Modeling and Control of Compliant Assembly Systems

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Abstract

The assembly of compliant, non-rigid parts is widely used in automotive, aerospace, electronics, and appliance manufacturing. Dimensional variation is one important measure of quality in such assembly. This paper presents models for analyzing the propagation of dimensional variation in multi-stage compliant assembly systems and the use of such models for robust design and adaptive control of assembly quality. The models combine engineering structure analysis with advanced statistical methods in considering the effect part variation, tooling variation, as well as part deformation due to clamping, joining and springback. The new adaptive control algorithm makes use of the fine adjustment capabilities in new programmable tooling in achieving reduction of assembly variation.

Keywords:
Assembly, control, dimensional

1. INTRODUCTION

Many products, including automobiles, aircrafts and home appliances, are constructed primarily from sheet metal parts. As these parts are large but relatively thin, they tend to be non-rigid. Hence, these parts are described as compliant to the forces experienced during assembly such as clamping and joining and the assembly processes are called "compliant assembly". In many of these products, the number of parts can be very large, such as the several hundred parts in a typical automobile body. Such a large number of parts will lead to multiple stages of assembly operations, where the output of one stage is the input into the next stage of assembly. Since parts and fixtures all have dimensional variation, understanding how these variations propagate through the system is of significant interest to the design and control of such systems.

Methods for analyzing variation in assemblies have been the subject of active research. Three primary approaches, worst case analysis, root sum squares and Monte Carlo simulation [1-2], have been widely adopted. All these methods assume that the parts in the assembly are rigid, which clearly does not hold for compliant sheet metal parts [3]. Inclusion of compliance in variation analysis requires new techniques, such as these proposed by Liu and Hu [4] and Camelio et al. [5], where deformation and springback effects are considered.

This paper presents the developments of variation propagation models at the station and system levels, then apply such models to the robust design and control of compliant assembly systems.

2. MODELING OF COMPLIANT ASSEMBLY

2.1 Station level model

In any assembly system, there are various sources of variation. For example, the incoming parts may have variation from their nominal dimensions, the fixtures may have errors with regards to nominal location. The method described by Liu and Hu [4] takes into account the primary sources of variation, the variation in the incoming parts and tooling. Their method breaks down the assembly process into four steps as shown in Figure 1 and analyzes the assembly by finite element and statistical methods:

1. Parts are located by the fixtures,
2. Clamps push the parts against the locators,
3. Weld guns join the parts, and
4. Weld guns and clamps are released, and the part experiences spring-back.

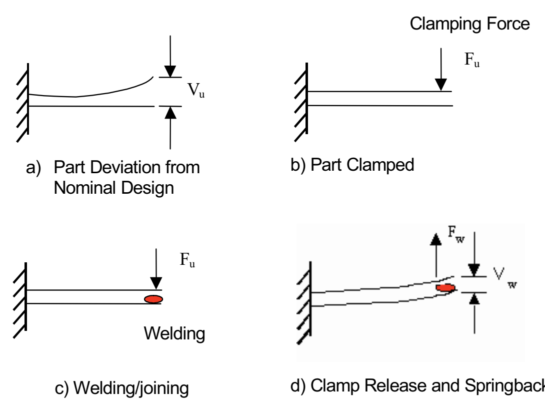

Figure 1: Four step compliant assembly process.

The deviation of the assembly V_a is related to the deviation of the incoming parts and tooling V_i in the following way:

$$V_a = SV_i \tag{1}$$

where the sensitivity matrix S is determined using the method of influence coefficients.

