A 60 MN Build-up Force Transfer System

Wan-sheng LI, Qing-zhong LI, Yu-cheng ZHAO, Yong SUN, Yun-hai SUN, Jian-guo WANG

ABSTRACT

This paper is an elaboration on principles, constructions and main specifications of a 60 MN force transfer system (FTS). This FTS is the biggest one in the world and used to do inter-comparison with force standards and transfer or calibrate large force for material manufacture such as metal forging, construction, shipbuilding, mining, etc. We have raised additional budget of its connecting to the uncertainty and non-uniformity of force applied to the FTS.

FOREWORD

The 60 MN build-up force transfer system, which is used to transfer or calibrate large force over 20 MN and to do inter-comparison with force standards, was established in 2014 in Fujian Institute of Metrology (FJIM), China. It had been used to compare large force between 60 MN build-up force standard machine (BM) in FJIM and 30 MN hydraulic amplification force standard machine (HM) in NPL, UK\textsuperscript{1,2,3}. The principles, constructions and main specifications of the 60 MN FTS are elaborated in this paper.

PRINCIPLE AND CONSTRUCTION

Appearance of the FTS, as is shown in figure 1, is consisted of three 20 MN load cells in parallel, and some connecting parts such as a base, a middle-plate, an upper-plate, and a couple of ball-seat for centering load applied, etc. The FTS has a height of 1.23 m, a weight of 3.5 t, a maximum outside diameter of 0.83 m. Each 20MN cell, of which relative expanded uncertainty is 0.01\% (k=3), was calibrated by a 20 MN HM in National Institute of Metrology (NIM). The calibration of the FTS had been done

\textsuperscript{1}First author, Wan-sheng LI, Shandong Institute of Metrology, No.28, East Qianfoshan Road, Jinan, China
Second author, Qing-zhong LI, Fujian Institute of Metrology, No.9, Pingdong Road, Fuzhou, China
Third author, Yu-cheng ZHAO, Shandong Institute of Metrology, Jinan, China
Fourth author, Yong SUN, Shandong Institute of Metrology, Jinan, China
Fifth author, Yun-hai SUN, Jinan Zhongluchang Testing Machine Manufacture Co. Ltd, Jinan, China
Sixth author, Jian-guo WANG, Jinan Xinguang Testing Machine Manufacture Co. Ltd, Jinan, China.
for two times following ISO 376-2011. The instrument of model DMP-40 made by HBM was used in calibration. In fact, it would be better to use three DMP-40 together to eliminate the influence of switching on the test results.

Figure 2 shows traceability of standard force generated by the 60 MN BM and the 30 MN HM to the 20 MN HM via the 60 MN FTS.

**MAIN SPECIFICATIONS**

**Specification of the Cells**

The three 20 MN cells are No. 001, No.002 and No.025. The No.001 and the No.002 were calibrated by the NIM 20 MN HM for two times while the No. 025 for three times following ISO 376-2011. The calibration results were listed in table 1: Eight budgets had contributions to the relative combined uncertainty of output of each cell, including the repeatability, the rotation effect, the resolution of the force, the zero recovery, the interpolation, the temperature effect on output, the long-term stability, and the relative expanded uncertainty of the force generated by the 20 MN HM.

**TABLE 1. CALIBRATION RESULTS OF THE 3 CELLS.**

<table>
<thead>
<tr>
<th>Cell</th>
<th>R (%)</th>
<th>R_σ (%)</th>
<th>R_e, mV/V</th>
<th>Z_σ mV/V</th>
<th>I_p (%)</th>
<th>S/°C</th>
<th>S_b %</th>
<th>w.cell %</th>
<th>W.cell%, k=2</th>
</tr>
</thead>
<tbody>
<tr>
<td>No.001</td>
<td>0.010</td>
<td>0.030</td>
<td>0.00004</td>
<td>0.00065</td>
<td>0.001</td>
<td>±</td>
<td>0.04</td>
<td>0.03</td>
<td>0.06</td>
</tr>
<tr>
<td>No.002</td>
<td>0.003</td>
<td>0.009</td>
<td>0.00042</td>
<td>0.0001</td>
<td>0.01%</td>
<td>±</td>
<td>0.06</td>
<td>0.04</td>
<td>0.08</td>
</tr>
<tr>
<td>No.025</td>
<td>0.010</td>
<td>0.020</td>
<td>0.00070</td>
<td>0.0002</td>
<td>0.01%</td>
<td>±</td>
<td>0.01</td>
<td>0.024</td>
<td>0.048</td>
</tr>
</tbody>
</table>

Remarks: 1) R-an average of the repeatability; R_σ-an average of the rotation effect; R_e-an average of the resolution; Z_σ-an average of the zero recovery; I_p-an average of the interpolation; S/°C-temperature effect on output; S_b-the long-term stability for 3 months; w.cell-an average of the relative combined uncertainty; W.cell-an average of the relative expanded uncertainty. 2) The change of temperature was taken as Δt=±2°C.

