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Surrogate Model Based Uncertainty Analysis and Key Process Parameter Determination for Product Reliability in Assembling Process

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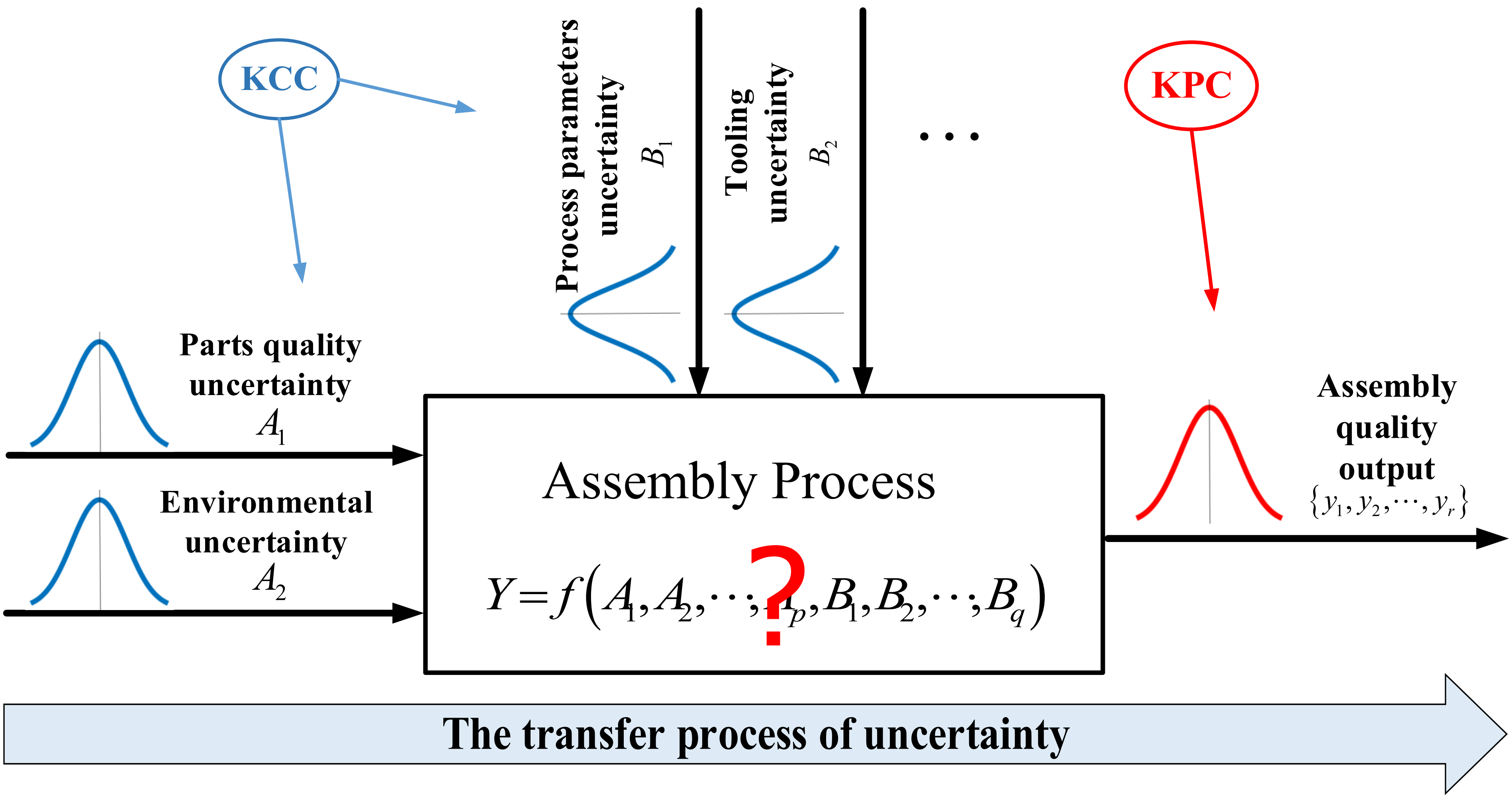
Problem

Some facts:

- Assembly is an important stage in product manufacturing process.
- The values of assembly quality characteristics are often uncertain.
- The variation of assembly quality characteristic value of high reliability products must be maintained in a reasonable range.