2.2 System level model

The station level model presented above can be extended for system level variation propagation analysis by considering part relocation from station to station. The propagation of the dimensional variation is modeled as a linear time discrete system, where the variable time $\boldsymbol{k}$ represents the station location (Eq. 2), **A** is the state matrix, **X** is the state vector, **B** is the input matrix, **U** is the input vector, **W** is a perturbation vector, **Y** is the measurement/observation vector, **C** is the observation matrix, and **V** is a measurement noise vector.

$$\mathbf{X(k) = A(k) \cdot X(k-1) + B(k) \cdot U(k) + V(k)} \qquad (2)$$
$$\mathbf{Y(k) = C(k) \cdot X(k) + V(k)}$$

Camelio et al. [5] developed a model to analyze the propagation of variation in multi-station compliant assembly systems. Equation (2) is re-written as below by considering part relocation and deformation:

$$\begin{aligned}\mathbf{X}_k = (\mathbf{S}_k - \mathbf{P}_k + \mathbf{I})(\mathbf{X}_{k-1} + \mathbf{M_i}(\mathbf{X}_{k-1} - \mathbf{U}_k^{3-2-1})) \\ - (\mathbf{S}_k - \mathbf{P}_k)(\mathbf{U}_k^{N-3} + \mathbf{U}_k^{g}) + \mathbf{V}_k\end{aligned} \qquad (3)$$

where $\mathbf{S_k}$ is the sensitivity matrix, $\mathbf{P_k}$ is the part deformation matrix, and $\mathbf{M_k}$ is the relocation matrix associated with station k. $\mathbf{U^{3\text{-}2\text{-}1}}$ is the variation vector of a *3-2-1* locating fixture, $\mathbf{U^{N\text{-}3}}$ is the variation vector for a *N-2-1* fixture with N>3, and $\mathbf{U^{g}}$ is the variation vector for welding guns. **V** represents the noise which is the propagated variation not accounted by this model.

3. APPLICATION OF COMPLIANT ASSEMBLY MODELS

The applications of the multi-station assembly model to tolerance allocation, robust design and adaptive control are presented in the following sections.

Using Equation (3) the variation propagation in a multi-stage assembly system can be analyzed. Figure 2 shows the propagation effect from different levels of subassembly to the final product in auto body assembly.

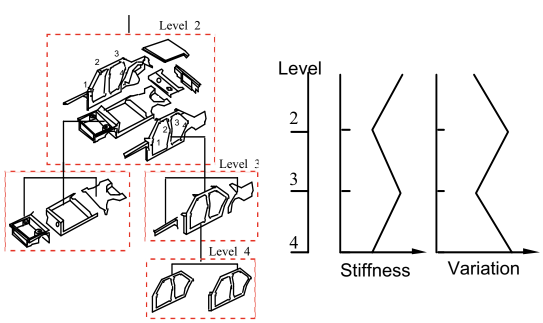

Figure 2: Variation propagation in multi-stage assembly, based on [6].

Hu [6] showed that an assembly process can magnify or suppress variation and suggests that this is largely dependent upon whether the assembly is parallel or serial. If the assembly is in parallel, such as door inner and outer assembly, and has greater stiffness than the individual components, the sources of variation tend to be suppressed. However, if the assembly is in serial and is less stiff than the individual components, then variation will be magnified.

3.1 Tolerance allocation

Assembly tolerance allocation consists of selecting the component tolerances to satisfy the final product tolerance targets. In general, the tolerance allocation process seeks to minimize total production cost based on some cost tolerance model subject to the tolerance constraints. One commonly used cost-tolerance model is of the exponential form [7]:

$$C(Tol) = k_1 + k_2 e^{-k_3 Tol} \qquad (4)$$

where k_1 represents the fixed costs, k_2 is the cost of producing a single component dimension to a specified tolerance *Tol*, k_3 describes how sensitive the process cost is to changes in tolerance specifications.

Li et al. [8] demonstrated that tolerance specifications for subassemblies and incoming parts can be determined such that the quality of the final product is optimal with respect to the available resources. The analytical target cascading (ATC) process is applied to allocate tolerances of the final assemblies to the parts and subassemblies. Taking advantage of the multilevel structure of the assembly systems, product design targets are cascaded to appropriate subsystem specifications in a consistent and efficient manner. The approach minimizes the gap between what the upper-level elements “want” and what the lower-level elements “can”.

