ITTC Quality System Manual

Sample Work Instruction

Work Instruction

Calibration of Load Cells

7.6	Control of Inspection, Measuring and Test Equipment
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Disclaimer

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Calibration of Load Cells

1. PURPOSE OF INSTRUCTION

This work instruction shall be applied to the calibration of load cells including dynamometers in towing tank resistance tests and thrust and torque transducers for propulsion tests. All calibrations shall be traceable to the National Metrology Institute (NMI) of each country. The information is applicable to calibrations within an ITTC laboratory and calibrations by a contractor.

2. SCOPE

The instruction defines the load-cell calibration requirements in naval hydrodynamics testing for ITTC. Additional information on instrument calibration is located in ITTC 7.5-01-03-01 (2017). Details on force calibration is contained in ASTM (2018).

Typically, load cells are calibrated on a calibration stand with weights. The calibration of the weights is described in ITTC Procedure 7.6-02-08 (2020).

3. WORK INSTRUCTION

3.1 Technical Requirements

3.1.1 Weight Set Requirements

The weight set shall meet the requirements of Class M_2 per OIML (2004) with a minimum tolerance of 0.016 %. The calibration of the weight set shall be traceable to an NMI. Additional requirements on the weights are contained in ITTC Procedure 7.6-02-08 (2020).

3.1.2 Calibration Interval

The minimum recommended calibration interval is annual. Preferably, a load cell should be calibrated just prior to the test and immediately after the test. If the calibration is in-house, the data acquisition system (DAQ) for calibration should be the same system for the test.

3.1.3 Certificates

The calibration certificate should include the following information:

- Date of the calibration and name of the person performing the calibration
- Weight classification with the calibration date and calibration due date
- Information on the data acquisition system: manufacturer, model and serial number, low pass filter setting, data rate, sampling interval, and number of samples
- List of applied loads in mass units (kg) and force units (N) and resulting voltage output with standard deviation if the results are from a DAQ
- Resolution of the output shall be consistent with the uncertainty estimate or the standard deviation of the voltage output.

3.2 Calibration Procedure

The load cell should be calibrated over the anticipated range of loads in the test. Calibration should be performed over a minimum of 10 increments with two measurements at each load.

ASTM (2018) recommends at least 30 force applications. The load cell should be loaded to its maximum range twice before data are taken.

4. ANALYSIS

4.1 Data Processing Equations

The loads in mass units during calibration are converted to force units by the following equation from ITTC 7.5-01-03-01 (2017) and ASTM (2018).

$$F = mg(1 - \rho_\mathrm{A}/\rho_\mathrm{M}) \tag{1}$$

where m is the mass in kg, g is local acceleration of gravity in m/s^2, ρ_A is air density, and ρ_M is the density of the weight in kg/m^3. The nominal values for Equation (1) are as follows:

g	9.80665 m/s^2 for standard gravity
ρ_A	1.2 kg/m^3
ρ_M	8000 kg/m^3

Local gravity is typically less than standard gravity. In the United States, local gravity may be calculated from Moose (1986). Previously, local gravity could be computed anywhere in the world from PTB (2019), but the PTB web page computation is currently unavailable. The last term in Equation (1) is an air buoyancy correction from Archimedes principle and is typically 0.017 %. The mass in Equation (1) is the sum of the weights added to the calibration stand.

$$m = \sum_{i=1}^{n} m_i \tag{2}$$

A calibration stand may include levers for increasing the force, in which case the force multiplier should be included in the above as follows

$$F_{L1/L2} = F(L_1/L_2) \tag{3}$$

where F is the force from Equation (1) and L_1 and L_2 are the length of the levers.

For thrust in a propulsion performance test, Equations (1) and (3) are applicable. Torque is computed as follows:

$$M = FL \tag{4}$$

where F is the force in N and L the length in m.

4.2 Uncertainty Analysis

Uncertainty estimates are obtained by application of the law of propagation of uncertainty from JCGM (2008) and ITTC 7.5-02-01-01 (2014). From Equation (1), the dominant term is in the uncertainty of the mass. Since the weights are calibrated to the same standard, the results are correlated. From ITTC Procedure 7.6-02-08 (2020), the combined and expanded uncertainty in mass is then

$$U_\mathrm{c} = \sum_{i=1}^{n} U_i = \sum_{i=1}^{n} \delta m_i \tag{5}$$

where δm_i is the tolerance of each weight. Nominally, the tolerance of 0.016 % is applied as the uncertainty estimate; consequently, the relative uncertainty in the force, F, is 0.016 % for Class M$_2$ weights or

$$U_F/F = U_m/m \tag{6}$$

From Equation (3), the relative uncertainty in force with the inclusion of the lever arms is

$$\frac{U_{F\mathrm{a}}}{F_\mathrm{a}} = \sqrt{\left(\frac{U_m}{m}\right)^2 + \left(\frac{U_{L1}}{L_1}\right)^2 + \left(\frac{U_{L2}}{L_2}\right)^2} \tag{7}$$

In this case, the dominant term is from the relative uncertainty in the shorter lever length as likely the two lengths are fabricated to the same tolerance, $U_{L1} = U_{L2}$.