Problem


KCC
KPC
Process parameters uncertainty
B_1
Tooling uncertainty
B_2
$\cdots$
Parts quality uncertainty
A_1
Environmental uncertainty
A_2
Assembly Process
$Y=f(A_1,A_2,\cdots,A_p,B_1,B_2,\cdots,B_q)$
?
Assembly quality output
$\{y_1,y_2,\cdots,y_r\}$
The transfer process of uncertainty

Problem

Research Questions:

- How to quantify the uncertainty in assembly process?
- How to reduce the fluctuation of assembly quality?

Methods

- Uncertainty Analysis Methods
  - Non-probabilistic method
    - Evidence theory
    - Possibility theory
    - Convex model
    - …
  - Probabilistic method
    - Monte Carlo Simulation(MCS)
    - Discrete probability tree
    - Bayesian Analysis
    - …

Methods

Advantages and disadvantages of MCS

Advantages

- Simple principle
- High accuracy
- Multiple unknown quantities can be calculated at the same time

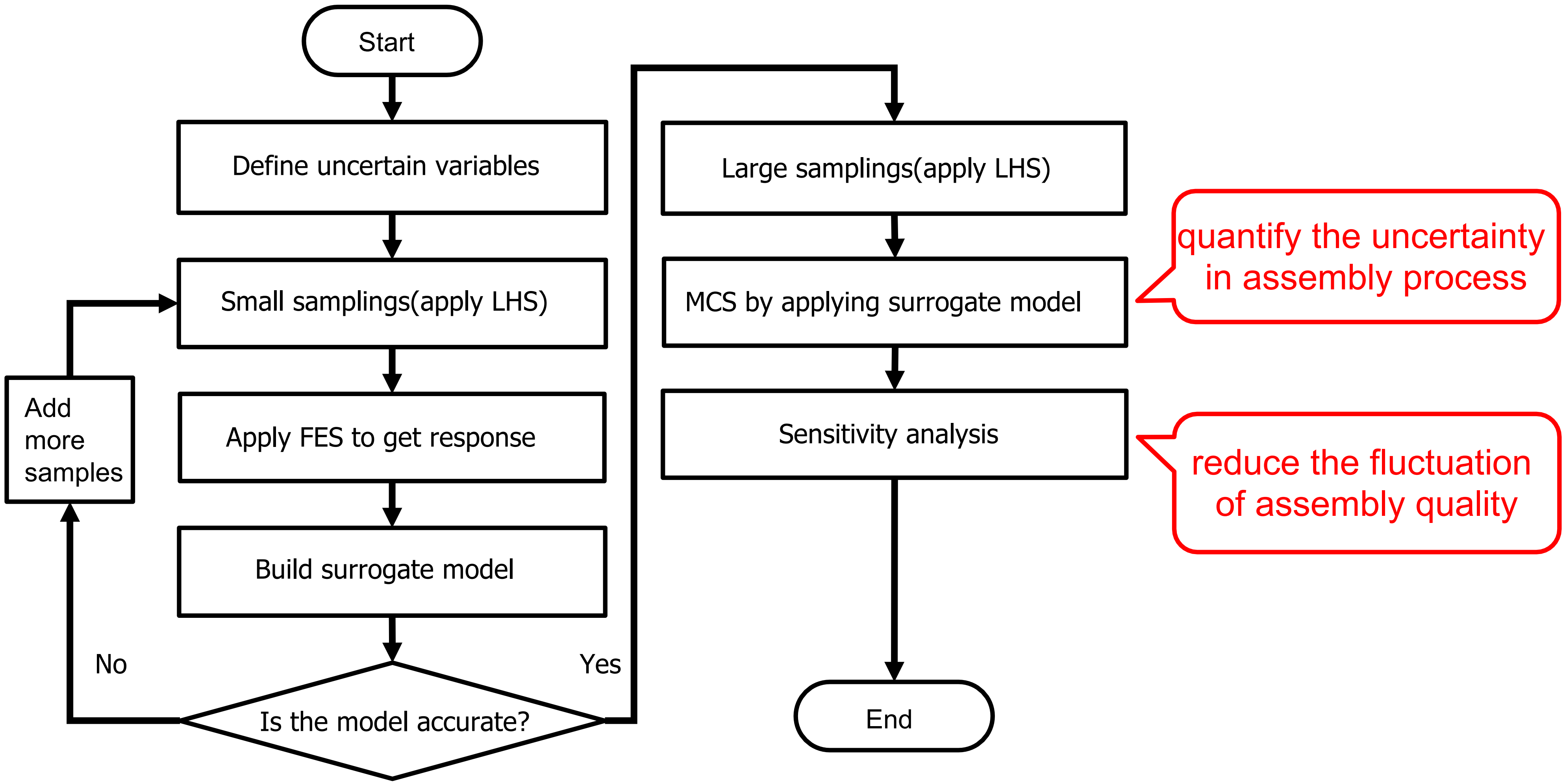
Disadvantages

- Large sample demand
- low computation speed

MCS using Surrogate model

- Using small sample data to obtain the complex mapping relationship between KCC and KPC
- Increase the speed of calculation

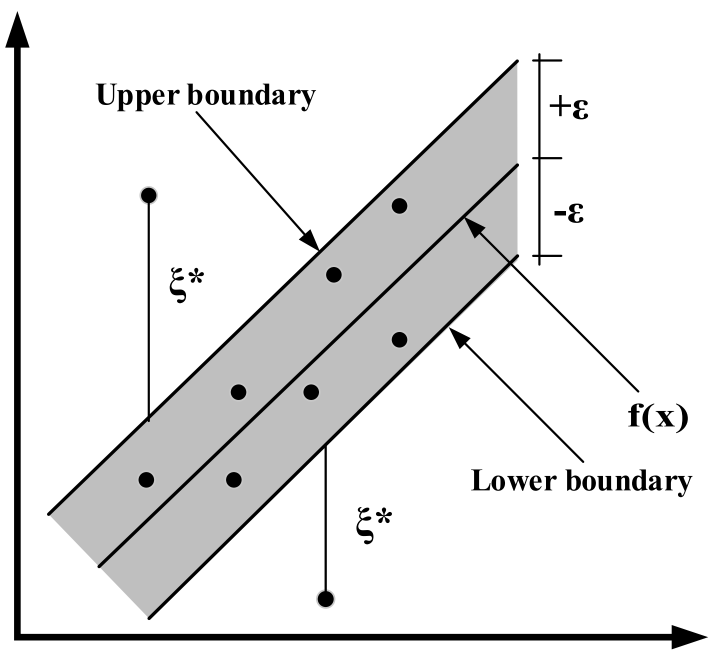
Flowchart of the surrogate model based uncertainty analysis



Construction of surrogate model

Support vector regression(SVR)

