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A comparative study of static, continuous, and dynamic calibration methods for high-precision low-force strain-gauge transducers

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1     **A comparative study of static, continuous, and dynamic calibration**  
2     **methods for high-precision low-force strain-gauge transducers**

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**Abstract**

The ISO 376 standard, which underpins static force calibration procedures, does not adequately address the time- and frequency-dependent effects encountered in real-world applications such as aerospace, automotive, and biomedical testing. This study investigates and compares static, continuous, and dynamic calibration methodologies applied to low-force strain-gauge transducers with capacities ranging from 50 N to 500 N. A 200 N transducer was calibrated using all three methods, while others were tested statically and dynamically. Static calibration yielded consistent sensitivity and low uncertainty across all force levels. Continuous calibration, based on DKD-R 3-9, produced comparable sensitivities but showed increased uncertainty, primarily due to reversibility effects and mechanical coupling imperfections. Dynamic calibration, conducted per DKD-R 3-10 using sinusoidal excitation, revealed a frequency-dependent sensitivity reduction, with Monte Carlo-based regression models used to characterize performance. While results across all methods are broadly compatible within declared uncertainties, significant divergence emerges when uncertainties are reduced to static levels. This raises important questions about the traceability and comparability of force measurements under non-static conditions. The findings underscore the need for further refinement in continuous and dynamic calibration methods to meet the demands of advanced material and structural testing.

**Keywords:** force transducer; force calibration; static; continuous; dynamic.

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## 72 **1. Introduction**

73 Mechanical and material testing play a vital role in a wide range of industrial domains, including aerospace,  
74 automotive, healthcare, and manufacturing, where product integrity, safety, and compliance are of critical im-  
75 portance. In these environments, force transducers are essential tools for measuring mechanical loads during  
76 both research and quality assurance processes. However, traditional force calibration methods are largely based  
77 on static loading scenarios, which do not accurately reflect the dynamic nature of many real-world applications.  
78 Effects linked to time- and frequency-dependent behavior are often neglected, undermining the metrological  
79 traceability and reliability of test data in dynamic use cases [1,2].

80 The existing ISO 376 standard [3] outlines detailed procedures for the static calibration of force transducers  
81 and is widely adopted for verifying uniaxial testing machines. However, as the use of force transducers in high-  
82 rate and cyclic loading applications becomes increasingly common, the limitations of ISO 376 have become  
83 more evident. To meet these evolving needs, new calibration approaches have been developed to extend trace-  
84 ability to continuous and dynamic loading conditions. In this regard, two complementary guidelines have  
85 emerged: DKD-R 3-9 [4], which addresses continuous calibration using comparison methods, and DKD-R 3-  
86 10 (Sheet 2) [5], which provides procedures for dynamic calibration via sinusoidal excitation. These documents  
87 aim to close the methodological gap between static calibration standards and the demands of modern materials  
88 testing and structural dynamics.

89 In parallel with these efforts, the ComTraForce project (EURAMET 18SIB08) [6] has significantly con-  
90 tributed to the advancement of dynamic force calibration methods. The project focused on developing tracea-  
91 bility solutions for force transducers operating under dynamic and continuous conditions. The project has de-  
92 livered validated primary calibration setups, improved measurement uncertainty models, and tested the ap-  
93 plicability of dynamic and continuous calibration across various transducer types. One of its core outcomes  
94 was to demonstrate the feasibility of applying dynamic and continuous calibration techniques at primary level,  
95 thereby laying the groundwork for future updates to international standards. The insights gained from ComTra-  
96 Force supported emerging calibration protocols and contributed directly to the development of novel practices.

97 Additionally, the standardization effort led by ISO/TC 164/SC 1/SG 1 [7] has sought to translate these  
98 technical advances into normative documents. The subgroup's mandate includes defining terminology, cali-  
99 bration procedures, and uncertainty evaluation methods specifically tailored for continuous force calibration.  
100 Their work reflects a growing consensus on the need to extend metrological traceability beyond static loading,  
101 especially for applications involving fast-changing , such as, material characterization, component validation,  
102 and industrial automation.

103 Within this broader overview, the present study provides a comparative investigation of high-precision  
104 strain-gauge force transducers, with a capacity of 50 N, 100 N, 200 N and 500 N, following up the work

105 presented in [8]. The 200 N was calibrated under the three calibration modes (static, continuous, and dynamic),  
106 while all the other transducers were calibrated statically and dynamically. Using dedicated equipment and  
107 protocols corresponding to ISO 376, DKD-R 3-9, and DKD-R 3-10, the transducers are calibrated in compres-  
108 sion. The aim is to assess consistency in sensitivity values, explore how uncertainty evolves under different  
109 loading regimes, and evaluate the compatibility of results across calibration types. In doing so, the study seeks  
110 to contribute to ongoing standardization efforts and support ISO/TC 164/SC 1/SG 1 and metrological commu-  
111 nity in defining best practices for traceable, application-relevant force calibration in both research and indus-  
112 trial contexts.

