In order to improve the efficiency and the quality of the shipbuilding process, the accuracy of every step must be controlled strictly. Shipbuilding procedures are very complex, since they are characterized by these features: 1) a large number of parts with different shapes and sizes to be assembled; 2) complicated measurement methods due to the large size and weight of parts causing measurement methods to be more complicated; 3) difficulties in obtaining a good design accuracy, which is important in the manufacturing process for large size parts; 4) most construction procedures are still dependent on manual operation, so construction quality depends largely on personnel skill; 5) the main method of precision control, the post hoc test still, cannot solve the quality problem; 6) because of machine errors and material deformation, it is difficult to control the regularity and the accuracy of the assembly processes such as cutting, heating, and welding. These complexities limit the development of the shipbuilding industry.

During the hull flat block assembly process, there are mainly four kinds of errors: part accumulative errors, part locating errors, welding deformation errors, and plate vertical errors. The deviation of every part will affect the precision of the final production. Inaccurate positioning processes will generate part locating errors. In the welding process, expansions caused by heat and contractions caused by the cold lead to defects such as deformation and cracking of the parts, which may result in welding deformation errors. Due to their increase, accumulation, and propagation, these dimensional variations will become important sources of final product variations. In the meanwhile, because of manual operational errors or instrument errors in the measurement of the final product, the ultimate deviation is also affected by the deviation of measurement. Generally, plate vertical deviation of the rib is so little that it is easily corrected by mechanical or flame-rectification methods. Therefore, in order to simplify the problem, rib plate vertical deviation will not be taken into consideration in this paper.

The automobile industry is a typical manufacturing and assembly industry. Many scholars have done research about auto assembly quality control. However, there are many differences in assembly methods of the hull block and automobile. First, the welding method is different. In the automotive assembly, the overlapping joint welding method is employed and the steel plate used is thin enough to ignore the welding deformation error. On the contrary, the thickness of the steel plate used in the hull block assembly is approximately 10 to 30 mm and the main welding method is the butt joint method, bringing out the welding deformation, which has a large influence on the accuracy of the hull block assembly process and cannot be ignored. The part location method is also different. Because of the thinness of the steel

---

**Received date:** 2012-03-08.

**Foundation item:** Supported by the National Science Foundation of China (Granted No.70872076) and Science Innovation Action Planning of Shanghai 2011 (No.11dz1121803).

**\*Corresponding author Email:** zyzhang08@tongji.edu.cn

© Harbin Engineering University and Springer-Verlag Berlin Heidelberg 2012

plate, locating pins and the numerical control (NC) blocks method are widely used in fixtures of the automobile assembly to fix the part in the assembly process. In shipbuilding, due to the relatively thick and heavy steel plates which are used, the part is fixed by weight. There is no fixture error in the shipbuilding assembly process. Therefore, the deviation in the hull block assembly process is different from that in automobile assembly. Some methods used in the automobile assembly quality control cannot be applied in block assembly.

Deviation diagnosis is an important method to control product deviation in the manufacturing process. Statistical process control (SPC) has been used as the primary methodology to analyze the part dimensional data and detect the process changes during production (Huang *et al.*, 2000). But SPC can only detect whether production parameters are changing, rather than diagnose the product deviation. Furthermore, this process control method mainly depends on the engineers' experience, so it cannot satisfy the requirements of deviation diagnosis (Mortell and Ruger, 1995). Principal components analysis (PCA) is a linear transform method which distinguishes the relevant multivariate variables collection by the non-relevant variables collection (Ceglarek and Shi, 1996). Hu and Wu (1992) used the PCA method to identify the error model according to the online measurements. However, this method is mainly based on statistical data, which require a lot of experiments, so it is not suitable for single-piece and small-batch production processes such as shipbuilding. Hu (1997) proposed a diagnosability definition of a manufacturing system based on qualitative analysis, lacking the quantitative analysis. Ding presented a diagnostic methodology which is based on the state space model of multistage manufacturing processes (MMP). This method is used to diagnose the fixture failures in MMP (Ding *et al.*, 2002). Huang *et al.* (2004) established a diagnosis method based on the state space model and recognized fault diagnosis in multistage manufacturing processes with the concept of virtual processes and virtual processing. Zhou *et al.* (2003) proposed the concept of the minimum diagnosis class which is used to diagnose an incomplete diagnosable multistage system. Then, he developed minimal diagnosable class algorithms to diagnose the source of deviation. Jin and Guo (2003) used the analysis of variance (ANOVA) method for variation component decomposition and diagnosis in the batch manufacturing processes. Johnson *et al.* (2004) combined customized analysis and visualization development into the digital close-range photogrammetry data acquisition and processing in order to automatically measure and analyze 3-D plate burning quality. Lightfoot *et al.* (2007) used the method of close range photogrammetry to measure the welding distortion in shipbuilding.

At present, the research of shipbuilding precision is in the concept stage. There are a few models to describe the

accuracy of the shipbuilding assembling process. A diagnostic method in the hull flat block assembling process was proposed in this paper. A systematic method of modeling variation propagation and the deviation vectors model is developed by using the state space model. Based on this model, the diagnosability of the deviation source is analyzed, diagnosing the part locating error and the welding deformation error. A case study and a Matlab simulation are conducted to illustrate and verify the effectiveness and practicality of the developed modeling and diagnosing method.

In this paper, the construction procedure of hull flat block is described in section 2.1. Then, the variation propagation model of hull flat block assemble is developed in section 2.2. Based on this model, section 3 presents the diagnosability analysis of part location deviation and welding deformation deviation. The analysis method is based on the parity equation. In section 4, a diagnosis method which is used to diagnose the deviation sources is presented. Computer simulation is used to verify the proposed method in section 5. Finally, the analysis is summarized in section 6.

## 2 Variation propagation model of hull flat block assembly

### 2.1 Construction procedure of a hull flat block

Based on the view of the blocks' structure and shape, most blocks in the middle of a ship are flat blocks. They represent a significant part of the hull. The structures of flat blocks are relatively stable and unchanged even in different types of ships. According to common practice, in shipbuilding, there are two methods of block construction: the obverse method and converse method. According to the obverse method the accessories are assembled in sequence on the outer bottom plate, until the inner bottom plate is finished. According to the converse method the accessories are assembled in sequence on the inner bottom plate, until the outer bottom plate is finished. Because of the outer bottom plates generally have a flexure curve surface, it is difficult to locate the blocks. The inner bottom plates are generally plane surfaces. In order to improve construction quality and efficiency, the converse method is often used in block construction. The flat blocks construction procedures follow several steps. First the inner bottom plate is set as the datum plane and then several steel plates are welded with the inner bottom plate on the mould bed (shown in Fig. 1(a)). The second step is to assemble the bottom girder plate and some small positioning accessories on the inner bottom plate to form the inner bottom ship fragment (shown in Fig. 1(b)). After that, the outer bottom plate is set as the datum plane and several steel plates are welded with the outer bottom plate on the shaped grid. Finally, the inner bottom fragment is assembled on top of the outer bottom fragment to form the hull bottom block (shown in Fig. 1(c)).