$$f(x) = \omega \cdot \varphi(x) + b \quad \omega, b?$$



$$\Downarrow$$

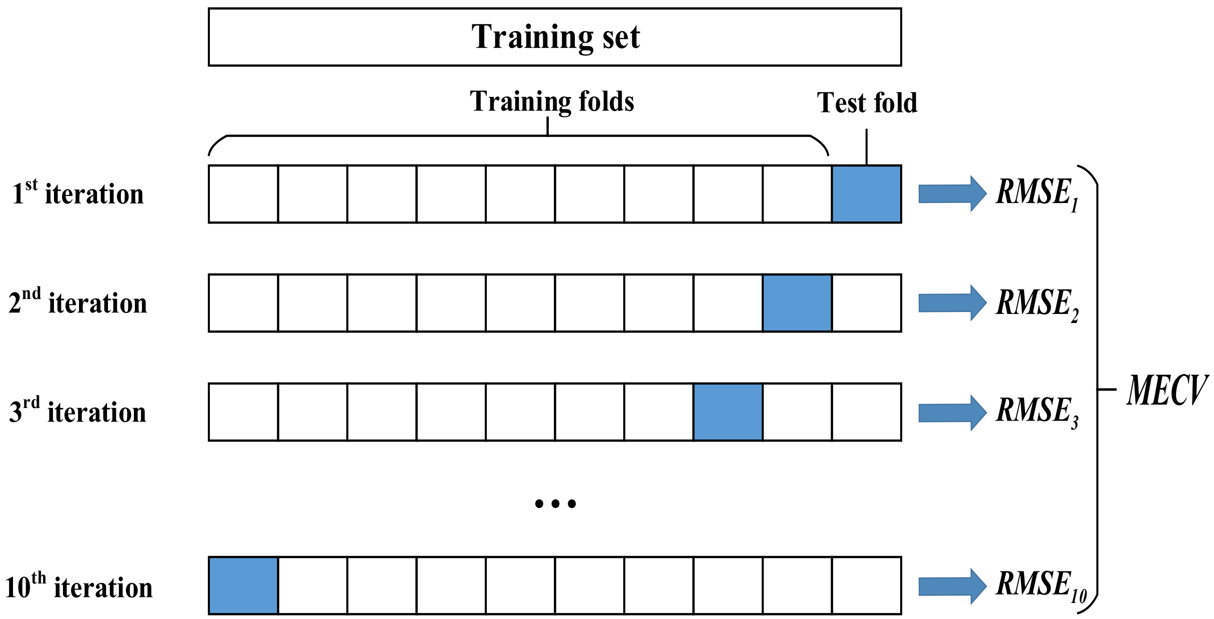
$$\boxed{\begin{aligned} &\min && \frac{1}{2}\|\omega\|^2 + c\sum_{i=1}^{n}(\xi_i + \xi_i^*) \\ &s.t. && \begin{cases} y_i - \omega \cdot \varphi(x_i) - b \le \varepsilon + \xi_i \\ \omega \cdot \varphi(x_i) + b - y_i \le \varepsilon + \xi_i^* \\ \xi_i, \xi_i^* \ge 0 \end{cases} \end{aligned}}$$

$$\Downarrow$$

Get *w* and *b*

Construction of surrogate model

Validation method of surrogate model accuracy



$$MECV = \frac{1}{k}\sum_{i=1}^{k} RMSE_k \qquad RMSE = \sqrt{\frac{1}{m_t}\sum_{i=1}^{m_t}(y_i - \widehat{y}_i)^2}$$

Steps:

1. Divide the experimental or simulation data into *k* equal parts;
2. Take one part for the validate of model accuracy, and the remaining parts are used as model training;
3. When each part has been used as model validation, stop training, take the model which has minimum residual error as the final model.

Sensitivity analysis based on MCS

Failure probability

$$P_f = P\{F\} = P\left\{y(x) < y^*_{down} \,||\, y(x) > y^*_{up}\right\} \qquad P_f = \int\cdots\int_F f_x(x_1, x_2, \cdots, x_n) dx_1 dx_2 \cdots dx_n$$

Dimensional sensitivity

$$S_{\theta^h_{x_i}} = \frac{\partial P_f}{\partial \theta^h_{x_i}}$$

$$= \int\cdots\int_F \frac{\partial f_X(\boldsymbol{x})}{\partial \theta^h_{x_i}} d\boldsymbol{x}$$

$$= \int\cdots\int_F \frac{\partial f_X(\boldsymbol{x})}{\partial \theta^h_{x_i}} \frac{1}{f_X(\boldsymbol{x})} f_X(\boldsymbol{x}) d\boldsymbol{x}$$

$$= E\left[\frac{I_F(\boldsymbol{x})}{f_X(\boldsymbol{x})} \frac{\partial f_X(\boldsymbol{x})}{\partial \theta^h_{x_i}}\right]$$

$$\hat{S}_{\theta^h_{x_i}} = \frac{1}{m}\sum_{j=1}^{m} \frac{I_F(\boldsymbol{x}_j)}{f_X(\boldsymbol{x}_j)} \frac{\partial f_X(\boldsymbol{x})}{\partial \theta^h_{x_i}}\bigg|_{\boldsymbol{x}=\boldsymbol{x}_j}$$