The ATC process consists of solving a sequence of optimization sub-problems associated with each station of the multi-level hierarchy in the assembly system. The mathematical formulation of the optimization sub-problem at station j of level i is:

$$\begin{aligned} & \textit{minimize} \quad \left\| \sigma^2_{X_{ij}} - \sigma^{2H}_{X_{ij}} \right\|_2^2 + \varepsilon_i \\ & \textit{w.r.t.} \ \sigma^2_{X_{(i+1)1}}, \sigma^2_{X_{(i+1)2}}, \ldots, \sigma^2_{X_{(i+1)M_{ij}}}, \varepsilon_i \\ & \textit{subject to} \quad \sum_{k=1}^{M_{ij}} \left\| \sigma^2_{X_{(i+1)k}} - \sigma^{2L}_{X_{(i+1)k}} \right\|_2^2 \le \varepsilon_i \\ & \qquad g(\sigma^2_{X_{(i+1)1}}, \sigma^2_{X_{(i+1)2}}, \ldots, \sigma^2_{X_{(i+1)M_{ij}}}) \le 0 \\ & \qquad h(\sigma^2_{X_{(i+1)1}}, \sigma^2_{X_{(i+1)2}}, \ldots, \sigma^2_{X_{(i+1)M_{ij}}}) = 0 \end{aligned} \qquad (5)$$

where, $\sigma^2_{X_{ij}} = f(\sigma^2_{X_{(i+1)1}}, \sigma^2_{X_{(i+1)2}}, \ldots, \sigma^2_{X_{(i+1)M_{ij}}})$ and superscripts H and L denote the target values cascaded down and passed up from “parent” and “children” stations, respectively. M_{ij} is the number of “children” stations, ε_i is the consistency variable, and g and h are general inequality and equality constraints. Note that the function f is linear and represents relations between the input (before assembly) and output variation (after assembly). In the optimization problem, the objective is to minimize the deviation between current variations and the targets cascaded from above subject to consistency constraints that take into account the variations that can be expected from the ”children” stations.

Figure 3 illustrates the tolerance allocation results for a two stage process for an auto body side assembly where the tolerances of fixtures in the two stages can be specified.

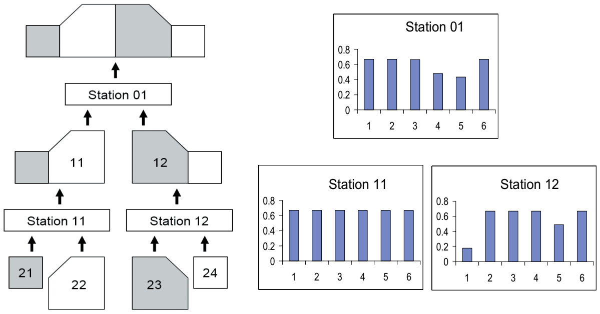

Figure 3: Tolerance allocated for the fixtures in the stations in a body side assembly process.

3.2 Robust Design

The variation propagation models can also be used to evaluate the robustness of an assembly system with regards to tooling and part variation. Robust design can be applicable to all phases of assembly process design, including joint design, fixture design, and assembly line configuration. In robust design, it is necessary to define indices that measure how robust or insensitive a system is to sources of variation. Based on the variation propagation models presented in Section 2.1, Hu et al. [9] presented two indices to measure the robustness, a transmission index R, and a sensitivity index, C. The transmission index reflects the ability of the system to suppress or amplify the sources of variation. The sensitivity index measure how sensitive the system is to incoming variation. A low sensitivity index insures that changes in the levels of source deviance cause little change in the deviance of the assembly.