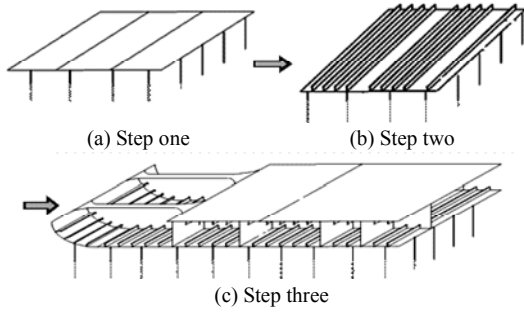


Fig. 1 Hull flat block assembling process

## 2.2 Variation propagation model based on the state space method

As mentioned above, the hull flat block assembly is a typical multi-station assembly process. There are four major errors in the block assembly process, which are the part accumulative errors, the part locating errors, the welding deformation errors, and rib plate verticality errors. While the process goes through, these dimensional variations increase, decrease, stack up, propagate, and become the final product's variation. In the meantime, because of the measurement errors due to artificial or instrumental factors, the ultimate deviation is also affected by the error of measurement.

The hull flat block assembly process is a discrete dynamic system. The state space model includes the following Eq.(1) and Eq.(2):

$$\Delta X(k) = A(k)\Delta X(k-1) + B(k)\Delta U(k) + C(k)\Delta G(k) + v(k) \quad (1)$$

$$\Delta Y(k) = D(k)\Delta X(k) + w(k) \quad k=1,2,\dots,m \quad (2)$$

Eq.(1), known as state equation, shows that part deviation at the work stage  $k$  is formed by the accumulated deviation up to the work stage  $(k-1)$  and the deviation contribution at station  $k$ . Eq.(2), known as the observation equation, implies that part deviation at the final work stage  $k$  is influenced by the deviation of the measurement.

System matrices  $A$ ,  $B$ ,  $C$ , and  $D$  are determined by the product/process design. Matrix  $A$  characterizes the assembly reorientation during part transfers between work stages. Matrix  $B$  is the coordinate transformation matrix from the part locating error to the part accumulative error. Matrix  $C$  is the coordinate transformation matrix from the welding deformation error to the part accumulative error. Matrix  $D$  represents the coordinate transformation matrix from the measurement error to the part accumulative error.  $v$  and  $w$  are noise terms, which represent the imperfections in this model due to such factors as the designed tolerance.

The variation propagation in hull flat block assembly process is shown in Fig. 2. First, due to the relatively thick and heavy steel plates which are used, the part is fixed by weight in shipbuilding. There is no fixture error generated because of the NC blocks location method used in the automobile assembly. There is only location error in the shipbuilding assembling process, which is presented as the

part locating deviation  $\Delta U(k)$ . Secondly, the thickness of the steel plate used in the hull block assembly is approximately 10 to 30 mm and the main welding method is the butt joint method. The welding deformation cannot be ignored in the hull block assembly process, but is ignored in the automotive assembly because of the thin plate and the welding method. The welding deformation deviation is presented as  $\Delta G(k)$  in the hull block assembling process. It is also seen as part accumulative deviation  $\Delta X(k-1)$ . In every work stage, the three kinds of deviations contribute to the entire assembling process. The ultimate deviation will be affected by measurement deviation. The measurement deviation is observed at work stage  $k$ .

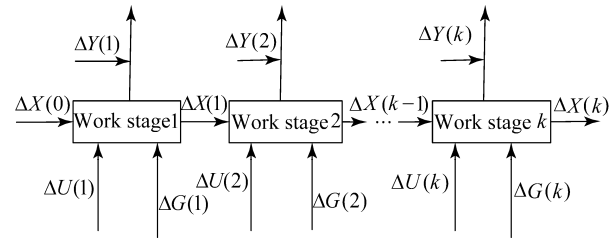


Fig. 2 Variation propagation of hull flat block assembling process

Generally, three kinds of welding deformations are common in the hull flat block welding process. They are transverse shrinkage deformation of the bottom plates during the butt welding process, shown in Fig. 3(a), transverse shrinkage deformation of the frame plate during the T-welding process, shown in Fig. 3(b), and angular deformation of the bottom plates during the T-welding process, shown in Fig. 3(b).

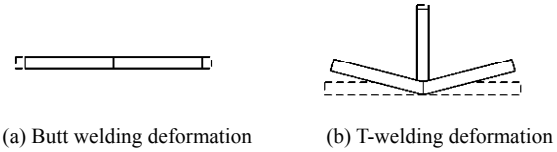


Fig. 3 Welding deformation

These deformations will affect the accuracy of the block. The state space model of the welding deformation is shown in the Eq.(3).

$$C(k)\Delta G(k) = p \cdot C(k)^h \Delta G(k)^h + q \cdot C(k)^z \Delta G(k)^z + q \cdot C(k)^j \Delta G(k)^j \quad (3)$$

where  $C(k)^h$ : coordinate transform matrix from the bottom plate transverse shrinkage deformation error to the part accumulative error;  $C(k)^z$ : coordinate transform matrix from the frame plate longitudinal deformation error to the part accumulative error;  $C(k)^j$ : coordinate transform matrix from the bottom plate angular deformation error to the part accumulative error;  $p$ ,  $q$ : the control vector.

$$p = \begin{cases} 1 & \text{welding the bottom plate} \\ 0 & \text{welding the frame plate} \end{cases}$$

$$q = \begin{cases} 1 & \text{welding the frame plate} \\ 0 & \text{welding the bottom plate} \end{cases}$$

According to the linear control theory, the propagation of the deviation on the  $k$ th work stage can be represented in the form of the state space Eq.(4):

$$\Delta X(k) = \phi_{k,i} \Delta X(0) + \sum_{i=1}^k \phi_{k,i} B(i) \Delta U(i) + \sum_{i=1}^k \phi_{k,i} C(i) \Delta G(i) + \sum_{i=1}^k \phi_{k,i} V(i) \quad (4)$$

where the state transition matrix  $\phi_{k,i}$  is as Eq.(5):

$$\phi_{k,i} = \begin{cases} A(k-1)A(k-2)\dots A(i) & k \geq i+1 \\ I & k = i \end{cases} \quad (5)$$

The input-output relationship can then be represented as Eqs.(6)–(10),

$$\Delta Y = H_B \Delta U + H_C \Delta G + H_0 \Delta X(0) + V \quad (6)$$

where

$$H_B = \begin{pmatrix} D(1)B(1) & \dots & 0 \\ D(2)\phi_{2,1}B(1) & \dots & 0 \\ \dots & \dots & \dots \\ D(N)\phi_{N,1}B(1) & \dots & D(N)B(N) \end{pmatrix} \quad (7)$$

$$H_C = \begin{pmatrix} D(1)C(1) & \dots & 0 \\ D(2)\phi_{2,1}C(1) & \dots & 0 \\ \dots & \dots & \dots \\ D(N)\phi_{N,1}C(1) & \dots & D(N)C(N) \end{pmatrix} \quad (8)$$

$$H_0 = \begin{pmatrix} D(1)\phi_{1,0} \\ D(2)\phi_{2,0} \\ \dots \\ D(N)\phi_{N,0} \end{pmatrix} \quad (9)$$

$$V = \begin{pmatrix} V(1) \\ V(2) \\ \dots \\ V(N) \end{pmatrix} \quad (10)$$

### 3 Diagnosability analysis based on parity equation

The diagnosability of a system is present when the root causes of the process variations can be diagnosed. The objective of a stream of variation diagnosis is to develop a method to identify the root causes of process variations. The stream of variation is diagnosable if all the variation observation matrices can be uniquely determined by the given measurement matrix on the selected stages.