From Equation (4), the relative uncertainty in the moment is

$$\frac{U_M}{M} = \sqrt{\left(\frac{U_F}{F}\right)^2 + \left(\frac{U_L}{L}\right)^2} \tag{8}$$

4.3 Example

As an example, the following is a discussion of a user calibration of a Kempf and Remmers H48 dynamometer in thrust on a Kempf and Remmers calibration stand at the U. S. Navy David Taylor Model Basin (DTMB). The following is a summary of the calibration parameters:

- Weights: NIST (1990) Class F with a tolerance of ±0.010 % in pounds mass (lbm)
- Local gravity, g: 9.80101 ±0.00004 m/s^2 from Moose (1986)
- Standard air density, ρ_A: 1.20 kg/m^3
- Conventional mass density for the weights, ρ_M: 8000 kg/m^3
- Sample rate: 100 Hz
- Sample interval: 5 s
- Number of samples: 500
- Calibration magnification: 5

The dynamometer was calibrated by two methods: sequential loading and random loading. In the sequential method, the load was increased in two lbm increments from zero (0) to 24 lbm and then decreased to zero (0). Thirteen (13) different weights were applied with a minimum of two repeats. For random loading, 15 different loads were applied with no repeats. The sequence of the applied loads is illustrated in Figure 1. The conversion factor from lbm to kg is 0.4535924 from Thompson and Taylor (2008).

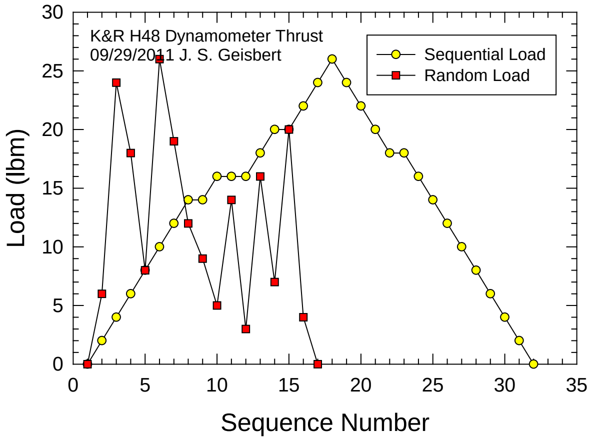

Figure 1: Loading sequence for Kempf & Remmers H48 dynamometer in thrust

The calibration results are presented as a residual plot in Figure 2. The analysis was performed per the instrument calibration procedure, ITTC Procedure 7.5-01-03-01 (2017). The calibration data are listed in the tables in Appendix A. The dashed line in the figure is the 95 % prediction limit from ITTC Procedure 7.5-01-03-01 (2017).

The error bars on the individual symbols is from the combined uncertainty in the applied load from Equation (7) and the Type A method from the standard deviation in the calibration voltages. The average voltages and the standard deviation are listed in the tables in Appendix A. In this case, only the mass uncertainty from Equation (7) is included as the lengths of the moment arms for the magnification and their uncertainties were not available. If the uncertainties in the lengths were included, their contribution would likely be larger than the other elements for the individual calibration points.

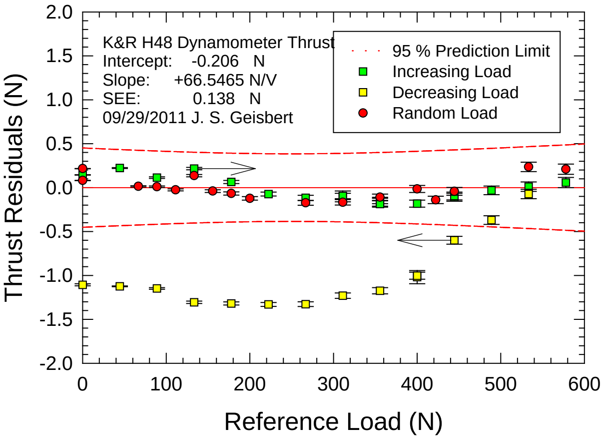

Figure 2: Calibration data for Kempf & Remmers H48 dynamometer in thrust

In Figure 2, the loads for the sequential and random loading are computed from the linear regression constants from the random load calibration. As the figure indicates, the data scatter is the largest contributor to the uncertainty. The data scatter for random loading is much smaller, and the sequential loading has a hysteresis loop.

The calibration constants are summarized in Table 1. The standard error of estimate, *SEE*, which is also a measure of the uncertainty in the curve fit, is much larger for the sequential loading. As the last column indicates, the maximum uncertainty for the sequential loading is more than 3 times larger. The Max Diff column is the largest difference in the data fit from the other data set. From a hypothesis test from ITTC Procedure 7.5-01-03-01 (2017), the slopes and intercepts for the two data sets are statistically the same. Either result as applied to the test data will yield statistically the same answer, but the uncertainty from the random loading is significantly less.