## 113 2. Materials and methods

### 114 2.1 Transducers under test

115 The experimental setup employs high-precision strain-gauge force transducers with nominal capacities of  
116 50 N, 100 N, 200 N, and 500 N, manufactured by HBK (model TOP-Z30A), illustrated in Fig. 1. These devices  
117 are engineered to accurately measure small-scale tensile and compressive forces and are classified as Class 00  
118 in accordance with ISO 376. Due to their high precision, the transducers are commonly employed as a reference  
119 standard in calibration systems or as transfer standards for machine verification in line with ISO 7500-1 [9].  
120 They are interfaced with a 4 channels NI-9237 measurement amplifier (Fig. 2), which features a resolution of  
121 0.00001 mV/V and connects via a 3-meter, 6-wire LAN-compatible cable. The amplifier is capable of simul-  
122 taneously powering and reading up to four bridge-based sensors with six-wire configurations and ensures zero  
123 phase delay between measurement channels. Data is transmitted to a computer through an NI-9162 USB carrier  
124 and subsequently processed using LabView software.

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Fig. 1. The 4 transducers under tests.



Fig. 2. NI-9237 measuring amplifier [8].

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### 132 2.2 Static calibration according to ISO 376

133 The static calibration in compression of the tested force transducers was carried out in accordance with ISO  
134 376, utilizing the INRiM 2.5 kN deadweight force standard machine. This calibration system has a declared  
135 Calibration and Measurement Capability (CMC) with a relative expanded uncertainty of 20 parts per million  
136 (ppm).

137 A sequence of ten evenly spaced force values, ranging from 10 % to 100 % of the transducers' capacity,  
138 was applied under both loading and unloading conditions. Each load step included a dwell period of at least  
139 30 seconds and was repeated at three angular positions (0°, 120°, and 240°) as prescribed by the ISO standard.  
140 To reduce signal noise, a 0.1 Hz Bessel filter was implemented. The calibration included the evaluation of  
141 sensitivity and other transducer characteristics such as repeatability, reproducibility, resolution, hysteresis, re-  
142 turn-to-zero behavior, and total relative expanded uncertainty for every 10% increment in force. Interpolation  
143 errors were not assessed, since the comparison was performed at each discrete load level (following ISO 376  
144 Case B).

145

### 146 2.3 Continuous calibration according to DKD-R 3-9

147 The continuous calibration under compression of the 200 N transducer was conducted following the DKD-  
148 R 3-9 guideline, using the INRiM 1 kN continuous force calibration machine, illustrated in Fig. 3. This appa-  
149 ratus produces continuous forces via a stepper motor (Orientalmotor  $\alpha$ -GRADE AR Series - AR HM 40093E  
150 24DC), which drives a screw mechanism through a gearbox. Originally developed for polymer testing [10],  
151 the system was later characterized for its suitability in continuous calibration of force transducers.

152 The reference force was monitored using a 1 kN high-accuracy transducer (HBM Z3H3), installed at the  
153 base of the setup and connected to the same NI-9237 module described previously. This reference device was  
154 previously calibrated in compliance with DKD-R 3-9 Annex A [4], ensuring optimal measurement perfor-  
155 mance of the system during continuous loading. The applied correction factors and associated uncertainties,  
156 accounting for long-term drift, hysteresis effects, and transducer transfer behaviour, were established based on

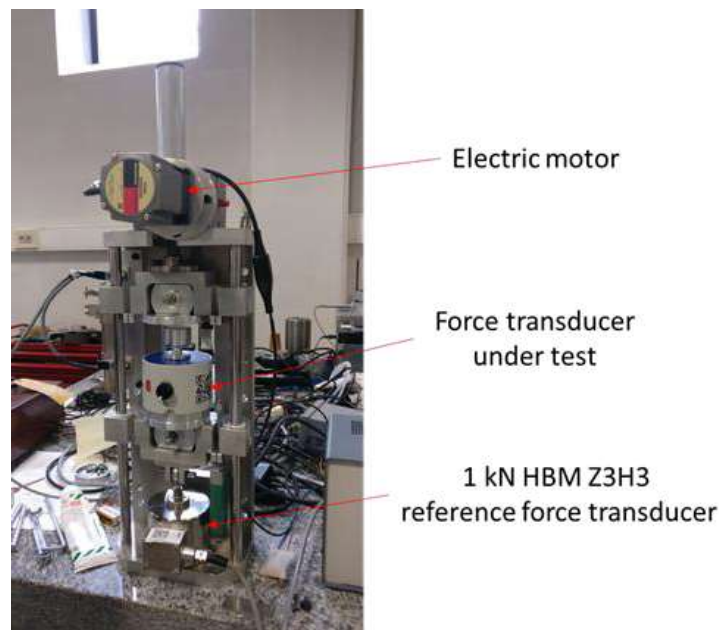
157 the Annex A.4.2 procedure. The relative expanded uncertainty of the generated continuous reference force was  
158 determined to be 0.27%.

159 The loading sequence applied compressive forces up to the transducer's 200 N nominal capacity over a  
160 120 s period, as recommended by the guideline. The transducer was rotated by 120° steps around its axis. A  
161 0.1 Hz Bessel filter was applied to both transducers, the reference and the one under test. Synchronicity of the  
162 two signals was guaranteed by the NI-9237 module, which simultaneously acquired both signals.