$$R^2 = \frac{Assembly\ Variance}{Source\ Variance} = \frac{S\Sigma_i S^T}{\Sigma_i} \tag{6}$$

$$C = \left\|\mathbf{S}^{-1}\right\|\left\|\mathbf{S}\right\| = \frac{\lambda_N}{\lambda_1} \tag{7}$$

where **S** is the sensitivity matrix as defined in Section 2.1, Σ_i is the covariance of the incoming part deviations, and λ_1 and λ_N are the square roots of the minimum and maximum eigenvalues of $[\mathbf{S}][\mathbf{S}]^T$, respectively. One important characteristic of both indices is that they are independent of the source of variation. Therefore, the robustness analysis can be conducted without knowing the amount of input variation on the system.

Using the transmission index and the sensitivity index a robustness evaluation method can be defined. An ideal assembly should transmit as little variation as possible and be insensitive to changes in the levels of the input variation. Therefore defining R(X) and C(X) as function of design alternatives X, the objective function for the design of a robust assembly systems is:

$$minimize\ f(X) = w_1 R(X) + w_2 C(X) \tag{8}$$

where, w_1 and w_2 are nonnegative weights.

4. ADAPTIVE CONTROL

As presented in the previous section, robust design methodologies focus on minimizing the effect of variation by selecting the right process at the design stage. After the assembly line is in production, continuous improvement activities are conducted to identify possible sources of variation using SPC tools. In recent years, with the development of new technologies, a new variation reduction opportunity has arisen though adaptive control using programmable tooling. For example, auto manufacturers have introduced robotic fixturing devices to improve the flexibility of auto body assembly. The fine adjustment capabilities of such robots allow them to be applied for compensation of dimensional deviations using either feed forward or feedback controls.

4.1 Variation reduction through tooling adjustment

There are two approaches for dimensional quality control depending of the objective. The first approach is to compensate the mean deviation of the assemblies. In this case, a non-nominal mean can be corrected once identified in a batch of production. The parts can be measured after assembly and a decision is made after measuring several assemblies. The second approach is to focus on reducing the dimensional variation of the system; this requires measuring and adjusting every single component. In this strategy there are two alternatives, the parts can be measured before assembly or just after assembly. The proposed methodology in this paper focuses in reducing the assembly variation. This approach requires measuring each component before assembly and adjusting it to minimize its deviation.

The control methodology consists of five steps as shown in Figure 4:

(1) Each component is located and clamped in the assembly station in its nominal position.

(2) The parts are measured to detect any non-nominal dimension.

(3) The dimensional problem is decomposed as a rigid body problem (part is located in the wrong position) or compliant problem (the part is deformed or has a non-nominal shape).

(4) A correction amount is determined depending on the assembly model to be used (rigid or compliant).

(5) The correction is applied, if it is feasible given the tooling workspace constraints and the parts are assembled.

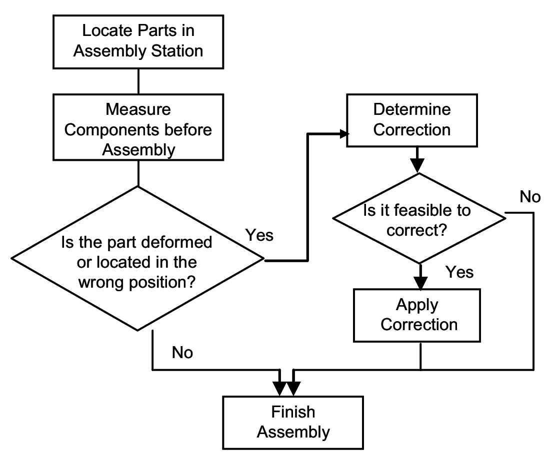

Figure 4: Dimensional variation reduction using programmable tooling.

From the five-step methodology, the challenge of the tooling adjusting algorithm is to determine the correction amount. The correction must be calculated in order to minimize the output assembly deviation. It must be clear that this is not directly a correction of the input components deviation. This is especially significant when the adjusting tools are able to only actuate on some of the components and not on every component.

