I.J. Intelligent Systems and Applications, **2009, 1,11-18**
Published Online October 2009 in MECS(http://www.mecs-press.org/)

Prediction of Operating Loads Contribution to Assembly Relation and Product Behavior

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***Abstract*—In the process of product manufacturing, control of assembly error will directly affect product operating behavior. When product running, operating loads will lead to change of assembly relation of product parts, affecting product behavior. Based on Jacobian-Torsor method, the Jacobian-Torsor tolerance model, considering contribution of operating loads, was extended and corrected, the assembly error (assembly relation change) resulted from operating loads can be calculated. Variation of running behavior with assembly error was divided to three phases: compensation phase, rapid loss phase and total loss phase. Based on changing curve of product behavior, function of behavior loss was constructed to describe behavior loss resulting from assembly error of a part of product. The conception and calculating method of behavior loss index (BLI) are given to reflect behavior changing status of whole product under certain assembly accuracy. Combined with extended Jacobian-Torsor method, the calculated results can be used to predict product behavior change led by operating loads. The prediction can help to know next measurement adopted in product design phase. An example is given to demonstrate calculating procedure of given method.**

***Index Terms*—contribution prediction, operating load, assembly relation, product behavior**

I. Introduction

In the process of product design and development, good control in assembly accuracy can improve assembly quality and ensure final running behavior of product. Running behavior is known as product functionality and usability, reflecting the degree to meet design requirements. Through assembling process, manufacturing process of product affects assembly accuracy and then running behavior.

Product assembly will finish assembly plan according to established assembling order, using proper method, tools and manpower. Assembly process realizes determined position and matching relationship of assembly cells. Whether product parts assembled according to designed purpose or not directly affects assembly accuracy.

However, even if the product, which assembled by parts meeting the design requirements, reaches all design and assembly requirements, the behavior index will not always accord with expected. This is because, when running, the impact of practical operating loads such as force loads endured and temperature changing will result in changes of assembly relation between parts, forming "acquired" assembly error. So it is necessary to determine the operating loads contribution to assembly relation and product behavior in product design phase.

This paper will analyze the changing tendency of running behavior with assembly error, put forward a conception "Behavior Loss" and its definition, find the relationship between product behavior and assembly accuracy, build Jacobian-Torsor based practical tolerance model to calculate assembly error under operating loads, realizing efficient control of impact from working environment and assembly error to product behavior.

II. Impact of Operating Loads on Assembly Relation

A. Impact Analysis under Operating Loads

In practical running status, operating loads will affect product parts and lead to parts geometry error, and the error will finally affect product behavior. Operating loads impact should be considered in tolerance analysis of product design and get mating feature of parts under working condition. It is very important for impact analysis under operating loads how to mathematically express geometry variations led by operating loads.

For assembled product, its close loop error is magnified by parts error through transfer of dimension chain, and finally affecting assembly quality and running performance.

In assembled body, variations of dimension, shape and position of every function factor can be expressed by a vector matrix,

Manuscript received January 21, 2009; revised June 14, 2009; accepted July 16, 2009.
This work is supported by projects of Chinese National Natural Science Foundation (No. 50675159) and Mega-projects of High-grade NC Machine Tools and Basic Manufacturing Equipment (No. 2009zx04001-072-02)

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$$\Delta = \begin{bmatrix} \Delta u & \Delta\alpha \\ \Delta v & \Delta\beta \\ \Delta w & \Delta\delta \end{bmatrix} \quad (1)$$

Here Δu, Δv and Δw are respectively translational vectors of coordinate origin in direction X, Y and Z; $\Delta\alpha$, $\Delta\beta$ and $\Delta\delta$ are respectively rotating vectors of coordinate system around X, Y and Z.

All variables of every degree of freedom in (1) can be gained through mechanical calculating method and finite element method.

Generally, operating loads mainly include force loads and heat. Geometry error and dimension change led by force loads are similar, just the changing direction and magnitude are determined by loads, and changes can be expressed as corresponding torsos. For heat, the change has no direction and is always regarded as a scale factor, characteristic dimension of parts increase and decrease proportionally in all direction, so these change can be expressed as torsos dependent each other of 6 degree interval value.

Fig.1 shows the process of tolerance modeling under operating loads. Using designed tolerance, assembly tolerance model is built by Jacobian-Torsor method. Then considering impact of operating loads, changes of parts dimension, shape and position led by this impact are calculated and expressed as torsor matrixes. As compensation, these changes are combined with tolerance model in ideal state, building practical assembly tolerance model under running status and defining contribution of operating loads to assembly relation.

B. Assembly Relation Calculation under Ideal State

Desrochers and Laperriere introduced rigid kinematics method to tolerance analysis, put forth Jacobian method and Torsor method, and adopted matrix equation to express the small variation of nominal geometric solid.