**Uncertainty Evaluation of the FTS**

Since the three cells were calibrated by the 20 MN HM, there were correlations among the three outputs. It was assumed that the correlation factors were taken as one output, and
relative combined uncertainty \( w_{3\text{cell}} \) of output-sum of the three cells in parallel would be the average of relative combined uncertainty of each cell output as following:

\[
    w_{3\text{cell}} = \frac{w_{\text{cell001}} + w_{\text{cell002}} + w_{\text{cell025}}}{3}
\]

where \( w_{\text{cell001}} \), \( w_{\text{cell002}} \), \( w_{\text{cell025}} \) are relative combined uncertainties of each cell output.

The relative expanded uncertainty \( W_{3\text{cell}} \) of output-sum of the three cells in parallel was equal to \( 2w_{3\text{cell}}(k=2) \) at a confidence level of 95% approximately. Based on the data in table 1, we can obtain \( W_{3\text{cell}} = 0.063\% \).

After considering influence of the connecting of the FTS on the relative expanded uncertainty \( W_{3\text{cell}} \), it was taken 1.2 times of \( W_{3\text{cell}} \) as final relative expanded uncertainty \( W_{f\text{ts}} \) as:

\[
    W_{f\text{ts}} = 1.2W_{3\text{cell}} = 0.076\%
\]

which had been confirmed in the inter-comparison of the force standards between China and UK.

**Additional Budget of \( W_{3\text{cell}} \)**

There was an additional factor to the relative expanded uncertainty, which was caused by the connecting of the FTS, and expressed as \( \alpha_{\text{FTS}} \). The \( \alpha_{\text{FTS}} \) was evaluated as \( 1 \leq \alpha_{\text{FTS}} \leq 1.5 \).

When a FTS is used as a reference standard to measure or control force generated by a build-up machine, it was called “Force Measuring System-FMS”, the \( \alpha_{\text{FTS}} \) above could be called \( \alpha_{\text{FMS}} \), being equal to \( \alpha_{\text{FTS}} \).

**Non-uniformity of Load Applied**

There was another factor called non-uniformity \( \beta_i \) which is caused by eccentricity of the load applied. \( \beta_i \) was represented non-uniformity of the load applied on the \( i^{th} \) cell as following:

\[
    \beta_i = f_i / \sum f_i - 1/n = f_i / F - 1/n
\]

where

\( f_i \) - the load applied on the \( i^{th} \) cell, MN or kN;

\( \sum f_i = F \) - a total load applied on a FTS or a FMS;

\( n \) - number of cells in parallel, usually 3.

Based on experiments, while the total load is applied on the FTS or FMS, it is not equal that each cell is loaded, which means \( \beta_i \neq 0 \). When it is \( \beta_i > 0 \), the load applied on the \( i^{th} \) cell is bigger than the average of load applied on each cell, namely \( f_i > F/n \); while \( \beta_i < 0 \), and \( f_i < F/n \).

While the full scale load is applied on the FTS or FMS, it would be concentrated that the maximum value of the \( \beta_i \) expressed as \( \beta_{\text{max-fs}} \). When \( \beta_{\text{max-fs}} = 3.3\% \) (\( n=3 \), same bellow), the responsible cell would be applied as much as 110%FS. Similarly if the 10%FS is applied on the FTS or FMS, it would be considered that the minimum value of the \( \beta_i \)
expressed as $\beta_{\text{min}-10\%fs}$. While $\beta_{\text{min}-10\%fs} = -16\%$, the responsible cell would be applied as low as 5\%fs of the cell.

**EXAMPLES**

**Example 1**

The 60 MN FTS was used to make inter-comparison of the 60 MN BM (as shown in figure 3), FJIM and 30 MN HM (as shown in figure 4), NPL in September, 2014.

![Figure 3. A photo of the 60 MN BM in FJIM.](image)

![Figure 4. A photo of the NPL 30 MN HM.](image)

The test method used was similar to the Key-comparison of the force\(^6,7,8,9\), of which 20 MN and 30 MN were taken as test points.