Dimensionless sensitivity

$$S_{\theta^h_{x_i}} = \frac{\partial P_f / P_f}{\partial \theta^h_{x_i} / \sigma_{x_i}}$$

$$= \int\cdots\int_F \frac{\sigma_{x_i}}{P_f} \frac{\partial f_X(\boldsymbol{x})}{\partial \theta^h_{x_i}} d\boldsymbol{x}$$

$$= \int\cdots\int_F \frac{\sigma_{x_i}}{f_X(\boldsymbol{x})} \frac{\partial f_X(\boldsymbol{x})}{\partial \theta^h_{x_i}} \frac{f_X(\boldsymbol{x})}{P_f} d\boldsymbol{x}$$

$$= E\left[\frac{\sigma_{x_i}}{f_X(\boldsymbol{x})} \frac{\partial f_X(\boldsymbol{x})}{\partial \theta^h_{x_i}}\right]$$

$$\hat{S}_{\theta^h_{x_i}} = \frac{1}{m}\sum_{j=1}^{m} \frac{\sigma_{x_i}}{f_X(\boldsymbol{x}_j)} \frac{\partial f_X(\boldsymbol{x})}{\partial \theta^h_{x_i}}\bigg|_{\boldsymbol{x}=\boldsymbol{x}_j}$$

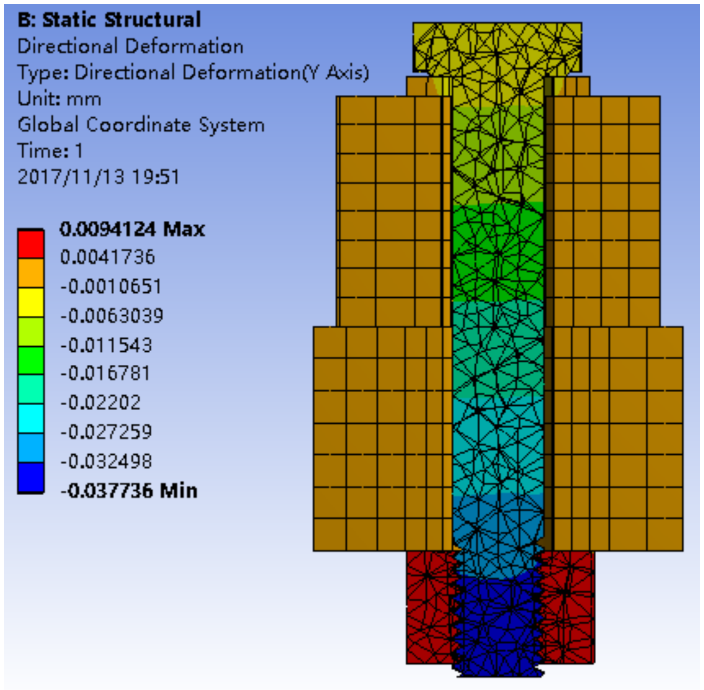
For normal variables

$$\hat{S}_{\sigma_{x_i}} = \frac{\partial P_f / P_f}{\partial \sigma_{x_i} / \sigma_{x_i}} = \frac{1}{m}\sum_{j=1}^{m} (u_{ji}^{\ 2} - 1)$$

$$\hat{S}_{\mu_{x_i}} = \frac{\partial P_f / P_f}{\partial \mu_{x_i} / \sigma_{x_i}} = \frac{1}{m}\sum_{j=1}^{m} u_{ji}$$