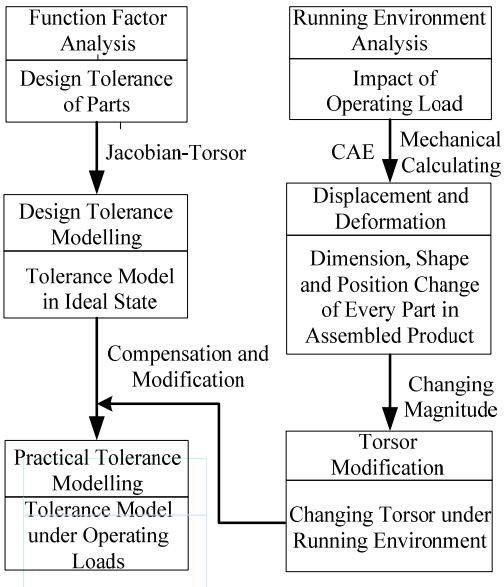

Figure 1. Tolerance modeling under operating load.

Jacobian method is based on matrix change theory of rigid open-loop kinematic link; and the small displacement is expressed by point set. In Torsor method, the small fluctuation of feature is denoted by restrained Torsor, and by which 3D tolerance field is described [1-3]. Their next work combined above two methods to give Jacobian-Torsor method, building mathematical tolerance model. Equation (2) is a basic expression of Jacobian-Torsor tolerance model is. This equation builds mathematical relation between function requirements (*FR*) at assembly level with function elemental factors (*FE*) at part level. The relative geometric relationship of *FE* to *FR* is expressed by Jacobian matrix product (*J*),

$$[FR] = [J][FE] \quad (2)$$

In (2), *FE* and *FR* are Torsors and expressed by interval. Each interval scope is the size of corresponding uncertainty field (tolerance or clearance). Equation (2) can be unfolded to (3) below,

$$\begin{aligned} &\left[[\underline{u},\overline{u}],[\underline{v},\overline{v}],[\underline{w},\overline{w}],[\underline{\alpha},\overline{\alpha}],[\underline{\beta},\overline{\beta}],[\underline{\delta},\overline{\delta}]\right]_{FR}^{T} \\ &= \left[[J_1J_2J_3J_4J_5J_6]_{FE1} \ldots [J_1J_2J_3J_4J_5J_6]_{FE2}\right] \\ &\bullet \left[\left[[\underline{u},\overline{u}],[\underline{v},\overline{v}],[\underline{w},\overline{w}],[\underline{\alpha},\overline{\alpha}],[\underline{\beta},\overline{\beta}],[\underline{\delta},\overline{\delta}]\right]_{FE1} \ldots \right. \\ &\left. \left[[\underline{u},\overline{u}],[\underline{v},\overline{v}],[\underline{w},\overline{w}],[\underline{\alpha},\overline{\alpha}],[\underline{\beta},\overline{\beta}],[\underline{\delta},\overline{\delta}]\right]_{FEn}\right]^{T} \end{aligned} \quad (3)$$

[*FR*]: Small displacement Torsor (fit or clearance) correlative to function requirements.

$$[FR] = \left[[\underline{u},\overline{u}],[\underline{v},\overline{v}],[\underline{w},\overline{w}],[\underline{\alpha},\overline{\alpha}],[\underline{\beta},\overline{\beta}],[\underline{\delta},\overline{\delta}]\right]_{FR}^{T}$$

[*FE*]: Uncertainty of function factors (tolerance or motion pair).

$$[FEi] = \left[[\underline{u},\overline{u}],[\underline{v},\overline{v}],[\underline{w},\overline{w}],[\underline{\alpha},\overline{\alpha}],[\underline{\beta},\overline{\beta}],[\underline{\delta},\overline{\delta}]\right]_{FEi}^{T}$$

$[J_1J_2J_3J_4J_5J_6]_{FEi}$: Geometrical relation Jacobian matrix of [FR] with corresponding [FE].

n: Torsor number in kinematic link.

$(\underline{u},\underline{v},\underline{w},\underline{\alpha},\underline{\beta},\underline{\delta})$ and $(\overline{u},\overline{v},\overline{w},\overline{\alpha},\overline{\beta},\overline{\delta})$: Lower and upper limit of *u, v,w,* α, β, δ.