The test results were showed in figure 5, which covered 1) indication error for each machine including the first test ($d_{A1}$) and the second test ($d_{A2}$) on 60 MN BM, which were within $\pm 0.02\%$; the test on 30 MN HM ($d_B$), which were within $\pm 0.055\%$; 2) the relative combined uncertainty of the force generated by each machine being less than 0.03\% for the 60 MN BM, 0.041\% for the 30 MN HM, of which budgets were repeatability and rotation error of the force, resolution of the FTS, zero recovery of the each cell in parallel, the indication error of the machine, and relative expanded uncertainty of the FTS.

![Figure 5. Calibration results of the two machines by the FTS: Indication error, relative combined uncertainty of the force generated by the two machines vs the force.](image)

Figure 6 shows that non-uniformity calculated of the force generated by the 60 MN BM on the 60 MN FTS (It was tested for three times on 0° position, one time on 120° as well as 240° and 360°, same as below). It could be seen that the maximum value of the non-uniformity was $\beta_{\text{max-30}} = 3.32\%$ appearing at 240° position of the FTS on the machine (shown as b53), which was responsible to the No. 025 cell.

Figure 7 shows that non-uniformity calculated of force generated by the 30 MN HM on the 60 MN FTS. It could be seen that $\beta_{\text{max-30}} = b51 = 1.42\%$, appearing at 240°, which is responsible to the No. 001 cell.
It could be seen from the figure 6 and figure 7 that several factors had influence on the non-uniformity, including self-characteristics of the FTS, load applied, position of the FTS on the machines, characteristics of the machines, mutual-influence of the machines and the FTS. It was clearly that the non-uniformity was decreasing with load applied up.

**Example 2**

In order to evaluate the relative combined uncertainty of the force generated by the 60 MN BM with the 60 MN FTS by means of the indirect method, as well as its non-uniformity, the 60 MN BM was recalibrated in October, 2014. Range of force calibrated was (6-60) MN. The calibration method was as followings: 1) preloading up to the rated force for three times step by step, and testing for three times at the 0° position; 2) turning the FTS around its vertical axial at 120°, then 240° and 360°, preloading and testing once on each position; 3) reading time at the non-zero load was taken as 2 min., and 3 min. at the zero load.

The calibration results of the 60 MN BM and its uncertainty evaluation are listed in
The indication error and the relative expanded uncertainty of the force are shown in figure 8. It could be seen that the indication error was within ±0.05%, the relative expanded uncertainty was less than 0.1%(k=2), at a approximate confidence level of 95%.

### Table 2. Calibration Results of the 60 MN BM and Its Uncertainty Evaluation.

<table>
<thead>
<tr>
<th>Force</th>
<th>MN</th>
<th>R</th>
<th>R_{ot}</th>
<th>R_{pred}</th>
<th>d_{F}</th>
<th>( w_{60\text{MNBM}} )</th>
<th>( w_{60\text{MNBM}.k=2} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>6E-04</td>
<td>1.6E-04</td>
<td>5.4E-04</td>
<td>0</td>
<td>3.1E-04</td>
<td>4.6E-04</td>
<td>9.3E-04</td>
</tr>
<tr>
<td>10</td>
<td>9.3E-05</td>
<td>4.5E-04</td>
<td>2.0E-05</td>
<td>-1.8E-16</td>
<td>1.4E-04</td>
<td>4.0E-04</td>
<td>7.9E-04</td>
</tr>
<tr>
<td>20</td>
<td>6.6E-05</td>
<td>2.0E-04</td>
<td>-2.8E-05</td>
<td>1.0E-05</td>
<td>3.4E-04</td>
<td>4.3E-04</td>
<td>8.6E-04</td>
</tr>
<tr>
<td>30</td>
<td>5.6E-05</td>
<td>1.1E-04</td>
<td>-4.5E-05</td>
<td>3.0E-05</td>
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<td>4.1E-04</td>
<td>8.3E-04</td>
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<tr>
<td>40</td>
<td>5.2E-05</td>
<td>8.5E-05</td>
<td>0</td>
<td>1.4E-04</td>
<td>2.7E-04</td>
<td>4.1E-04</td>
<td>8.3E-04</td>
</tr>
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<td>50</td>
<td>4.5E-05</td>
<td>6.6E-05</td>
<td>2.0E-06</td>
<td>1.4E-04</td>
<td>2.7E-04</td>
<td>4.1E-04</td>
<td>8.3E-04</td>
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<tr>
<td>55</td>
<td>4.3E-05</td>
<td>5.6E-05</td>
<td>-1.1E-05</td>
<td>2.8E-04</td>
<td>4.1E-04</td>
<td>8.3E-04</td>
<td></td>
</tr>
<tr>
<td>60</td>
<td>5.3E-05</td>
<td>5.7E-05</td>
<td>3.3E-06</td>
<td>3.2E-04</td>
<td>4.2E-04</td>
<td>8.5E-04</td>
<td></td>
</tr>
</tbody>
</table>