163 A ramp-type force-time profile was used, and data acquisition was performed at 25 Hz for both the reference  
164 and test transducers. Measurements were recorded during both loading and unloading phases. The evaluation  
165 of sensitivity, as well as key performance parameters, such as repeatability, hysteresis, reproducibility, and  
166 zero return, was carried out for ten force steps from 20 N to 200 N using the same procedures adopted during  
167 static calibration. Temperature effects were not considered, as all tests were performed in a thermally con-  
168 trolled environment at  $21.0 \pm 0.5$  °C.

169 An example of what is obtained at two 0° repetition from the two transducers is depicted in Fig. 4. The non-  
170 perfect unloading ramp is due to the mechanical plug adapter behaviour, used primarily for materials tensile  
171 tests and adapted here for compression calibration. This impacted reversibility error, as shown in the following  
172 Section.

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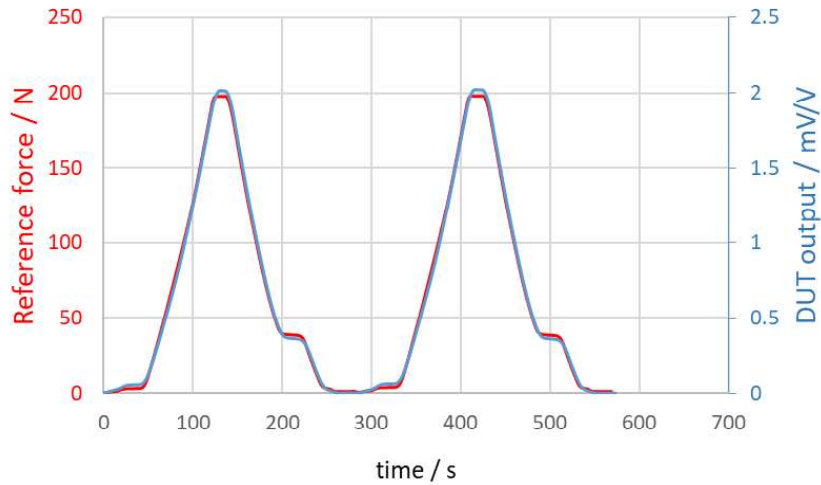


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Fig. 3. The INRiM 1 kN continuous force calibration machine [8].



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Fig. 4. Calibration output at 0° rotations from the reference transducer (red) and the 200 N transducer under test (blue).

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#### 181 2.4 Dynamic calibration according to DKD-R 3-10

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The dynamic calibration of the transducers under test was performed in accordance with DKD-R 3-10 (Sheet 2), utilizing the INRiM primary vibration calibration system, as depicted in Fig. 5 [11,12]. This system comprises a vibrating platform (PCB model TMS 2075E), which is capable of generating sinusoidal oscillations up to 6000 Hz, and a Polytec OFV-5000 laser interferometer, employed to measure the acceleration of the loading mass, an essential parameter for determining dynamic force.

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The setup includes several cylindrical test weights (210.67 g, 316.50 g, 422.44 g, and 528.88 g) that are mounted to the transducer during testing. To investigate resonance effects, an additional single-ended accelerometer is used to capture the motion of the vibrating base. Signal acquisition is facilitated by PCB 482C signal conditioners, as well as National Instruments NI 4431, NI 9162, and NI 9237 data acquisition modules. The latter has a flat frequency response within  $\pm 0.0025$  dB [13]. Signals are acquired with a sampling rate of 5 kHz. Control of vibration frequency and amplitude is managed via LabView, while data analysis is carried out using MATLAB and Microsoft Excel.

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For each calibration run, the force transducer's output ( $U_f$ ) and the accelerations of both the loading mass ( $a_t$ ) and the vibration platform ( $a_b$ ) are recorded. As per DKD-R 3-10 [5], dynamic sensitivity is defined as the frequency-dependent ratio between the transducer's output signal  $U_f$  (in mV/V) and the actual dynamic force, which is computed by multiplying the total mass (external  $m_t$  plus internal mass of the transducer  $m_i$ ) by the measured acceleration of the load  $a_t$ . This relationship is given in Eq. (1).

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$$S_{\text{dyn}} = \frac{U_f}{(m_t + m_i)a_t} \quad (1)$$

202 Since this model assumes rigid body motion, deviations can occur due to elastic effects near the resonance  
 203 frequency of the mass-spring system. In practice, the acceleration measured on the top surface of the load mass  
 204 by the laser vibrometer may differ slightly from that of the base platform. To account for this elastic behavior,  
 205 the dynamic sensitivity is also modeled using a second-order approximation recommended by DKD-R 3-10  
 206 [5], described in Eq. (2), with parameters  $p_1$  and  $p_2$  derived through linear regression on experimental sensitiv-  
 207 ity data across frequencies  $f$ .