C. Calculation of Jacobian matrix and Interval Torsor

From (2), it can be known that Jacobian matrix express transfer relationship of [*FE*] and [*FR*], normally, Jacobian matrix can be expressed as follows [4],

$$[J]_{FEi} = [J]_0^i = \begin{bmatrix} [R_0^i]_{3\times3} & \vdots & [W_i^n]_{3\times3} \cdot \left([R_0^i]_{3\times3} \cdot [R_{PTi}]_{3\times3}\right) \\ \cdots & \vdots & \cdots \\ [0]_{3\times3} & \vdots & [R_0^i]_{3\times3} \cdot [R_{PTi}]_{3\times3} \end{bmatrix}_{6\times6} \quad (4)$$

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Here $[R_0^i]$: variation of coordinate *i* relative to coordinate *0,* and

$$[R_0^i]=[C_{1i}C_{2i}C_{3i}]$$

$\boldsymbol{C_{1i}}$, $\boldsymbol{C_{2i}}$ and $\boldsymbol{C_{3i}}$ are respectively direction vectors of axis X_i, Y_i and Z_i of coordinate *0*.

W_i^n : a matrix composed of vector $[\boldsymbol{d_n}-\boldsymbol{d_i}]$, and express position variation of coordinate *n* relative to coordinate *i*. $\boldsymbol{d_i}$ is position vector of origin of coordinate *i* in coordinate *0*.

$$\left[W_i^n\right]_{3\times3}=\begin{bmatrix}0 & -dz_i^n & dy_i^n\\ dz_i^n & 0 & -dx_i^n\\ -dy_i^n & dx_i^n & 0\end{bmatrix}$$

here

$$dx_i^n=dx_n-dx_i$$

$$dy_i^n=dy_n-dy_i$$

$$dz_i^n=dz_n-dz_i$$

$[R_{PTi}]$: reflecting consistency of tolerance direction with three axes of coordinate *i*.

$$[R_{PTi}]=[C_1C_2C_3]_{PTi}$$

$\boldsymbol{C}_1$, $\boldsymbol{C}_2$ and $\boldsymbol{C}_3$ are respectively direction vectors of three directions of tolerance analyzed in coordinate *I*, withal $[FE_i]$ is related to $[R_{PTi}]$.

In torsor theory, for a single part, torsos of interior dimension, shape and position tolerance (interior pair) are listed by Table I; for assembly tolerance between parts (kinematic pair), Table II.

D. Jacobian-Torsor Based Tolerance Modeling under Operating Loads

In product running process, because of the influence of a series of factors such as force loads, heat and etc., the calculated assembly relation in ideal state can't reflect its trueness. Therefore, to get the actual assembly changes under operating loads, the environment factors must be considered in Jacobian-Torsor method.

Influence of external factors mainly results in changes of dimension, shape and position of parts, namely changes of function factors (*FE*), and then [*J*] and [*FE*] correlative to above *FE* in (1) will change correspondingly, finally entire assembly requirements [*FR*] will be affected.

Fig. 2 shows the FE change of some function factors impacted by running environment, including coordinate translation and rotation in free status.

By Fig. 2, it can be known that function factor change is composed of coordinate translation and rotation of axes,

TABLE I.
TOLERANCE AREA AND TORSOR OF INTERIOR PAIR

1	Planar rotary disk	$\begin{Bmatrix}0 & 0\\ v & 0\\ w & 0\end{Bmatrix}$ $-t/2\le v\le t/2 \quad -t/2\le w\le t/2$, $v^2+w^2=(t/2)^2$
2	Planar ring plane	$\begin{Bmatrix}0 & 0\\ v & 0\\ w & 0\end{Bmatrix}$ $v^2+w^2=(t/2)^2$
3	Linear plane band	$\begin{Bmatrix}0 & 0\\ 0 & \beta\\ w & 0\end{Bmatrix}$ $-t/2\le w\le t/2 \quad -t/L\le\beta\le t/L$
4	Parallelepiped	$\begin{Bmatrix}0 & 0\\ v & \beta\\ w & \delta\end{Bmatrix}$ $-t_2/2\le v\le t_2/2 \quad -t_1/2\le w\le t_1/2$, $-t_2/L\le\beta\le t_2/L \quad -t_1/L\le\delta\le t_1/L$
5	Cylinder	$\begin{Bmatrix}0 & 0\\ v & 0\\ w & 0\end{Bmatrix}$ $-\phi t/2\le v\le\phi t/2 \quad -\phi t/2\le w\le\phi t/2$, $-\phi t/L\le\beta\le\phi t/L \quad -\phi t/L\le\delta\le\phi t/L$, $v^2+w^2=(\phi t/2)^2$
6	Planar rotary disk	$\begin{Bmatrix}0 & 0\\ v & 0\\ w & 0\end{Bmatrix}$ $v=(t/2)\cos(\theta)$, $v^2+w^2=(t/2)^2$, $w=(t/2)\sin(\theta)$, $-(\phi t/L)\le\beta\le(\phi t/L)$, $-(\phi t/L)\le\gamma\le(\phi t/L)$
7	Plane	$\begin{Bmatrix}0 & \alpha\\ 0 & \beta\\ w & 0\end{Bmatrix}$ $-t/2\le w\le t/2 \quad -t/L_1\le\alpha\le t/L_1$, $-t/L_2\le\beta\le t/L_2$
8	Curve	$\begin{Bmatrix}u & 0\\ v & 0\\ 0 & \delta\end{Bmatrix}$ Undefined
9	Curved face	$\begin{Bmatrix}u & \alpha\\ v & \beta\\ w & \delta\end{Bmatrix}$ Undefined