The Eq.(6) shows that the final part accumulative variation can be accumulated because of the part locating variation, or

the welding deformation variation, or both of them. So even if the final part accumulative variation  $\sum_k^Y$  is zero, the part locating variation and the welding deformation variation can also exist in the assembly process. Therefore, in order to diagnose the root causes of the process variations, one of the variation variables should be controlled. This paper chooses a parity equation to diagnose whether the root causes of the process variations are diagnosable.

Assume: the measurement equation is  $m = HX + \varepsilon$ . The parity vector is  $p = Vm$ .  $V$  is the unknown matrix. Hence,  $p = VHX + V\varepsilon$ .

To make  $p$  independent of  $\varepsilon$  and only relevant with  $X$ , let  $V\varepsilon = 0$ . So,  $p = VHX$ . Thus, the root causes of the measurement errors are only relevant with  $X$  (Zhang and Ye, 2006).

#### 3.1 Diagnosability analysis of the part locating deviation

Without loss of generality, the initial part accumulative error variation is assumed to be the null parity equation which is set as follows:

$$V = \{v | v^T H_0 = 0\} \quad (11)$$

Here,  $v$  is the parity vector. If the parity vector  $v^T$  is independent with the welding deformation error and the initial part accumulative error as Eq.(12), the final measurement error will only be related with part locating error.

$$v^T [H_C \quad H_0] = 0 \quad (12)$$

If and only if the rank of matrix  $(H_C \ H_0)$  is less than or equal to the rank of the matrix  $(H_C \ H_0 \ 0)$ , that is,  $R(H_C \ H_0) \leq R(H_C \ H_0 \ 0)$ , Eq.(12) is a solvable equation. The  $v^T$  will have a solution. Thus, the final measurement error is not related with the welding deformation error, and the initial part accumulative error does not exist.

Then, Eq.(6) can be simplified as Eq.(13).

$$\begin{pmatrix} \Delta Y(k) \\ \Delta Y(k+1) \\ \dots \\ \Delta Y(N) \end{pmatrix} = \begin{pmatrix} D(k)B(k) \\ D(k+1)B(k+1) \\ \dots \\ D(N)\phi_{N,k}B(k) \end{pmatrix} \begin{pmatrix} \Delta U(k) \\ \Delta U(k+1) \\ \dots \\ \Delta U(N) \end{pmatrix} + \begin{pmatrix} V(k) \\ V(k+1) \\ \dots \\ V(N) \end{pmatrix} \quad (13)$$

$$H_B(k) = \begin{pmatrix} D(k)B(k) \\ D(k+1)B(k+1) \\ \dots \\ D(N)\phi_{N,k}B(k) \end{pmatrix} \quad (14)$$

Here,  $H_B(k)$  is the diagnosis matrix of work stage  $k$  for the part locating error. If and only if  $H_B(k)^T H_B(k)$  is the full rank matrix or  $R(H_B(k)) = p$  ( $p$  is the number of part location deviation source in the work stage  $k$ ), the part locating error in the work stage  $k$  will be diagnosable (Hu and Wu, 1992). If all the part locating deviations in every

work stage are diagnosable and are relatively independent, the part locating error of the whole system will be diagnosable.

### 3.2 Diagnosability analysis of the welding deformation error

If the parity vector  $\mathbf{v}^T$  is independent with the part locating error and the initial part accumulative error as Eq.(15), the final measurement error will only be related with the welding deformation error.

$$\mathbf{v}^T [\mathbf{H}_B \quad \mathbf{H}_0] = 0 \quad (15)$$

If and only if the rank of matrix  $(\mathbf{H}_B \quad \mathbf{H}_0)$  is less than or equal to the rank of the matrix  $(\mathbf{H}_B \quad \mathbf{H}_0 \quad 0)$ , that is  $R(\mathbf{H}_B \quad \mathbf{H}_0) \leq R(\mathbf{H}_B \quad \mathbf{H}_0 \quad 0)$ , Eq.(15) is a solvable equation. The  $\mathbf{v}^T$  is the solution. Then the final measurement error is not related to the part locating error. At the same time, the initial part accumulative error does not exist. Then, Eq.(6) can be simplified as Eq.(16).

$$\begin{pmatrix} \Delta \mathbf{Y}(k) \\ \Delta \mathbf{Y}(k+1) \\ \dots \\ \Delta \mathbf{Y}(N) \end{pmatrix} = \begin{pmatrix} \mathbf{D}(k)\mathbf{C}(k) \\ \mathbf{D}(k+1)\mathbf{C}(k+1) \\ \dots \\ \mathbf{D}(N)\phi_{N,k}\mathbf{C}(k) \end{pmatrix} \begin{pmatrix} \Delta \mathbf{G}(k) \\ \Delta \mathbf{G}(k+1) \\ \dots \\ \Delta \mathbf{G}(N) \end{pmatrix} + \begin{pmatrix} \mathbf{V}(k) \\ \mathbf{V}(k+1) \\ \dots \\ \mathbf{V}(N) \end{pmatrix} \quad (16)$$

$$\mathbf{H}_c(k) = \begin{pmatrix} \mathbf{D}(k)\mathbf{C}(k) \\ \mathbf{D}(k+1)\mathbf{C}(k+1) \\ \dots \\ \mathbf{D}(N)\phi_{N,k}\mathbf{C}(k) \end{pmatrix} \quad (17)$$

Here,  $\mathbf{H}_c(k)$  is the diagnosis matrix of work stage  $k$  for the part welding deformation error. If and only if  $\mathbf{H}_c(k)^T \mathbf{H}_c(k)$  is the full rank matrix or  $R(\mathbf{H}_c(k))=p$  ( $p$  is the number of part welding deformation deviation source in the work stage  $k$ ), the part welding deformation error in the work stage  $k$  is diagnosable (Hu and Wu, 1992). If all the part welding deformation errors in every work stage is diagnosable and relatively independent, the part welding deformation error of the whole system will be diagnosable.