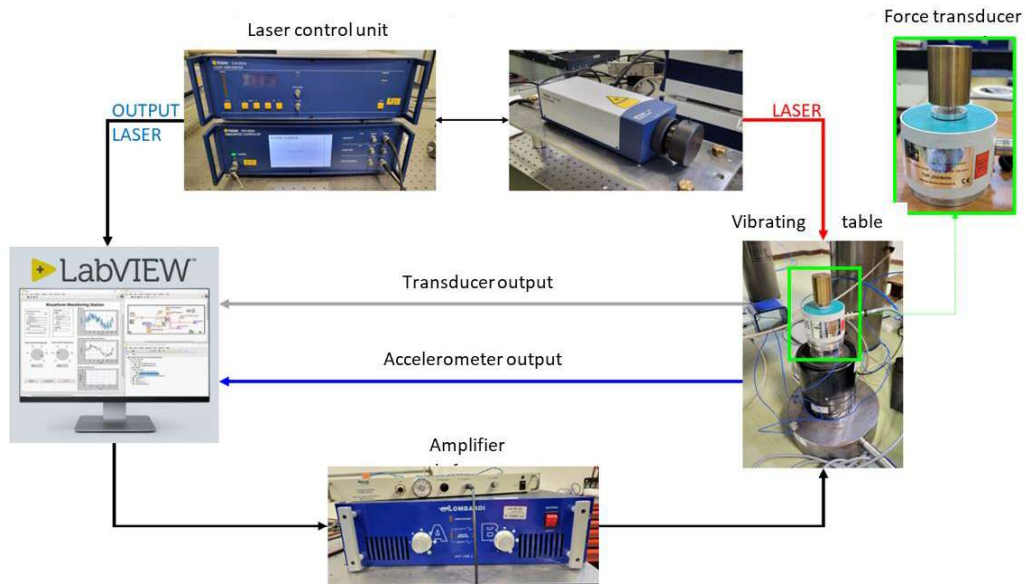
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$$209 \quad S_{\text{dyn,fit}} = p_1 \left( 1 - p_2 4\pi^2 f^2 \right) \quad (2)$$

210

211 Prior to testing, the transducers' internal inertial mass  $m_i$  was determined using the method outlined in  
 212 DKD-R 3-10 (§3.3.1) [5], yielding a value of approximately 122 g for each transducer. Calibration measure-  
 213 ments were then conducted using all available weights, producing 91 sinusoidal force signals (30 seconds  
 214 each) across the 10-100 Hz frequency range with a nominal amplitude of  $2 \text{ m s}^{-2}$ .  $U_f$  and  $a_t$  values correspond  
 215 to the mean amplitudes computed by the software during the acquisition time. The generated dynamic force  
 216 amplitudes ranged from approximately 0.7 N to 1.3 N, with maximum compressive forces, due to static load,  
 217 reaching up to 6.4 N. Uncertainties for individual dynamic sensitivity values were calculated using the GUM  
 218 framework (JCGM 100:2008) [14], considering the measurement uncertainties in mass, acceleration, trans-  
 219 ducer output, and internal mass determination. These were propagated using a Monte Carlo simulation (as per  
 220 JCGM 101:2008 [15] and DKD-R 3-10 §3.4 [5]) to produce the uncertainty estimates for the model described  
 221 in Eq. (2).

222



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Fig. 5. INRiM dynamic force and vibration calibration system.

225 **3. Results and discussion**226 *3.1 Static calibration results*

227 The static calibration outcomes from the tested transducers in terms of static sensitivity  $S_{\text{stat}}$  and relative  
 228 expanded uncertainty  $W(S_{\text{stat}})$ , as function of the ratio between the generated force  $F$  and the transducer's  
 229 capacity  $F_c$ , obtained in compliance with ISO 376, are presented in Table 1. The force transducers satisfies the  
 230 criteria for Class 00 performance for the whole force range. Across the entire calibrated force interval, the  
 231 sensitivity values exhibit a high degree of consistency and stability, confirming the reliability of the transducer  
 232 under static load conditions.

233

234 Table 1. Results according to ISO 376 in compression.

$F/F_c /$ %	$S_{\text{stat}} /$ (mV/V)/N				$W(S_{\text{stat}}) / \%$			
	50 N transducer	100 N transducer	200 N transducer	500 N transducer	50 N transducer	100 N transducer	200 N transducer	500 N transducer
10	0.039959	0.019996	0.010001	0.004002	0.020	0.014	0.010	0.003
20	0.039959	0.019995	0.010001	0.004002	0.015	0.010	0.004	0.004
30	0.039959	0.019995	0.010001	0.004002	0.013	0.006	0.004	0.004
40	0.039958	0.019994	0.010001	0.004002	0.012	0.007	0.003	0.004
50	0.039959	0.019994	0.010000	0.004002	0.013	0.006	0.003	0.003
60	0.039960	0.019994	0.010001	0.004002	0.012	0.006	0.003	0.003
70	0.039960	0.019994	0.010001	0.004002	0.011	0.006	0.003	0.003
80	0.039960	0.019993	0.010001	0.004002	0.011	0.006	0.003	0.003
90	0.039959	0.019993	0.010000	0.004002	0.011	0.006	0.004	0.003
100	0.039959	0.019993	0.010000	0.004002	0.011	0.006	0.002	0.003

235

236 *3.2 Continuous calibration results*

237 The compression-mode results for continuous calibration using a ramp force-time profile are provided in  
 238 Table 2 for the 200 N transducer, with the uncertainty contribution mentioned in the reference guideline. The  
 239 transducer's sensitivity  $S_{\text{cont}}$  response is generally linear across the measured range, though minor deviations  
 240 from the static trend are observed at force levels of 40 N, 100 N, and 200 N. The increase in uncertainty,  
 241 especially in the reversibility component, is attributed not only to the intrinsic behavior of the transducer under  
 242 continuous loading, but also to imperfections in the mechanical coupling between the test and reference trans-  
 243 ducers. In particular, the non-ideal unloading ramp is likely due to the behavior of the mechanical plug adapter,  
 244 originally designed for tensile tests and adapted here for compression calibration, as mentioned in the previous

245 Section. Similar patterns have been reported in earlier studies, such as those involving piezoelectric sensors  
 246 [16].