$$\left[o_i'o_i\right]=\begin{bmatrix}\Delta u_i & \Delta\alpha_i\\ \Delta v_i & \Delta\beta_i\\ \Delta w_i & \Delta\delta_i\end{bmatrix}$$

Δu_i, Δv_i and Δw_i :Translation vectors of coordinate origin in direction *X,Y* and *Z.*

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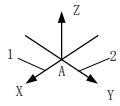
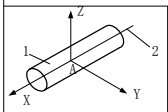
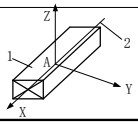
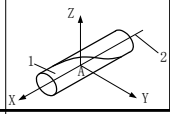
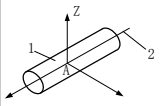
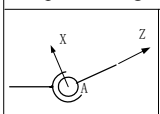
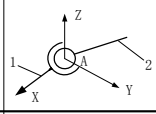
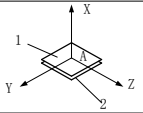
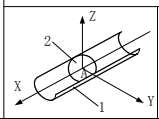
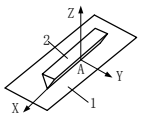
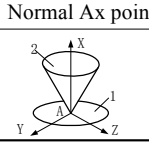
TABLE II.
TOLERANCE AREA AND TORSOR OF EXTERIOR PAIR

1	Rigid Pair	 $\{T_{(2\to1)}\}=\begin{Bmatrix} u & \alpha \\ v & \beta \\ w & \delta \end{Bmatrix}$
2	Rotating around axis **Ax**	 $\{T_{(2\to1)}\}=\begin{Bmatrix} u & 0 \\ v & \beta \\ w & \delta \end{Bmatrix}$
3	Sliding along axis **Ax**	 $\{T_{(2\to1)}\}=\begin{Bmatrix} 0 & \alpha \\ v & \beta \\ w & \delta \end{Bmatrix}$
4	Spiral along axis Ax, θ -lead angle, R-radius	 $\{T_{(2\to1)}\}=\begin{Bmatrix} u & \alpha \\ v & \beta \\ w & \delta \end{Bmatrix}$ $\alpha=k\cdot u$ $k=((Tan(\theta))R)$
5	Cylinder sliding along axis *x*	 $\{T_{(2\to1)}\}=\begin{Bmatrix} 0 & 0 \\ v & \beta \\ w & \delta \end{Bmatrix}$
6	Spheric hinge rotating around axis **Ax**	 $\{T_{(2\to1)}\}=\begin{Bmatrix} u & 0 \\ v & 0 \\ w & \delta \end{Bmatrix}$
7	Spheric hinge rotating around center point **A**	 $\{T_{(2\to1)}\}=\begin{Bmatrix} u & 0 \\ v & 0 \\ w & 0 \end{Bmatrix}$
8	Normal **Ax** planar contact	 $\{T_{(2\to1)}\}=\begin{Bmatrix} u & 0 \\ 0 & \beta \\ 0 & \delta \end{Bmatrix}$
9	Constraint of linear pipe to sphere	 $\{T_{(2\to1)}\}=\begin{Bmatrix} 0 & 0 \\ v & 0 \\ w & 0 \end{Bmatrix}$
10	Linear contact of a trigone edge with face	 $\{T_{(2\to1)}\}=\begin{Bmatrix} u & 0 \\ 0 & 0 \\ 0 & \delta \end{Bmatrix}$
11	Normal Ax point contact	 $\{T_{(2\to1)}\}=\begin{Bmatrix} u & 0 \\ 0 & 0 \\ 0 & 0 \end{Bmatrix}$

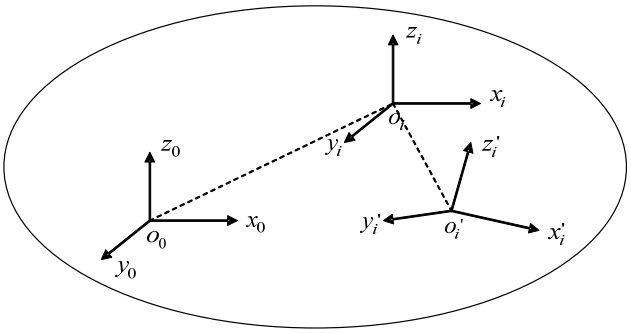


Figure 2. Change of function factors under operating loads

$\Delta\alpha_i$, $\Delta\beta_i$ and $\Delta\delta_i$:Rotation vectors of coordinate with axes *X, Y* and *Z*.