## 4 Diagnostic method of the deviation source

In the variation propagation of the hull flat block assembly process, the input deviation is shown as an average movement and a variance increase. The average movement reflects the automatic welding equipment wearing and aging, which may make mean a move to the higher or to the lower value. The variance increase reflects the part random error such as marking error and machine noise, when welding or positioning. Based on the state space model, the average movement and the variance increase of the deviation sources can be diagnosed through the observation matrix  $\Delta \mathbf{Y}$ . According to characteristics of variation propagation, the state space model may be supposed as follows:

1)  $\Delta \mathbf{X}(k)$ ,  $\Delta \mathbf{Y}(k)$ ,  $\Delta \mathbf{U}(k)$  and  $\Delta \mathbf{G}(k)$  are normal distribution.

2) The part locating error and part welding deformation error are relatively independent in every work stage. The matrices of the position error only have the diagonal elements, as do the matrices of welding deformation error.

3) The noise error is very small if compared to the part locating error and the part welding deformation error in the production process. So, it is always neglected.

$\Delta \bar{\mathbf{U}}$  and  $\Delta \tilde{\mathbf{U}}$  are the mean value and the variance value for the part locating deviation  $\Delta \mathbf{U}$ , respectively.  $\Delta \bar{\mathbf{G}}$  and  $\Delta \tilde{\mathbf{G}}$  are the mean value and the variance value for the part welding deformation deviation  $\Delta \mathbf{G}$ , respectively. Since the part initial deviation  $\Delta \mathbf{X}(0)$  is known, without loss of generality, if  $\Delta \mathbf{X}(0)=0$ , the observation equation can be further expressed as Eq.(18).

$$\Delta \mathbf{Y} = \mathbf{H}_B \Delta \bar{\mathbf{U}} + \mathbf{H}_B \Delta \tilde{\mathbf{U}} + \mathbf{H}_c \Delta \bar{\mathbf{G}} + \mathbf{H}_c \Delta \tilde{\mathbf{G}} \quad (18)$$

$\Delta \mathbf{Y}(k)$  is normal distribution shown as  $\Delta \mathbf{Y} \sim N(\Delta \bar{\mathbf{Y}}, \sigma_{\Delta \mathbf{Y}}^2)$ ;

$\Delta \mathbf{U}(k)$  is normal distribution shown as  $\Delta \mathbf{U} \sim N(\Delta \bar{\mathbf{U}}, \sigma_{\Delta \mathbf{U}}^2)$ ;

$\Delta \mathbf{G}(k)$  is normal distribution shown as  $\Delta \mathbf{G} \sim N(\Delta \bar{\mathbf{G}}, \sigma_{\Delta \mathbf{G}}^2)$ .

### 4.1 Part locating deviation source diagnosis

When there is only a part locating error in the hull flat block assembly process, the parity vector  $\mathbf{v}^T$  is decoupled from the welding deformation error and the initial part accumulative error as Eq.(12) and the final measurement error is only related with the part locating error. Because  $\Delta \mathbf{Y}(k)$  and  $\Delta \mathbf{U}(k)$  are normal distributions, the relationship between the measurement value of the product's key points and the deviation source of the part locating error is as follows:

$$\Delta \bar{\mathbf{Y}} = E(\Delta \mathbf{Y}) = \mathbf{H}_B \cdot \Delta \bar{\mathbf{U}} \quad (19)$$

$$\sigma_{\Delta \mathbf{Y}}^2 = \sum_{i=1}^n \mathbf{H}_{Bi} \sigma_{\Delta \mathbf{U}i}^2 \mathbf{H}_{Bi}^T \quad (20)$$

$$\sigma_{\Delta \mathbf{Y}i}^2 = \mathbf{H}_{Bi} \sigma_{\Delta \mathbf{U}i}^2 \mathbf{H}_{Bi}^T \quad (21)$$

where  $\mathbf{H}_{Bi}$  represents the  $i$ th column vector of  $\mathbf{H}_B$ .

Therefore, the mean and variance of  $\Delta \mathbf{U}$  can be estimated from the mean and the variance of  $\Delta \mathbf{Y}$ . The mean and the variance of the part locating deviation can be estimated by the variance estimation method. The mean of  $\Delta \mathbf{U}$  is known. Then,

$$\sigma_{\Delta \mathbf{Y}}^2 = E\{[\Delta \mathbf{Y} - E(\Delta \mathbf{Y})]^2\} = E[(\Delta \mathbf{Y} - \mathbf{H}_B \Delta \bar{\mathbf{U}})^2] \quad (22)$$

$$\sigma_{\Delta \mathbf{Y}}^2 = E[(\Delta \mathbf{Y} - \mathbf{H}_B \cdot \Delta \bar{\mathbf{U}})(\Delta \mathbf{Y} - \mathbf{H}_B \cdot \Delta \bar{\mathbf{U}})^T] \quad (23)$$

From the above Eqs.(22) and (23),  $\Delta \bar{\mathbf{U}}$  and  $\sigma_{\Delta \mathbf{Y}}^2$  can be estimated from the measurement value  $\Delta \mathbf{Y}$  and the system design matrix  $\mathbf{H}_B$ . Then the variance of the part locating deviation sources can be estimated through Eqs.(20) and (21).

### 4.2 Part welding deformation source diagnosis

From Eq.(3), there are three kinds of the part welding

deformation deviation:

$C(k)^h \Delta G(k)^h$ : Part transverse shrinkage deformation deviation;

$C(k)^z \Delta G(k)^z$ : Part longitudinal shrinkage deformation deviation;

$C(k)^j \Delta G(k)^j$ : Part angular deformation deviation.

#### 4.2.1 Part transverse shrinkage deformation source diagnosis

When in the hull flat block assembling process there is only part transverse shrinkage deformation error, the parity vector  $\mathbf{v}^T$  is only related with the part transverse shrinkage deformation error  $\Delta \mathbf{G}^h(k)$ . So, the parity vector  $\mathbf{v}^T$  is independent with respect to the part locating error, the part initial accumulative error, the part longitudinal shrinkage deformation error, and the part angular deformation error; that means,  $\mathbf{v}^T [\mathbf{H}_B \quad \mathbf{H}_0 \quad \mathbf{H}_C^z \quad \mathbf{H}_C^j] = 0$ . The final output deviation is only sensitive to the part transverse shrinkage deformation error. It is known that  $\Delta \mathbf{Y}$  and  $\Delta \mathbf{G}^h$  are assumed to be normally distributed. Then, the relationship between measured value of the product key points and deviation source of part welding deformation is as follows:

$$\Delta \bar{\mathbf{Y}} = E(\Delta \mathbf{Y}) = \mathbf{H}_C^h \cdot \Delta \bar{\mathbf{G}}^h \quad (24)$$

$$\sigma_{\Delta Y}^2 = \sum_{i=1}^n \mathbf{H}_{Ci}^h \sigma_{\Delta G_i^h}^2 \mathbf{H}_{Ci}^{hT} \quad (25)$$

$$\sigma_{\Delta Y}^2 = E[(\Delta \mathbf{Y} - \mathbf{H}_C^h \cdot \Delta \bar{\mathbf{G}}^h)(\Delta \mathbf{Y} - \mathbf{H}_C^h \cdot \Delta \bar{\mathbf{G}}^h)^T] \quad (26)$$

$\mathbf{H}_{Ci}^h$  is the  $i$ th column vector of  $\mathbf{H}_C^h$ . Therefore, the mean and the variation of  $\Delta \mathbf{G}^h$  can be estimated from the mean and the variation of  $\Delta \mathbf{Y}$ . The estimating process is the same as the estimating process of the part locating deviation sources.