247

248 Table 2. Results of the 200 N transducer under continuous loading according to DKD-R 3-9 with the ramp  
 249 force time profile in compression mode.

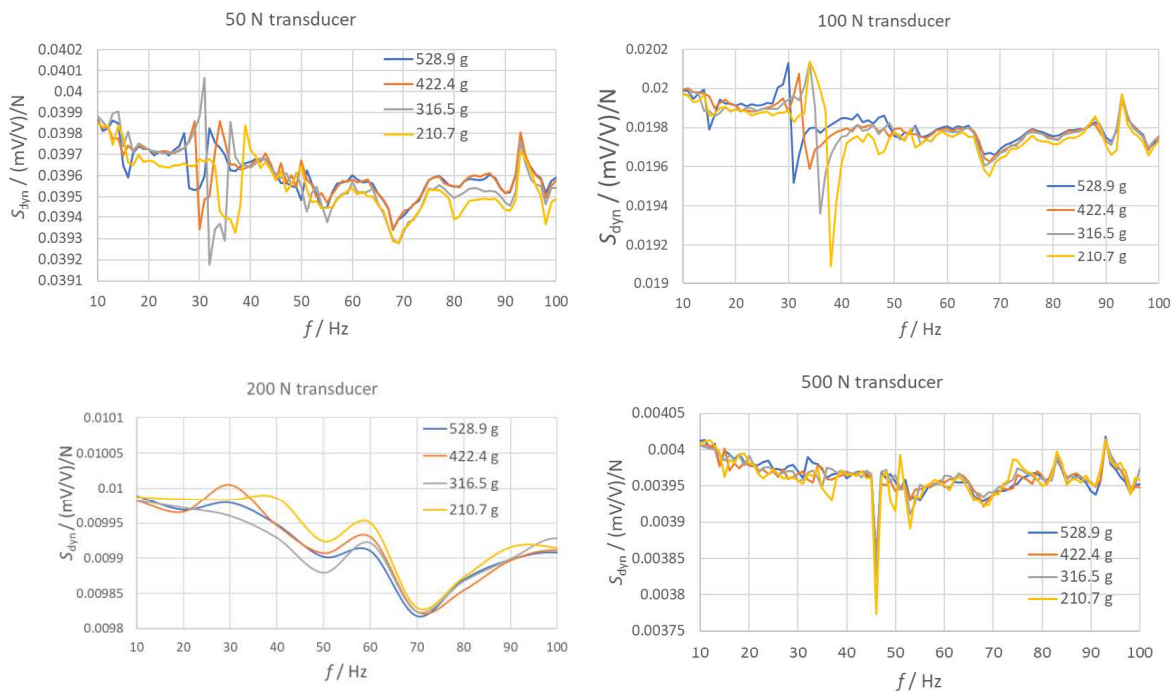
$F / \text{N}$	$S_{\text{cont}} / (\text{mV/V})/\text{N}$	$w_{\text{rep}} / \%$	$w_{\text{rot}} / \%$	$w_{\text{rev}} / \%$	$W(S_{\text{cont}}) / \%$
20	0.00998	0.009	0.013	0.456	0.95
40	0.00988	0.002	0.007	0.222	0.52
60	0.01001	0.000	0.014	0.219	0.52
80	0.00999	0.001	0.013	0.341	0.73
100	0.00992	0.001	0.006	0.427	0.90
120	0.00999	0.001	0.004	0.535	1.10
140	0.00999	0.000	0.005	0.505	1.05
160	0.00999	0.000	0.006	0.435	0.91
180	0.01000	0.000	0.007	0.362	0.77
200	0.01005	0.000	0.011	///	0.27

250

251 3.3 Dynamic calibration results

252 The dynamic sensitivity of the force transducers under test as a function of both excitation frequency and  
 253 applied loading mass, evaluated according to Eq. (1), is depicted in Fig. 6. As anticipated, sensitivity slightly  
 254 decreases with increasing frequency. Minor fluctuations in the data can be attributed to resonance effects  
 255 within the mechanical couplings rather than the primary mass-spring resonance of the system.