Due to function factors changes, direction change $[R_0^i]$ of coordinate *i* relative to coordinate *0* will change,

$$\left[R_0^i\right]=[\vec{C}_{1i}\ \vec{C}_{2i}\ \vec{C}_{3i}]\cdot[C_x]\cdot\left[C_y\right]\cdot[C_Z] \tag{5}$$

$[C_x]$: Transition matrix of rotation $\Delta\alpha_i$ of coordinate *i* around its axes *X*,

$$\left[C_x\right]=\begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\Delta\alpha_i & -\sin\Delta\alpha_i \\ 0 & \sin\Delta\alpha_i & \cos\Delta\alpha_i \end{bmatrix}$$

$[C_y]$: Transition matrix of rotation $\Delta\beta_i$ of coordinate *i* around its axes *Y*,

$$\left[C_y\right]=\begin{bmatrix} \cos\Delta\beta_i & 0 & \sin\Delta\beta_i \\ 0 & 1 & 0 \\ -\sin\Delta\beta_i & 0 & \cos\Delta\beta_i \end{bmatrix}$$

$[C_z]$: Transition matrix of rotation $\Delta\delta_i$ of coordinate *i* around its axes *Z*,

$$\left[C_z\right]=\begin{bmatrix} \cos\Delta\delta_i & -\sin\Delta\delta_i & 0 \\ \sin\Delta\delta_i & \cos\Delta\delta_i & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

W_i^n is the position change of coordinate *n* relative to coordinate *i*. dx_i^n , dy_i^n and dz_i^n in W_i^n have corresponding changes with coordinate translation,

$$dx_i^n = dx_n - dx_i + \Delta u_i$$
$$dy_i^n = dy_n - dy_i + \Delta v_i$$
$$dz_i^n = dz_n - dz_i + \Delta w_i$$

$[R_{PTi}]$ reflects inconsistency of tolerance direction with three axes direction of coordinate *i*, and

$$\left[R_{PTi}\right]=[C_1C_2C_3]_{PTi}\cdot\left[C_x\right]\cdot\left[C_y\right]\cdot\left[C_z\right]$$

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Knowing above changes of $[R_0^i]$, W_i^n and $[R_{PTi}]$, Jacobian matrix [*J*] under working loads can be calculated.

III. Analysis of Changing Tendency of Running Behavior with Assembly Changes

There are some research results about assembly quality. К.Я.Муценек analyzed the relationship between quality of the assembled product and technics parameters of assembly process [6]; Riley studied on impact of parts design tolerance on assembly quality [7]; Nevins and Whitney put forward fault in assembly procedure is a direct factor resulting in problem of assembly quality [8]; Selke and his partners thought assembly process parameters are key factors to affect whole assembly procedure [9]. Other researchers also referred assembly quality when evaluating robot assembly system. When building assembly system model of robot, Rampersad considered the problem that parts flaws lead parts cannot match in gear [10]; Dore and Lo analyzed that assembly quality is affected by disaccord of parts tolerance scope with equipment performance and the change of external factors [11].

A. Changing Tendency of Working Behavior

Generally, it can be known in running process that changing tendency of product behavior has its own regular pattern. With assembly error increase, working behavior will become bad slowly; over here the behavior changing is named as Behavior Loss. At this time the changing doesn't lead product breakdown, behavior loss can be covered by measurement such as error compensation (Compensation Phase). When assembly error accumulates to a certain extent, working behavior will sharply become worse (Rapid Loss Phase). With continuous increase of assembly error, product will lose its using value and becomes waster (Total Loss Phase) [12].

Changing tendency of product behavior with assembly error is shown by Fig. 3.

B. Function of Behavior Loss

Genichi Taguchi method gave a concept of loss function of quality, which unified two different category concepts quality and economy, supplying a precondition to quantified analysis of quality fluctuant. Here quality loss is described by economical loss. However, in this method, no measurement can tell the change of product behavior, limiting practical application of the method. Following text will take assembly error, which reflect assembly accuracy, as variable to construct a function of product behavior loss to show changing pattern with assembly error.