Case study

Finite element simulation of bolt assembly



Entity model parameters

major diameter: 10mm **pitch diameter:** 9.026mm

minor diameter: 8.376mm **pitch:** 1.5mm

half-thread angle: 30° **bolt effective length:** 65mm

FES parameters

material of the bolt, nut and gasket: stainless steel

material of connecting parts: structural steel

grid size of bolt, nut and gasket: 1mm

grid size of connecting parts: 3mm

elastic modulus: 1.93×10^{13}pa

friction coefficients: 0.15, 0.2

Loading parameters

torque: 20N **loading time:** 1s

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Case study

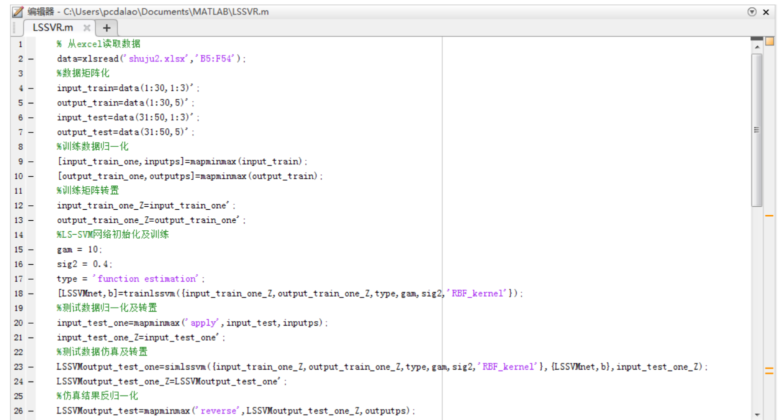
Construction of surrogate model

Table 1 The probability parameters of uncertain variables

Variable	Mean value	Standard Deviation
T	$20000(N \cdot mm)$	133
u_1	0.15	0.001
u_2	0.2	0.00133

Table 2 Samples and responses of bolt assembly with sample number of 50

Number	Inputs			Outputs	
	$T(N \cdot mm)$	u_1	u_2	$\Delta L(mm)$	$F_0(N)$
1	19896	0.1474	0.2038	0.0374	6121.364
2	20040	0.1509	0.1993	0.0378	6186.691
3	19624	0.1521	0.1967	0.0372	6090.653
4	19960	0.1505	0.2036	0.0372	6092.076
5	19656	0.1484	0.1974	0.0375	6139.046
⋮	⋮	⋮	⋮	⋮	⋮



MECV = 3.63

Meet the needs of MCS!

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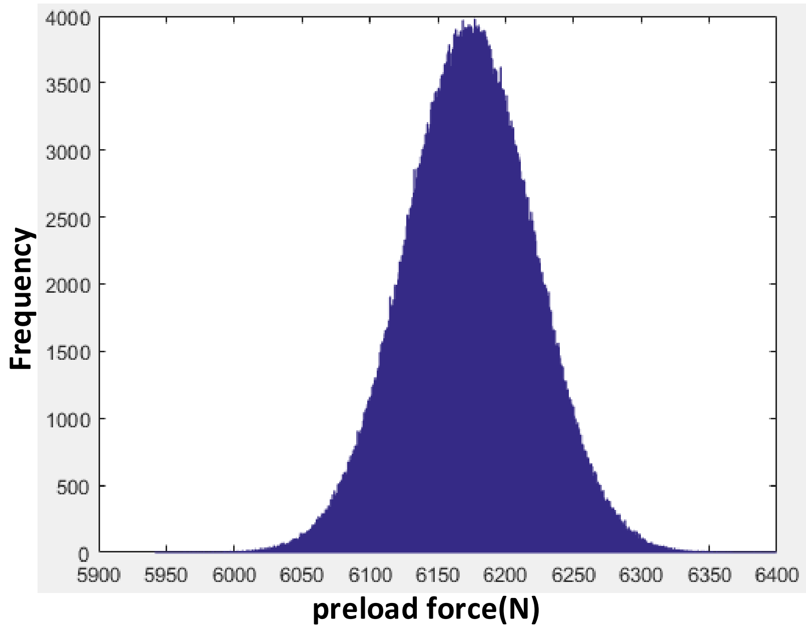
Case study

Surrogate model based MCS and sensitivity calculation



Calculation results

mean: 6173N

standard deviation: 2205N

qualified rate: 89% (between 6100N to 6250N)

calculation time: 30s

Table 3 Result of uncertain variables Sensitivity

	T	u_1	u_2
$S_\mu(\times 10^{-7})$	17.618	3.914	2.747
$S_\sigma(\times 10^{-7})$	-10.142	1.394	1.400

Torque T is the key factor

Closure

❖ This paper include

- *Theory* and *steps* of an uncertainty analysis method in product assembly process based on surrogate model and Monte Carlo Simulation.
- A *case study* of bolt assembly to verify the efficiency and correctness of the proposed method.

❖ Future work

- How to determinate the *influencing factors* of assembly quality exactly before the uncertainty analysis?
- How to analyze the sensitivity of parameters if they are *not random variables*?

Acknowledgements

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Thanks for your listening!

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