256



257

258

259 Fig. 6. Dynamic sensitivity as function of frequency and loading mass for the 4 transducers under test.

260 The associated relative expanded uncertainties of these values range from 0.1 % and 0.7 %, encompassing  
 261 measurement uncertainties due to mass  $m_t$  (resolution of the mass balance), transducer signal output (resolution  
 262 of the NI acquisition system), acceleration data (vibration calibration CMC at INRiM), and the internal mass  
 263 estimation  $m_i$  (standard deviation of the fitting procedure). As an example, the expanded uncertainty associated  
 264 with dynamic sensitivity for the 200 N trasducer with the 528.88 g loading mass at 10 Hz is reported in Table  
 265 3.  $u^2(x_k)$  represents the variance of the individual uncertainty contributions ( $x_k$ ),  $c_k$  is the sensitivity coefficient,  
 266  $u_k^2(S_{dyn})$  is the variance of the dependent variable  $S_{dyn}$  due to the individual uncertainty contributions, and  
 267  $U(S_{dyn})$  is the expanded uncertainty.

268  
 269 Table 3. Uncertainty budget (according to GUM) for  $S_{dyn}$  evaluated for the 200 N transducer with a loading mass of  
 270 528.9 at a frequency of 10 Hz.

Symbol	Variable $x_k$			$u^2(x_k)$	$c_k$	$u_k^2(S_{dyn})$
	Value	Meas. Unit	Note			
$U_f$	0.01305	mV/V	Type B	3.3E-11	7.7E-01	2.0E-11
$a_t$	2.0065	m s <sup>-2</sup>	Type A	4.0E-06	-5.0E-03	1.0E-10
$m_t$	0.5289	kg	Type B	8.3E-12	-1.5E-02	2.0E-15
$m_i$	0.1222	kg	Type A	3.7E-07	-1.5E-02	8.8E-11
$S_{dyn}$	6.260			Variance, $u^2(S_{dyn})$		2.1E-10
				Exp. Unc. $U(S_{dyn})$		2.8E-05
				Rel. Exp. Unc. $W(S_{dyn})$		0.28 %

271  
 272 After that, experimental curves in Fig. 6 are fitted according to Eq. (2) using a Monte Carlo (MC) method.  
 273 Probability density functions (PDFs), such as the normal distribution derived from uncertainty evaluation ac-  
 274 cording to Table 3, are assigned to each experimental dynamic sensitivity as function of frequency. By utilizing  
 275 the MC method, dynamic sensitivities are systematically sampled from their respective PDFs. This sampling  
 276 allows for a Multiple Linear Regression (MLR) analysis to be performed according to Eq. (2). For each  $i$ -th  
 277 MC iteration, MLR outputs are  $p_{1,i}$  and  $p_{2,i}$  parameters together with their associated standard uncertainty from  
 278 ordinary least squares (OLS),  $u_{OLS}(p_i)$ . At the end of the MC iteration,  $N_{MC}$  iterations and regression planes,  
 279 typically in the order of  $10^6$  to  $10^7$  as recommended in previous studies [17], are found. These regression planes  
 280 are used to find the mean values of  $p_1$  and  $p_2$  ( $p$ , generally speaking) with associated standard deviations  
 281  $u_{MC}(c)$ , as illustrated in Eqs. (3) and (4).

282

$$283 \quad p = \frac{1}{N_{MC}} \sum_{i=1}^{N_{MC}} p_i \quad (3)$$

$$284 \quad u_{MC}(p) = \sqrt{\frac{\sum_{i=1}^{N_{MC}} (p_i - p)^2}{N_{MC}(N_{MC} - 1)}} \quad (4)$$

285

286 The total standard uncertainty of sensitivity coefficients is then determined by summing the squares of  
 287  $u_{MC}(p)$  and  $u_{OLS}(p)$ , according to

288  
 289 
$$u(p) = \sqrt{u_{MC}(p)^2 + u_{OLS}(p)^2} \quad (5)$$

290  
 291 where  $u_{OLS}(p)$  is the mean standard uncertainty from the  $N_{MC}$  OLS given by

292  
 293 
$$u_{OLS}(p) = \frac{1}{N_{MC}} \sum_{i=1}^{N_{MC}} u_{OLS}(p_i) \quad (6)$$

294  
 295 Expanded uncertainty  $U(p)$  is then determined by multiplying standard uncertainty  $u(p)$  by 2. By propagating  
 296 the uncertainties of  $p_1$  and  $p_2$  according to Eq. (2) model, the uncertainty associated with  $S_{dyn,fit}$  can be ob-  
 297 tained.

298 Table 4 summarizes the regression-derived parameters  $p_1$  and  $p_2$  for all tested transducers for all loading  
 299 masses.  $p_1$  values closely align with the static sensitivity across all masses, while  $p_2$  coefficients vary depending  
 300 on the attached load.