#### 4.2.2 Part longitudinal shrinkage deformation source diagnosis

When in the hull flat block assembling process there is only part longitudinal shrinkage deformation error, the parity vector  $\mathbf{v}^T$  is only related with the part longitudinal shrinkage deformation error  $\Delta \mathbf{G}^z(k)$ , decoupled from part locating error, part initial accumulative error, part transverse shrinkage deformation error and part angular deformation error as  $\mathbf{v}^T [\mathbf{H}_B \quad \mathbf{H}_0 \quad \mathbf{H}_C^h \quad \mathbf{H}_C^j] = 0$ . The final output deviation is only sensitive to the part longitudinal shrinkage deformation error. It is known that  $\Delta \mathbf{Y}$  and  $\Delta \mathbf{G}^z$  are assumed to be normally distributed. So the relationship between the measured value of products' key points and the deviation source of the part welding deformation is as follows:

$$\Delta \bar{\mathbf{Y}} = E(\Delta \mathbf{Y}) = \mathbf{H}_C^z \cdot \Delta \bar{\mathbf{G}}^z \quad (27)$$

$$\sigma_{\Delta Y}^2 = \sum_{i=1}^n \mathbf{H}_{Ci}^z \sigma_{\Delta G_i^z}^2 \mathbf{H}_{Ci}^{zT} \quad (28)$$

$$\sigma_{\Delta Y}^2 = E[(\Delta \mathbf{Y} - \mathbf{H}_C^z \cdot \Delta \bar{\mathbf{G}}^z)(\Delta \mathbf{Y} - \mathbf{H}_C^z \cdot \Delta \bar{\mathbf{G}}^z)^T] \quad (29)$$

$\mathbf{H}_{Ci}^z$  is the  $i$ th column vector of  $\mathbf{H}_C^z$ . Therefore, the mean

and variation of  $\Delta \mathbf{G}^z$  can be estimated from the mean and variation of  $\Delta \mathbf{Y}$ . The estimating process is similar to the process of estimating the part locating deviation sources.

#### 4.2.3 Part angular deformation source diagnosis

When in the hull flat block assembling process there is only part angular deformation error, the parity vector  $\mathbf{v}^T$  is only related with the part angular deformation error  $\Delta \mathbf{G}^j(k)$ , decoupled from part locating error, part initial accumulative error, part transverse shrinkage deformation error, and part longitudinal shrinkage deformation error as  $\mathbf{v}^T [\mathbf{H}_B \quad \mathbf{H}_0 \quad \mathbf{H}_C^h \quad \mathbf{H}_C^z] = 0$ . The final output deviation is only sensitive to the part angular deformation error. It is known that  $\Delta \mathbf{Y}$  and  $\Delta \mathbf{G}^j$  are assumed to be normally distributed. The relationship between the measured value of the product key points and the deviation source of the part welding deformation is as follows:

$$\Delta \bar{\mathbf{Y}} = E(\Delta \mathbf{Y}) = \mathbf{H}_C^j \cdot \Delta \bar{\mathbf{G}}^j \quad (30)$$

$$\sigma_{\Delta Y}^2 = \sum_{i=1}^n \mathbf{H}_{Ci}^j \sigma_{\Delta G_i^j}^2 \mathbf{H}_{Ci}^{jT} \quad (31)$$

$$\sigma_{\Delta Y}^2 = E[(\Delta \mathbf{Y} - \mathbf{H}_C^j \cdot \Delta \bar{\mathbf{G}}^j)(\Delta \mathbf{Y} - \mathbf{H}_C^j \cdot \Delta \bar{\mathbf{G}}^j)^T] \quad (32)$$

$\mathbf{H}_{Ci}^j$  is the  $i$ th column vector of  $\mathbf{H}_C^j$ . Therefore, the mean and variation of  $\Delta \mathbf{G}^j$  can be estimated from the mean and variation of  $\Delta \mathbf{Y}$ . The estimating process is similar to the process of estimating the part locating deviation sources.

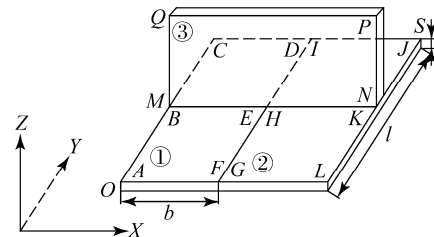
## 5 Case study and result analysis

### 5.1 Case interpretation

In this section, a multi-stage assembling process is proposed. The process is abstracted from a hull flat block assembling process, including two bottom plates and one frame plate. The design parameters of bottom plate and frame plate are presented in Table 1. They are the key dimensions that should be monitored. The assembling sequence is shown in Fig. 4, where ① is assembled firstly, ① and ② are assembled secondly and, finally, ①, ②, and ③ are assembled together.

**Table 1 Design parameters of plates** mm

Name of plate	Length	Width	Height
Bottom plate(①,②)	5 180	2 970	16
Frame plate(③)	5 940	1 700	11



**Fig. 4 Assembly diagram**

The key point is the point whose coordinate should be monitored in order to meet the manufacturing precision. In the assembling process, the key points of every bottom plate are listed in Table 2. The points (shown in Fig. 4)  $M$  and  $K$  coincide with the points  $B$  and  $N$ , which are the points on the contact surface of the bottom plate and the flame plate. After assembly, the key measurement points are  $A$ ,  $C$ ,  $J$ ,  $L$ ,  $M$ ,  $N$ ,  $Q$ , and  $P$ . The dimensions of the bottom plate's geometrical parameter such as length, width, diagonal length, and flatness should be controlled, as well as those of the flame plate such as length, width, diagonal length, verticality, and welding dimensions.

**Table 2 The key points of bottom plate and frame plate**

Name of plate	Key points
①	$A, D$
②	$G, J$
③	$M, N, Q, P$

A coordinate system is shown in Fig. 4, in order to describe the state space model of the hull straight block assembly process. The point  $O$  on the bottom plate is the base point of the standard coordinate system. The  $X$ - $Y$ - $Z$  axes are shown in the figure. Bottom plates and flame plates positioning and welding deviation refer to this coordinate system.

The initial coordinates of the key points and of the measurement points are listed in Table 3 and Table 4.