Table 1: Summary of calibration results in thrust for Kempf and Remmers H48 dynamometer (N)

Load	**N**	**Slope**	**Intercept**	**SEE**	**Max Diff**	**Umax**
Sequential	13	66.5936	-0.870	0.561	1.33	1.67
Random	15	66.5465	-0.206	0.138	0.88	0.49

5. SUMMARY

This work instruction describes the calibration of a dynamometer or load cell on a calibration stand with weights. As a minimum, the weights should be OIML (2004) class M_2 with a tolerance of ±0.016 %. The instruction also outlines the uncertainty analysis for the calibration. The calibration shall be traceable to an NMI and follow the procedures in this instruction and ASTM (2018).

Traditionally, the calibration is performed with the addition of weights sequentially and then removing them sequentially. The result is usually a hysteresis loop as shown in Figure 2. The preferred method is random loading per ASTM (2018). For the example in this instruction, the calibration results for both random and sequential loading have statistically the same calibration factors, but the uncertainty estimate is significantly less for random loading. The calibration example for random loading does not strictly follow this instruction and ASTM (2018) but was the best available for a comparison of sequential and random loading results.

6. SYMBOLS

6.1 English

F	Force	N
$F_{L1/L2}$	Force magnification, Equation (3)	N
g	Local acceleration of gravity	m/s^2
L	Length	m
M	Moment	N·m
m	Mass	kg
N	Number of applied loads	1
SEE	Standard Error of Estimate	
U	Expanded uncertainty	

6.2 Greek

ρ_A	Air density	kg/m^3
ρ_M	Weight density	kg/m^3

7. REFERENCES

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APPENDIX A: EXAMPLE DATA

Table A - 1: Calibration data for thrust of Rempf and Remmers H58 with sequential load

xref (lbm)	xref (N)	y Output (V)	StdDev (V)	Std Resid
0.00	0.000	0.00092	0.00042	1.451
2.00	44.450	0.66770	0.00039	1.536
4.00	88.900	1.33729	0.00057	1.283
6.00	133.350	2.00370	0.00039	1.411
8.00	177.800	2.67394	0.00051	1.081
10.00	222.250	3.34397	0.00044	0.777
12.00	266.700	4.01256	0.00189	0.644
14.00	311.150	4.68027	0.00893	0.617
14.00	311.150	4.68020	0.00066	0.625
16.00	355.600	5.34922	0.00442	0.442
16.00	355.600	5.34893	0.00163	0.476
16.00	355.600	5.34952	0.00041	0.405
18.00	400.050	6.01741	0.00056	0.357
20.00	444.500	6.68428	0.00060	0.429
20.00	444.500	6.68406	0.00057	0.456
22.00	488.950	7.35105	0.00083	0.514
24.00	533.400	8.01836	0.00085	0.535
26.00	577.850	8.68562	0.00166	0.562
24.00	533.400	8.01962	0.00060	0.384
22.00	488.950	7.35613	0.00065	-0.093
20.00	444.500	6.69164	0.00059	-0.450
18.00	400.050	6.02999	0.01068	-1.147
18.00	400.050	6.02975	0.00056	-1.118
16.00	355.600	5.36437	0.00046	-1.369
14.00	311.150	4.69725	0.00041	-1.413
12.00	266.700	4.03076	0.00058	-1.531
10.00	222.250	3.36285	0.00046	-1.480
8.00	177.800	2.69473	0.00029	-1.403
6.00	133.350	2.02657	0.00050	-1.322
4.00	88.900	1.35626	0.00033	-0.984
2.00	44.450	0.68794	0.00031	-0.883
0.00	0.000	0.01973	0.00188	-0.796

Table A - 2: Calibration data for thrust of Rempf and Remmers H58 with random load

xref (lbm)	xref (N)	y Output (V)	StdDev (V)	Std Resid
0.00	0.000	-0.0002	0.00032	1.568
6.00	133.350	2.00491	0.00032	0.987
24.00	533.400	8.01498	0.00071	1.711
18.00	400.050	6.01490	0.00060	-0.112
8.00	177.800	2.67591	0.00037	-0.485
26.00	577.850	8.68333	0.00067	1.520
19.00	422.275	6.35075	0.00045	-1.014
12.00	266.700	4.01342	0.00038	-1.258
9.00	200.025	3.01072	0.00031	-0.888
5.00	111.125	1.67337	0.00044	-0.188
14.00	311.150	4.68128	0.00041	-1.214
3.00	66.675	1.00481	0.00032	0.102
16.00	355.600	5.34837	0.00043	-0.794
7.00	155.575	2.34153	0.00037	-0.288
20.00	444.500	6.68327	0.00052	-0.311
4.00	88.900	1.33885	0.00031	0.075
0.00	0.000	0.00187	0.00031	0.589