Based on the variation propagation model presented in Section 2.2, a new control term, $\mathbf{u}_c$ can be included in the model (Eq. 9). This approach can be extended to a multi-station systems, where the control vector $\mathbf{u_c}$ will include more than one adaptive tools in the system and the measurement vector will correspond to the final assembly deviation, $\mathbf{y_N}$.

$$\begin{aligned} \mathbf{x}^B{}_k &= \mathbf{A}_{k-1} \cdot \mathbf{x}_{k-1} + \mathbf{B}_k \cdot \mathbf{u}_k + \mathbf{w}^B{}_k \quad + \mathbf{B}_k \cdot \mathbf{u}_c \\ \mathbf{y}^B{}_k &= \mathbf{C}_k \cdot \mathbf{x}^B{}_k + \mathbf{v}^B{}_k \end{aligned} \tag{9}$$

Therefore, the objective of the optimal control algorithm is to find the fixture correction vector, $\mathbf{u_c}$, that minimizes the deviation of the key product characteristics represented by $\mathbf{y_k}$ for the single station k (Eq. 10) or a vector $\mathbf{u_c}$ that minimizes the final assembly deviation $\mathbf{y_N}$. Reducing the deviation of each assembly will imply a reduction on the variation of the system.

$$\begin{aligned} &\underset{\mathbf{u}_C}{minimize} \quad \tilde{\mathbf{y}}_k{}^T \cdot \mathbf{Q} \cdot \tilde{\mathbf{y}}_k \\ &subject\ to \quad \mathbf{u}_{Min} \le \ |\mathbf{u}_C| \le \mathbf{u}_{Max} \end{aligned} \tag{10}$$

4.2 Hood bracket application

As an example, Figure 4 shows of the application of the adaptive control in the assembly of a hood bracket. The bracket is located using a robotic fixture that holds the top of the bracket. If there is an angle error in any of the bracket flanges, the bracket can be rotated to minimize the deviation in the hood pin location in the assembly. Figure 5 shows the effect of fixture correction on the final pin position. Simulation results based on assembly models have shown promising results in the capacity of adapting tooling to compensate part and fixture deviation for rigid and compliant assemblies.

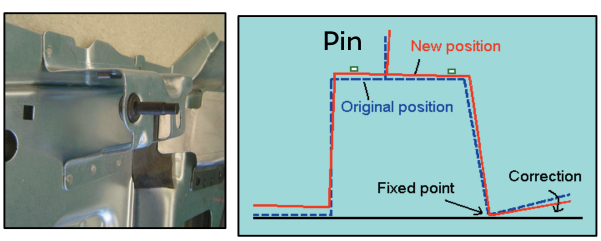

Figure 4: Hood bracket assembly.

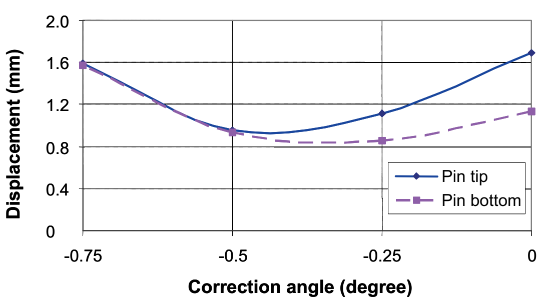

Figure 5: Effect of compensation on position.

5. CONCLUSIONS

This paper presents the recent developments of variation simulation models for compliant assembly and the application of such models in robust design and adaptive control of assembly quality. First, assembly models at station and multi-station levels are presented. Second, different applications of the models are introduced. The applications presented include: 1) a variation propagation analysis; 2) tolerance allocation using an analytical target cascading optimization process; 3) robust design based on variation transmission; and 4) variation reduction based on adaptive control using programmable tools. The adaptive control of assembly represents a new approach to reducing variation in assembly systems.

6. REFERENCES

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