**Table 3 The initial coordinates of the part key points before welding**

Key points	Initial coordinate values
$O$	(0.00,0.00,0.00)
$G$	(2 970.23,0.00,16.00)
$A$	(0.00,0.00,16.00)
$M$	(0.00,2 330.15,16.00)

**Table 4 The initial coordinates of the measurement points/mm**

Measurement points	Initial coordinate values
$A$	(0.00,0.00,16.00)
$J$	(5 950.69,5 175.40,16.00)
$M$	(0.00,2 330.15,16.00)
$Q$	(0.00,2 330.15,1 716.00)
$C$	(0.00,5 180.59,16.00)
$L$	(5 941.29,-5.18,16.00)
$N$	(5 942.10,2 330.15,16.00)
$P$	(5 942.10,2 330.15,1 716.00)

The bottom plate and the flame plate are positioned and assembled. The assembly variation is measured only after the completion of the final process. Therefore, the state space model of the assembling process is as shown by Eqs.(33) and (34).

$$\Delta X(k) = A(k)\Delta X(k-1) + B(k)\Delta U(k) + C(k)\Delta G(k) + v(k) \quad (33)$$

$$\Delta Y(k) = D(k)\Delta X(k) + w(k) \quad (34)$$

$k$  is the  $k$ th work stage,  $k=1,2,3$ .

State variable  $\Delta X(k)$  is expressed by the parts' key points. Each bottom plate of ① and ② has two key points, namely  $A, D$  and  $G, L$ . There are four key points for the flame plate, namely  $M, N, P$ , and  $Q$ . The deviation of each key point is a  $4 \times 1$  dimensional vector as follows:

$$\Delta u_{ij} = (\Delta x_{ij}, \Delta y_{ij}, \Delta z_{ij}, \Delta \theta)^T$$

Therefore,  $\Delta X(k)$  is a  $(4 \times 8) \times 1$  dimensional vector. That is,

$$\Delta X(k) = (\Delta U_1(k), \Delta U_2(k), \Delta U_3(k))_{(4 \times 8) \times 1} \cdot \Delta U_1(k), \Delta U_2(k)$$

and  $\Delta U_3(k)$  are the deviation vector of the plates ①, ②

and ③, respectively. And,  $\Delta U_1(1) = (\Delta u_{1A}(1), \Delta u_{1D}(1))_{(2 \times 4) \times 1}$ ;

$$\Delta U_2(2) = (\Delta u_{2G}(2), \Delta u_{2L}(2))_{(2 \times 4) \times 1};$$

$$\Delta U_3(3) = (\Delta u_{3M}(3), \Delta u_{3N}(3), \Delta u_{3P}(3), \Delta u_{3Q}(3))_{(4 \times 4) \times 1};$$

The finished product is measured after welding. The measurement points are  $A, C, J, L, M, N, P$ , and  $Q$ .  $\Delta Y(k)$  is a  $(4 \times 8) \times 1$  dimensional vector.

$$\Delta Y(4) = (\Delta U_{1A}(4), \Delta U_{1C}(4), \Delta U_{1J}(4), \Delta U_{1L}(4), \Delta U_{1M}(4),$$

$$\Delta U_{1N}(4), \Delta U_{1P}(4), \Delta U_{1Q}(4))_{(8 \times 4) \times 1}$$

Then, numerical expressions of  $A$ ,  $B$ , and  $C$  of the assembling process in Fig. 3 are given as follows:

$$A(k) = I$$

$$B(1) = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 1 & 0 & 0 & 5180.59 \\ 0 & 1 & 0 & -2970.59 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \quad B(2) = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 1 & 0 & 0 & 5175.3982 \\ 0 & 1 & 0 & -2979.1673 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

$$B(3) = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 1 & 0 & 0 & 5939.9986 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & -4.1469 \\ 0 & 0 & 0 & 1 \\ 1 & 0 & 0 & 5938.8117 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & -1704.1465 \\ 0 & 0 & 0 & 1 \\ 1 & 0 & 0 & 1699.9996 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & -1.186824 \\ 0 & 0 & 0 & 1 \end{pmatrix} \quad C_3^z(3) = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

$$\begin{aligned}
D(1) &= \begin{pmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & -2970.13 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix} \\
D(2) &= \begin{pmatrix} 1 & 0 & 0 & 5180.59 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & -2970 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 5180.5821 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & -9.04183 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix} \\
C_1^h(2) &= \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} \quad C_1^j(3) = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 2590 & 0 & 0 \\ 0 & 0 & 2590 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & -2590.59 & 0 & 0 \\ 0 & 0 & 2590.59 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} \\
C_2^h(2) &= \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 2 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} \quad C_2^j(3) = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 2590 & 0 & 0 \\ 0 & 0 & 2590 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & -2585.4 & 0 & 0 \\ 0 & 0 & 2585.4 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} \\
D(3) &= I_{16} \quad C_3^h(2) = \mathbf{0}_{16 \times 4} \quad (\text{the } 16 \times 4 \text{ zero matrix}), \\
C_1^z(3) &= \mathbf{0}_{8 \times 4} \quad C_2^z(3) = \mathbf{0}_{8 \times 4} \quad C_3^z(3) = \mathbf{0}_{16 \times 4}
\end{aligned}$$

## 5.2 MATLAB simulation

**5.2.1 The simulation of part locating deviation source diagnosis**  
Based on the state space model mentioned above, if the parity vector  $\mathbf{v}^T$  is decoupled from the welding deformation error and the initial part accumulative error as Eq.(12), the final measurement error will be only related with the part locating error. At this moment, parity space  $R(\mathbf{H}_C \mathbf{H}_0) = R(\mathbf{H}_C \mathbf{H}_0 \mathbf{0}) = 32$  and  $\mathbf{v}^T$  are solvable. Then, the control matrix  $\mathbf{H}_B$  is as follows:

$$\mathbf{H}_B = \begin{pmatrix} D(1)\mathbf{B}(1) & 0 & 0 \\ D(2)\phi_{2,1}\mathbf{B}(1) & D(2)\mathbf{B}(2) & 0 \\ D(3)\phi_{3,1}\mathbf{B}(1) & D(3)\phi_{3,2}\mathbf{B}(2) & D(3)\mathbf{B}(3) \end{pmatrix}$$

The rank of the matrix  $\mathbf{H}_B$  is 12. That means,  $R(\mathbf{H}_B) = 12$ .

The part locating deviation vector is described as:

$$\Delta \mathbf{U} = (\Delta \mathbf{u}_A(1), \Delta \mathbf{u}_G(2), \Delta \mathbf{u}_M(3))_{(3 \times 4) \times 1}$$

There are twelve causes for the error of the part locating in the manufacturing process. Their number is equal to the rank of matrix  $\mathbf{H}_B$ . Then, the source of the part locating deviation is diagnosable.