Through investigation of changing tendency curve shown by Fig. 4, an approximate expression of function of behavior loss can be deduced:

$$L(e) = k(e - n_0)^{1/3}$$

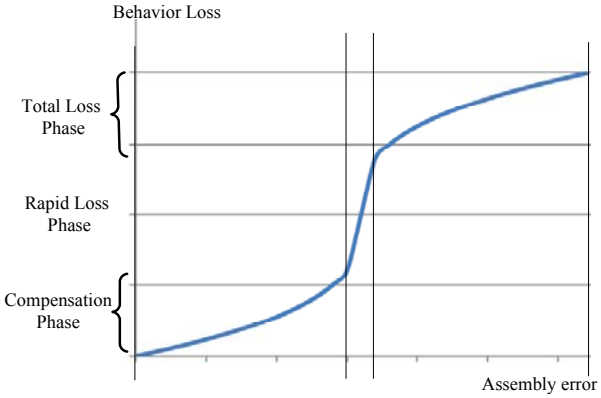

Figure 3. Changing tendency of Product behavior along with assembly error

To describe working behavior changing definitely, this exponential function should meet some conditions below,

- The value of *L(e)* denotes behavior loss resulting from assembly error of a part, its span is [0, 1] and expressed by percent, named as behavior loss rate (*BLR*).
- *e* is a variable indicating assembly error, under an uniform standard, which can be defined by quantitative description of assembly error to a certain part or a category of similar parts.
- n_0 is the characteristic value of assembly error *e*. The characteristic value of assembly error denotes assembly error *e* reaches a certain range of n_0, product behavior will run into rapid loss phase and lose use-value rapidly. When e locates less than a certain range of n_0, product has a partial behavior loss, and this loss can be compensated. Here value of *L(e)* shows changing status of product behavior.
- *k* is a proportion factor relating to n_0 to ensure the value span of behavior loss in [0, 1].

Phase partition of behavior loss. Referring to function curve of exponential function $y = x^{1/3}$, behavior loss turns into rapid phase when *L(e)* becomes more than 30% and total loss phase when more than 70%. Namely the span of rapid loss phase is $30\% \le L(e) \le 70\%$, and n0 is equal to center value in span of rapid loss phase.

To meet above terms, function of behavior loss can be modified as follows,

$$\begin{aligned} L(e) &= k(n_0^{1/3} + (e - n_0)^{1/3}) \\ k &= \frac{1}{2} n_0^{-1/3}, \quad 0 \le e \le 2n_0 \end{aligned} \tag{6}$$

Through (6), when in rapid loss phase, e span is $0.936n_0 \le e \le 1.064n_0$.

Function curve of behavior loss and phase partition are shown on Fig. 4.

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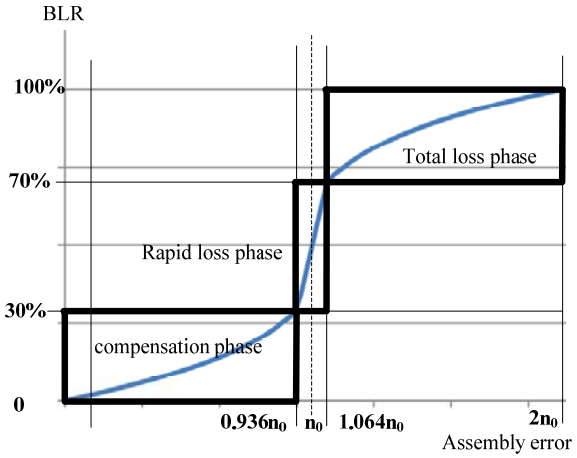

Figure 4. Function curve of behavior loss and loss phase partition

Behavior loss index (BLI) of product

Normally, a product is assembled by many parts. The *BLR* of part *i* can be calculated by (1),

$$L^i(x) = k_i(n_{i0}^{1/3} + (e - n_{i0})^{1/3})$$

$$k_i = \frac{1}{2} n_{i0}^{-1/3}, \quad 0 \le e_i \le 2n_{i0}$$

Suppose a product made up of m parts, and in assembly process the contribute factor of part *i* to final assembly error is c_i, here

$$\sum_{i=1}^{m} c_i = 1$$

Then Behavior loss index (*BLI*) of this product can be defined by following equation,

$$BLI(x) = \sum_{i=1}^{m} c_i L^i(e) = \sum_{i=1}^{m} c_i k_i (n_{i0}^{1/3} + (e_i - n_{i0})^{1/3})$$

$$k_i = \frac{1}{2} n_{i0}^{-1/3}, \quad 0 \le e_i \le 2n_{i0}$$

Definition of n_{io}: Generally, the upper or lower limit of design tolerance can be taken as characteristic error value n_{io}.

If possible, characteristic error value of a part or similar ones can be determined by statistic method, which sample values come from some testing runs. In this testing, assembly status of a certain part is changed continuously, and data of running behavior after every change is recorded as a sample.