Remarks:
- R: Repeatability of the 60 MN BM;
- R_{ot}: Rotation effect of the 60 MN BM;
- R_{pred}: Reproducibility at position 0°;
- d_{F}: the indication error of the 60 MN BM;
- \( Z_r/f_s = 0.00002/f_s \): the zero recovery divided by the rated output;
- \( R_{es} \): the resolution = 0.2 kN which was taken at the pick to the pick of output as the fluctuation of the 60 MN BM;
- \( w_{FTS} = 0.038\% \): relative combined uncertainty of the 60 MN FTS.

![Figure 8](image1.png)

Figure 8. Indication error of the 60 MN BM, relative expanded uncertainty vs. force.

![Figure 9](image2.png)

Figure 9. Non-uniformity of the 60 MN FTS vs force.
Figure 9 shows the non-uniformity of force applied on the 60 MN FTS. It could be seen that: 1) the absolute value of the non-uniformity was decreasing with the force applied on the FTS increasing; 2) at the force point of 10%fs, 6 MN, the $\beta_{min.10%fs}=b_{51}=-11.8\%$, the responsible cell was No.001, the FTS was located on the position 240°, the cell was applied at 1.3 MN. Since then, each cell would be calibrated as low as 5%fs=1MN, otherwise, the specifications of the cells could be effected; 3) at the force point of 100%fs, 60 MN, the $\beta_{max.fs}=b_{53}=3.2\%$, the responsible cell was No.025, the FTS was located in the position 240°, the cell was applied at 21.9 MN. Since then, each cell would be calibrated as much as 110%fs, 22MN, otherwise, the specifications of the cells could be effected; 4) It would be consequent that the $\beta_{min.10%fs}$ and $\beta_{max.fs}$ were located at the same position of the FTS.

Figure 10 shows the non-uniformity of force applied on the 60 MN FMS of the 60 MN BM, which consisted of three HBM 20 MN cells as the force measuring system.

It could be seen that: 1) the absolute value of the non-uniformity was decreasing with the force applied on the FMS increasing; 2) at the force point of 10%fs, 6 MN, the $\beta_{min.10%fs}=b_{13}=-1.58\%$, the responsible cell was located in the position 0°, the cell was applied at 1.91 MN. Since then, it was accepted that each cell was calibrated as 10%fs, 2MN. 3) at the force point of 100%fs, 60 MN, the $\beta_{max.fs}=b_{11}=0.43\%$, the responsible cell was located in the position 0°, the cell was applied at 20.26 MN. Since then, it was accepted that each cell was calibrated as 100%fs, 20MN.

![Figure 10. Non-uniformity of the FMS of the 60 MN BM vs force generated.](image)

**CONCLUSION**

The paper has given the traceability of the force generated by the 60 MN BM to the 20 MN HM in NIM; uncertainty evaluation method of the build-up force transfer system or force measuring system; the 60 MN FTS used to calibrate the 60 MN BM, FJIM, China, as well as the 30 MN HM, NPL, UK, and evaluation of the uncertainty based on the calibration results.
It has been raised that 1) the additional factor of the relative expanded uncertainty of the FTS or FMS, which was caused by the connecting of the FTS or FMS, and expressed as $\alpha_{FTS}$ or $\alpha_{FMS}$. The $\alpha_{FTS}$ or $\alpha_{FMS}$ was evaluated as $1 \leq \alpha_{FTS} \leq 1.5$; 2) the non-uniformity of load applied on the cells of FTS or FMS. It had been found while full-scale load is applied on the FTS or FMS, and $\beta_{max-FS} = 3.3\%$ for a cell, the each cell of FTS or FMS in parallel would be calibrated as much as $110\%$FS; while $10\%$FS load applied on the FTS or FMS, and $\beta_{min-10\%FS} = -16\%$ for a cell, the each cell would be calibrated as low as $5\%$FS.

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REFERENCES