As mentioned above,  $\Delta \mathbf{U} = \Delta \bar{\mathbf{U}} + \Delta \tilde{\mathbf{U}}$ , and  $\Delta \mathbf{Y} = \Delta \bar{\mathbf{Y}} + \Delta \tilde{\mathbf{Y}}$ . The normal distribution of  $\Delta \mathbf{Y}(k)$  is expressed as:

$\Delta \mathbf{Y} \sim N(\Delta \bar{\mathbf{Y}}, \sigma_{\Delta \mathbf{Y}}^2)$ . As  $\Delta \mathbf{Y}$  shown in Eq.(6), the following input-output relationship can be obtained:

$$\Delta \bar{\mathbf{Y}} = E(\Delta \mathbf{Y}) = \mathbf{H}_B \cdot \Delta \bar{\mathbf{U}}$$

$$\sigma_{\Delta \mathbf{Y}}^2 = E[(\Delta \mathbf{Y} - \mathbf{H}_B \cdot \Delta \bar{\mathbf{U}})(\Delta \mathbf{Y} - \mathbf{H}_B \cdot \Delta \bar{\mathbf{U}})^T]$$

If the design tolerance of all the part locating errors is 0.2mm, then  $6\sigma_{\Delta U_i} = 0.2$ . The 5th and 6th part location deviation fluctuations are  $6\sigma_{\Delta U_i} = 1.0$ , which is over the design standards.

The simulation is done through a Matlab tool kit. First, 100 groups of the random number  $\Delta \mathbf{U}$  are generated, which are the normal distribution of (0, 0.2). So, the mean of  $\Delta \bar{\mathbf{U}}$  is obtained.  $\Delta \bar{\mathbf{Y}}$  can be calculated through Eq.(18).  $\sigma_{\Delta U_i}^2$  can be obtained through Eq.(19) and  $\sigma_{\Delta \mathbf{Y}}^2$ . The estimating results of  $\sigma_{\Delta U_i}^2$  are shown in Table 5.

**Table 5 The estimated diagnosis results of  $\sigma_{\Delta U_i}^2$**

$\sigma(x)_{\Delta U_A}^2$	$\sigma(y)_{\Delta U_A}^2$	$\sigma(z)_{\Delta U_A}^2$	$\sigma(\theta)_{\Delta U_A}^2$
0.046 4	0.044 6	0.020 9	3.309 7e-9
$\sigma(x)_{\Delta U_G}^2$	$\sigma(y)_{\Delta U_G}^2$	$\sigma(z)_{\Delta U_G}^2$	$\sigma(\theta)_{\Delta U_G}^2$
6.524 8	1.537 3	0.060 4	1.115 3e-7
$\sigma(x)_{\Delta U_M}^2$	$\sigma(y)_{\Delta U_M}^2$	$\sigma(z)_{\Delta U_M}^2$	$\sigma(\phi)_{\Delta U_M}^2$
0.027 2	0.010 1	0.011 0	3.366 8e-9

From Table 5, it can be known that the variances of  $\sigma(x)_{\Delta U_G}^2$  and  $\sigma(y)_{\Delta U_G}^2$  are 6.524 8 and 1.537 3, respectively, which do not meet the design standards. Other variances of the part locating deviation are below 0.2. From the simulation, it can be proven that this method can accurately diagnose the source of the part locating error.

### 5.2.2 The simulation of part welding deformation deviation source diagnosis

1) Part transverse shrinkage deformation source diagnosis.  
Based on the state space model mentioned above, when the parity vector  $\mathbf{v}^T$  is only related with the part transverse shrinkage deformation error  $\Delta \mathbf{G}^h(k)$ , the parity equation



$R(\mathbf{H}_B \ \mathbf{H}_0 \ \mathbf{H}_C^z \ \mathbf{H}_C^j) = R(\mathbf{H}_B \ \mathbf{H}_0 \ \mathbf{H}_C^z \ \mathbf{H}_C^j \ 0) = 32$ , and  $\mathbf{v}^T$  is solvable.

The rank of the matrix  $\mathbf{H}_C^h$  is 2, that is  $R(\mathbf{H}_C^h) = 2$ . The matrix of the part transverse shrinkage deformation deviation is  $\Delta\mathbf{G}^h = (\Delta\mathbf{G}_1^h, \Delta\mathbf{G}_2^h, \Delta\mathbf{G}_3^h)_{(3 \times 4) \times 1}$ . Only plate ① and plate ② have the part transverse shrinkage deformation. There are two causes for the part transverse shrinkage deformation deviation in the manufacturing process, which is equal to the rank of matrix  $\mathbf{H}_C^h$ . Then, the source of the part transverse shrinkage deformation deviation is diagnosable.

Assuming that the design tolerance of all the part transverse shrinkage deformation errors is 0.2 mm,  $6\sigma_{\Delta G_i^h} = 0.2$ .

Simulation is performed using a Matlab tool kit. 100 random number groups are generated of  $\Delta\mathbf{G}^h$ , which are the normal distribution of (0, 0.2). Then, the mean of  $\Delta\bar{\mathbf{G}}^h$  is calculated, and  $\Delta\mathbf{Y}$  is obtained by Eq.(24). Thus,  $\sigma_{\Delta G_i^h}^2$

can be obtained through Eq.(25) and  $\sigma_{\Delta Y}^2$ .  $\sigma(x)_{\Delta G_1^h}^2 = 0.0389$ ,  $\sigma(x)_{\Delta G_2^h}^2 = 0.0317$ . Both of the variances are less than 0.2, which is concordant with the assumption. From the simulation, it can be proven that this method can accurately diagnose the source of part transverse shrinkage deformation error.

2) Part longitudinal shrinkage deformation source diagnosis. Based on the state space model mentioned above, when the parity vector  $\mathbf{v}^T$  is only related with the part longitudinal shrinkage deformation error, the parity space  $R(\mathbf{H}_B \ \mathbf{H}_0 \ \mathbf{H}_C^z \ \mathbf{H}_C^j) = R(\mathbf{H}_B \ \mathbf{H}_0 \ \mathbf{H}_C^z \ \mathbf{H}_C^j \ 0) = 32$ , and  $\mathbf{v}^T$  is solvable.

The rank of the matrix  $\mathbf{H}_C^z$  is 1, that is  $R(\mathbf{H}_C^z) = 1$ . The matrix of part longitudinal shrinkage deformation deviation is  $\Delta\mathbf{G}^z = (\Delta\mathbf{G}_1^z, \Delta\mathbf{G}_2^z, \Delta\mathbf{G}_3^z)_{(3 \times 4) \times 1}$ . Only plate ③ has the part longitudinal shrinkage deformation. So in the manufacturing process there is only one cause for error of the part longitudinal shrinkage deformation deviation, which is equal to the rank of matrix  $\mathbf{H}_C^z$ . Then, the source of the part longitudinal shrinkage deformation deviation is diagnosable.

Assuming that the design tolerance of the part longitudinal shrinkage deformation error is 0.2 mm,  $6\sigma_{\Delta G_i^z} = 0.2$ . First, simulation is performed using a Matlab tool kit, by which 100 random number groups are generated of  $\Delta\mathbf{G}^z$ , which are the normal distribution of (0,0.2). Then, the mean of  $\Delta\bar{\mathbf{G}}^z$  is calculated and  $\Delta\bar{\mathbf{Y}}$  is obtained by Eq.(27). Thus,

$\sigma_{\Delta G_i^z}^2$  can be obtained through Eq.(28) and  $\sigma_{\Delta Y}^2$ .