Definition of contribute factor c_i: Reference [13] has a detailed relation.

IV. BLI and Extended Jacodian-Torsor Method Based Design and Development Process

BLI and extended Jacobian-Torsor method can be used to establish a decision-making system to help design and development of product. After finishing a design process, with practical operating loads, assembly relation changes can be calculated by extended Jacobian-Torsor method. And according to existing assembly condition, design parameters and changing value of assembly relation, the behavior loss index of product can be calculated. The calculating result helps to determine the next step adopted. BLI and extended Jacobian-Tosor method based design and development process of product is shown by Fig. 5. The process shown is not whole detailed but a rough procedure relating to BLI. When BLI locates at compensation phase, if behavior loss can be compensated by technical measurement based on development experience, the design proposal and technical requirement are feasible. If this result locates at rapid loss phase, the design proposal and technical requirements need a directed modification according to contribute factor. If at total loss phase, a full check and modification must be done.

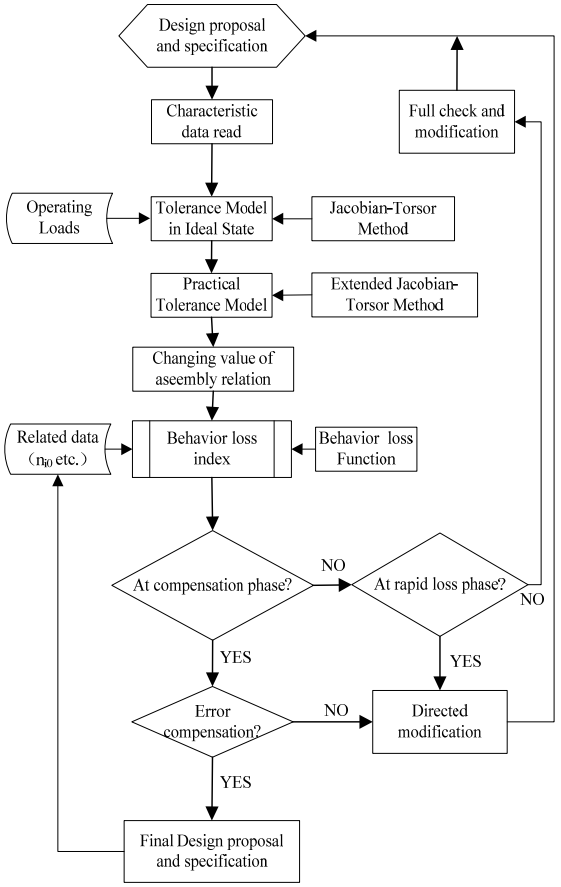

Figure 5. BLI and Extended Jacobian-Torsor Method Based Design and Development Process

V. Example of Behavior Change Prediction under Operating Loads

A. Extended Jocabian-Torsor Method Based Calculation of Assembly Error Resulted from Operating Loads

Fig. 6 shows a parts drawing of a gear pump, the pump has three parts: pump body (P_1), drive gear (P_2) and driven gear (P_3). The back lash of two gears is assembly clearance need to ensure and control between the three parts[5].

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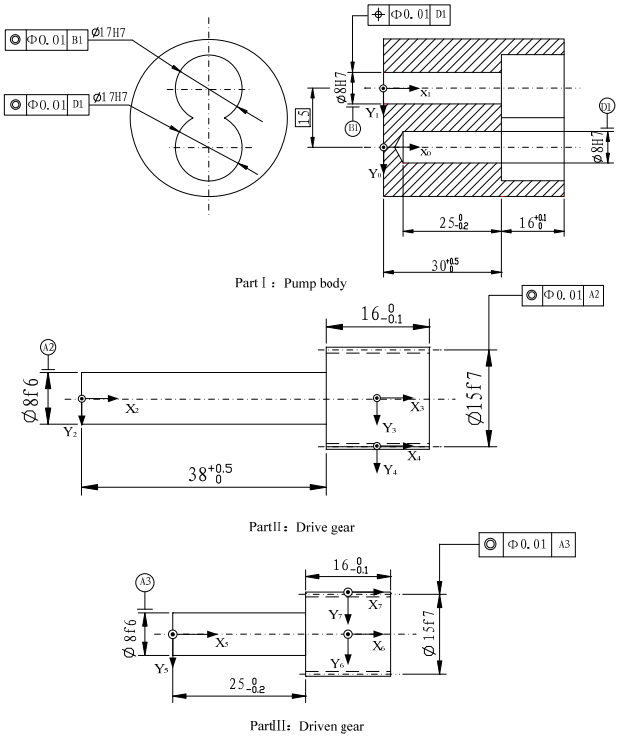