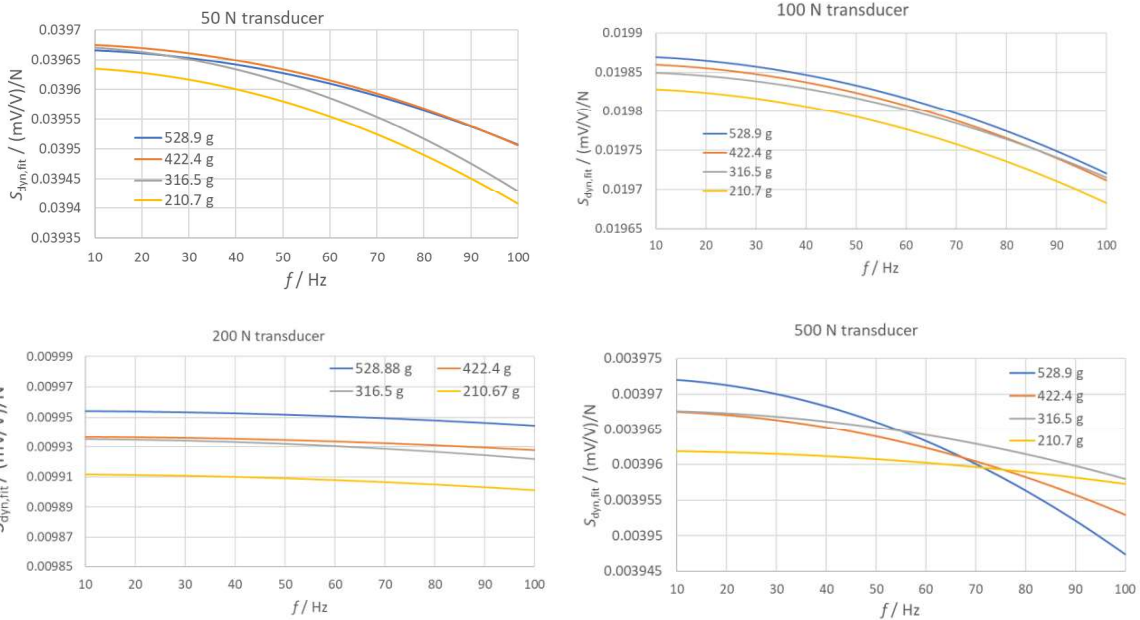
301 Fig. 7 displays the resulting model curves from which the decay of sensitivity as function of frequency is  
 302 evident, while Fig. 8 compares, for example, experimental and modeled sensitivity curves for the 100 N trans-  
 303 ducer with the 422.4 g loading mass, showing how the model effectively smooths out irregularities caused by  
 304 mechanical resonances.

305 Regarding the uncertainties, the OLS contributions dominate due to the variability of measurements near  
 306 resonance zones. Uncertainty levels range from about 1% to nearly 8%, due to increasing signal dispersion  
 307 and regression error.

308  
 309 Table 4. Values of  $p_1$  and  $p_2$  coefficients according to Eq. (2) as a function of the loading mass for the  
 310 tested transducers.

$m_t / g$	$p_1 / (mV/V)/N$				$p_2 / s^2$			
	50 N transducer	100 N trans- ducer	200 N transducer	500 N transducer	50 N transducer	100 N transducer	200 N transducer	500 N transducer
210.67	0.039638	0.019830	0.009912	0.003962	1.47E-08	1.88E-08	2.70E-09	2.99E-09
316.46	0.039674	0.019851	0.009935	0.003968	1.55E-08	1.73E-08	3.40E-09	6.22E-09
422.40	0.039677	0.019861	0.0099 37	0.003968	1.09E-08	1.91E-08	2.27E-09	9.44E-09
528.88	0.039669	0.019871	0.009954	0.003972	1.03E-08	1.92E-08	2.48E-09	1.59E-08

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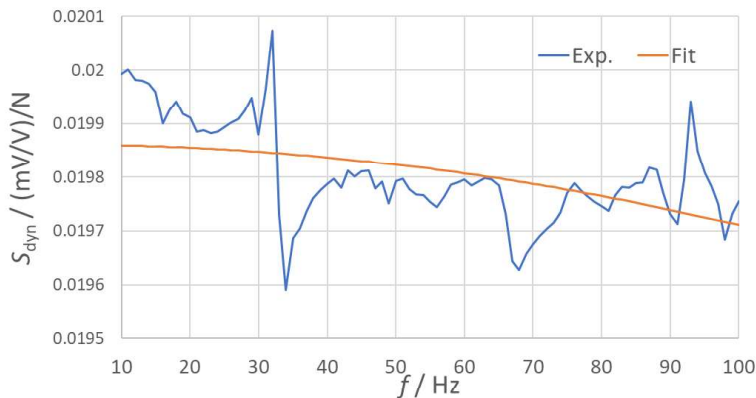
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Fig. 7. Fitted dynamic sensitivity as function of frequency and loading mass for the 4 transducers under test.



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### 321 3.4 Comparison of Results from Different Calibration Methods

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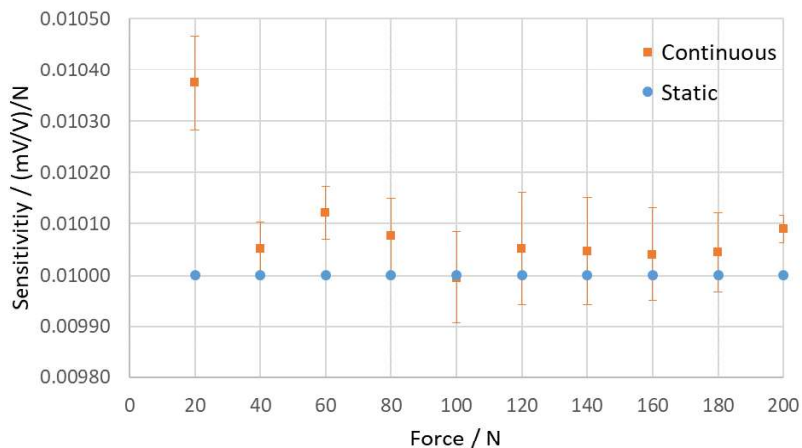
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Fig. 8. Comparison between  $S_{dyn}$  and  $S_{dyn,fit}$  curves for the 100 N transducer with the 422.4 g loading mass.