$\sigma(x)_{\Delta G_3^z}^2 = 0.0208$ . The variance is less than 0.2, which is concordant with the assumption. From the simulation, it can be proven that this method can accurately diagnose the source of the part longitudinal shrinkage deformation error.

### 3) Part angular deformation source diagnosis.

Based on the state space model mentioned above, when the parity vector  $\mathbf{v}^T$  is only related with the part angular deformation error, the parity space,  $R(\mathbf{H}_B \ \mathbf{H}_0 \ \mathbf{H}_C^h \ \mathbf{H}_C^j) = R(\mathbf{H}_B \ \mathbf{H}_0 \ \mathbf{H}_C^h \ \mathbf{H}_C^j \ 0) = 32$  and  $\mathbf{v}^T$  is solvable.

The rank of the matrix  $\mathbf{H}_C^j$  is 4.  $R(\mathbf{H}_C^j) = 4$ . The matrix of part angular deformation deviation is  $\Delta\mathbf{G}^j = (\Delta\mathbf{G}_1^j, \Delta\mathbf{G}_2^j, \Delta\mathbf{G}_3^j)_{(3 \times 4) \times 1}$ .

Only plate ① and plate ② have the part angular shrinkage deformation. There are four error causes for the part angular deformation deviation in the manufacturing process, which is equal to the rank of matrix  $\mathbf{H}_C^j$ . Then, the source of the part angular deformation deviation is diagnosable.

Assuming that the design tolerance of all the part angular deformation errors is 0.2 mm,  $6\sigma_{\Delta G_i^j} = 0.2$ . Simulation is

performed using Matlab. 100 random number groups are generated of  $\Delta\mathbf{G}^j$ , which are the normal distribution of (0, 0.2). The mean of  $\Delta\bar{\mathbf{G}}^j$  is calculated. Then,  $\Delta\mathbf{Y}$  can be obtained by Eq.(30).  $\sigma_{\Delta G_i^j}^2$  can be obtained through Eq.(31)

and  $\sigma_{\Delta Y}^2$ . Then,  $\sigma(y)_{\Delta G_1^j}^2 = 1.8175e-9$ ,  $\sigma(z)_{\Delta G_1^j}^2 = 1.8345e-9$ ,  $\sigma(y)_{\Delta G_2^j}^2 = 9.0987e-9$ ,  $\sigma(z)_{\Delta G_2^j}^2 = 9.1836e-9$ . The variances are all less than 0.2, which is concordant with the assumption. From the simulation, it can be proven that this method can accurately diagnose the source of part angular deformation error.

## 6 Conclusions

In this paper, a method is presented which is used to diagnose the variation propagation of the hull flat block erection process in shipbuilding. Based on state space model, the diagnostic method described the propagation of variation in such a manufacturing process, built the state space model, analyzed the diagnosability of the deviation source, and diagnosed the part locating error and the welding deformation error. Since there are so many work stages and the number of parts in the assembly and welding process of the hull flat block construction is huge, the variation propagation is complex. The current manufactures are paying more and more attention to the product quality and accuracy control in the manufacturing process. This paper is an important contribution to the control of the source of the deviation in the shipbuilding process. The welding process

is considered especially, and thus contribution is made to the control of the assembly process before welding by the use of anti-deformation or an expansion joint, achieving a precise control of the final product.

## References

- Ceglarek D, Shi J (1996). Fixture failure diagnosis for auto body assembly using pattern recognition. *ASME J. Eng. Ind.*, **118**, 55-65.
- Ding Y, Ceglarek D, Shi JJ (2002). Fault diagnosis of multi-station manufacturing processes by using state space approach. *ASME Journal of Manufacturing Science and Engineering*, **124**(2), 313-322.
- Ding Y, Ceglarek D, Shi JJ (2002). Design evaluation of multi-station assembly processes by using state space approach. *Journal of Mechanical Design*, **124**(3), 408-417.
- Huang Q, Zhou N, Shi J (2000). Stream of variation modeling and diagnosis of multi-station machining processes. *Proceedings of the 2000 ASME International Mechanical Engineering Congress and Exposition*, Orlando, 81-88.
- Huang Q, Zhou S, Shi J (2002). Diagnosis of multi-operational machining processes through process analysis. *Robotics and Computer Integrated Manufacturing*, **18**, 233-239.
- Huang Q, Shi J (2004). Variation transmission analysis and diagnosis of multi-operation machining processes. *IEEE Transactions on Quality and Reliability*, **36**, 807-815.
- Huang Qiang, Zhou Nairong, Shi Jianjun (2000). Stream of variation modeling and diagnosis of multi-station machining processes. *International Mechanical Engineering Congress & Exposition*, Orlando, Florida, 5-10.
- Hu SJ (1997). Stream-of-variation theory for automotive body assembly. *Annals of CIRP*, **46**(1), 1-6.
- Hu SJ, Wu SW (1992). Identifying root cause of variation in automobile body assembly using principal component analysis. *Transactions of NAMRI*, **20**, 311-316.
- Jin J, Guo H (2003). ANOVA method for variation component decomposition and diagnosis in batch manufacturing processes. *The International Journal of Flexible Manufacturing Systems*, **15**(2), 167-186.
- Johnson GW, Laskey SE, Robson S, Shortis MR (2004). Dimensional & accuracy control automation in shipbuilding fabrication: an integration of advanced image interpretation, analysis and visualization techniques. *ISPRS Congress*, Istanbul, Turkey, Commission V, WG V/1.
- Lightfoot MP, Bruce GJ, Barber DM (2007). The measurement of welding distortion in shipbuilding using close range photogrammetry. *2007 Annual Conference of the Remote Sensing and Photogrammetry*, Newcastle, UK.
- Mortell RR, Ruger GC (1995). Statistical process control of multiple stream process. *Journal of Quality Technology*, **27**(1), 1-12.
- Zhang P, Ye H (2006). On the relationship between parity space and H2 approaches to fault detection. *System & Control Letters*, **55**(2), 94-100.
- Zhou S, Ding Y, Chen Y, Shi J (2003). Diagnosability study of multistage manufacturing processes based on linear mixed-effects models. *Technometrics*, **45**(4), 312-325.



**Zhiying Zhang** was born in 1971. He is currently an Associate Professor in School of Mechanical Engineering, Tongji University, China. He received his PhD degree from Beijing Institute of Technology, China, in 2003. His research interests include production planning and scheduling, Industrial Engineering. He is a member of Chinese Society of Naval Architects and Marine Engineers.



**Yinfang Dai** was born in 1986. She received M.S. degree in Industrial Engineering from Tongji University, Shanghai, China in 2012. Her research interests are the quality improvement methodologies for complex manufacturing processes, and advanced statistics and engineering knowledge.