Figure 6. Parts dimension and rectangular coordinate

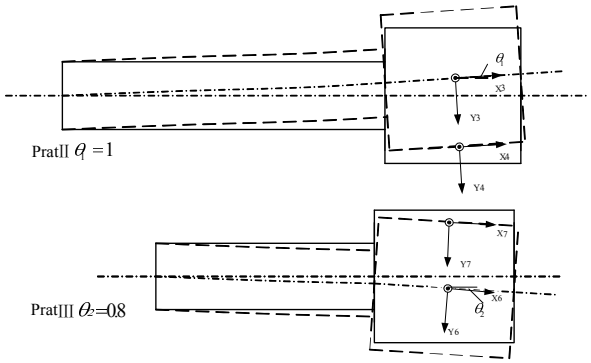

Figure 7. Bending gear axes and changing FE under meshing force

In Fig. 6, the back lash (*FR* in this example) between two gears, all correlative function factors (*FE*) and its dummy coordinate azimuth are lined out. *FE4* is graduation line of drive gear at meshing point, and *FE7* is graduation line of driven gear at meshing point. The difference between them is assembly error need to control.

Only the influence of meshing force to gear axes is taken into account. When gear pump running steadily, two acting forces in opposite direction apply to gears and make their axes bent, see Fig. 7.

Axes bend brings changes of $[R_0^i]$, W_i^n and $[R_{PTi}]$, and then $[J]$ will change correspondingly. $[R_{PTi}]$ is correlative to $[FE]$, $[FE]$ changes also. All variables of Jacobian method in free status will change.

Calculating results of assembly error are listed in Table Ⅰ. It can be found that, because of meshing force, assembly clearance increases, namely the back lash between two gears increases. Accordingly, the parallelism error of gear axes in *Y* direction has a notable increase.

TABLE I.
ASSEMBLY ERROR CALCULATING RESULTS

	Central distance deviation (mm)	Axes parallelism error	
		Δf_x	Δf_y
Free	[-0.179, 0.178]	[-0.026, 0.026]	[-0.026，0.026]
Working	[-0.212, 0.226]	[-0.026, 0.026]	[-0.564，0.564]

B. Behavior Change Prediction under Operating Loads

According to practical testing data and assembly requirements, the deviations of central distance of drive and driven gear should be limited at [-0.25, 0.25], here $n_o = 0.25$. Then

$$k = \frac{1}{2} n_0^{-1/3} = 0.7937$$

For central distance deviation [-0.178, 0.18] in free status, $x = 0.179$, its *BLI* can be calculated as follows,

$$BLI = L(x) = k(n_0^{1/3} + (x - n_0)^{1/3}) = 0.1713 = 17.13\%$$

Under the influence of working environment, the central distance deviation will be [-0.212 ， 0.226], here $x = 0.226$, and $BLI = 0.2711 = 27.11\%$.

Though *BLI* in working condition, shown by calculating results, locates in compensation phase, gear pump loses more approximate 10% (27.11%-17.13%) behavior because working environment influence, bringing the pump to the edge of rapid loss phase. Based the result, it can be determined to adopt improving measurements such as changing structure design, assembly technics and etc.

II. DISCUSSION

Through applying extended Jacobian-Torsor to assembly analysis under operating loads, assembly relation change led by these loads can be quantificationally calculated. Combined with function of behavior loss of product, this result can be used to give a product *BLI* under operating loads. Using function of behavior loss, product *BLI* in ideal state can also be calculated. With the difference between two *BLI*s, changing information of product behavior led by operating loads can be clearly known. With characteristic value of assembly error, developer can know timely working behavior changing resulted from variations of design, producing environment or operating loads. And based on above method, developer can know reasonable design or technics parameters, realizing product quality pre-control.

It can be known in application of *BLI* method that definition of characteristic error value is very important, which is the base whether the calculating results reflect actual status or not. However, in many company especially in traditional enterprise, there has large amount of data about design, production and running of similar product to use for reference.

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About project progress using modified Jacobian-Torsor in tolerance analysis, the project team will publish a special paper later.

ACKNOWLEDGMENT

The research was done thanks to financial support of the Chinese National Natural Science Foundation project 50675159 “Digital Mockup Based Key Technology of Tolerance Design and Its Impact Forecast” and project of Mega-project of High-grade NC Machine Tools and Basic Manufacturing Equipment (2009zx04001-072-02) “HTM40100 horizontal mill-turn compound machine center”.

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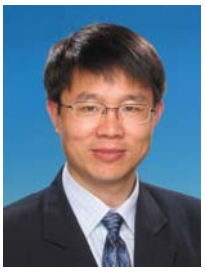

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