A comparison between static and continuous calibration results was first conducted for the 200 N transducer at overlapping force levels ranging from 20 N to 200 N. As illustrated in Fig. 9, the sensitivity values obtained from both methods are plotted alongside their respective expanded uncertainties. Although static calibration consistently yields lower uncertainties, both data sets show general agreement, with the exception of some deviations at 40 N and 200 N in the continuous case. A similar anomaly is observed at 100 N, though in that instance the associated uncertainty compensates for the discrepancy. These differences may stem from signal

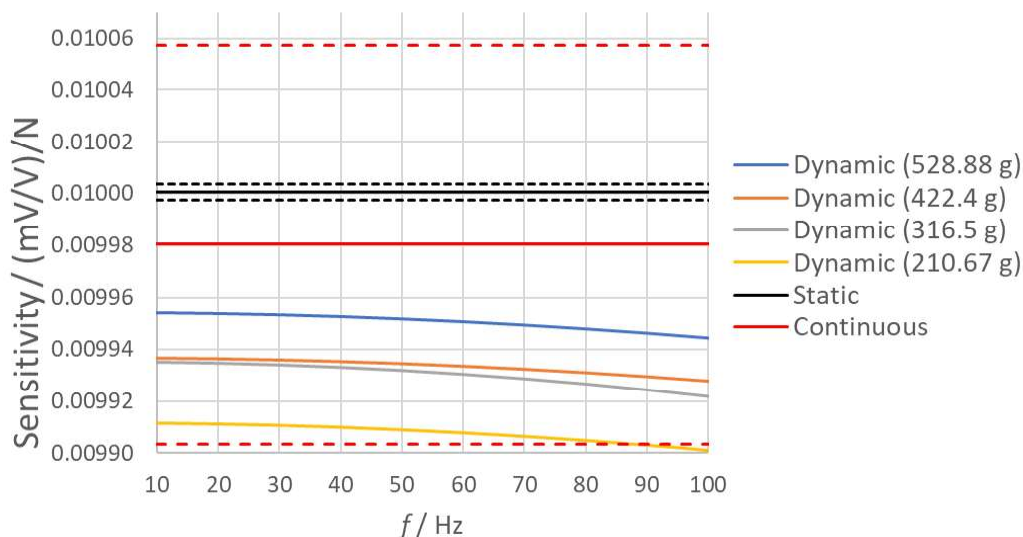
328 instability in zero-point detection or from imperfections in the mechanical interface between the reference and  
 329 test transducers.  
 330



331  
 332 Fig. 9. Comparison between static and continuous calibration results of the 200 N transducer in terms of  
 333 sensitivity as function of applied load [8].  
 334

335 To enable a broader comparison with the dynamic results, mean sensitivity values were calculated:  
 336 0.010001 (mV/V)/N for static and 0.009980 (mV/V)/N for continuous calibration. Expanded uncertainties for  
 337 both means were computed using the root-sum-square of the average standard uncertainty and the standard  
 338 deviation across all measured steps [18]. The resulting relative uncertainties were 0.030% and 0.772%, respec-  
 339 tively.

340 Fig. 10 presents a comparative overview of static, continuous, and dynamic sensitivity values for the 200  
 341 N transducer. Notably, dynamic sensitivities trend lower than static and continuous ones. Anyway, compati-  
 342 bility is visually assessed using the uncertainty bands of the static and continuous sensitivities. For clarity,  
 343 dynamic uncertainties (which range around 1% below 100 Hz) are omitted from the figure.  
 344



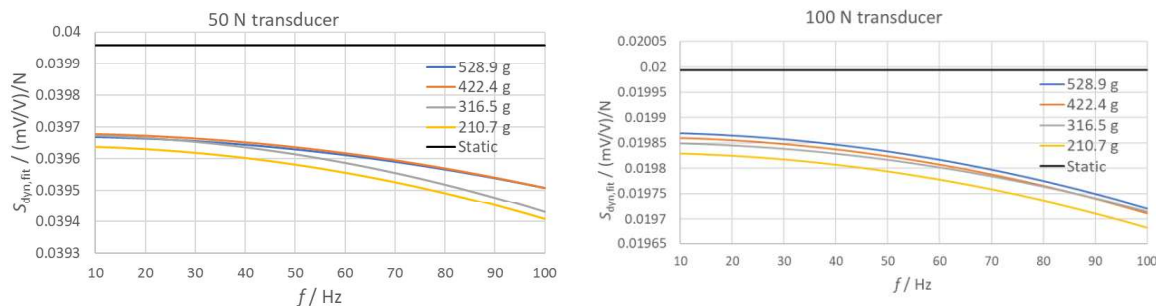
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346 Fig. 10. Comparison between static, continuous and dynamic calibration sensitivities up to 100 Hz for the  
 347 200 N transducer. Dotted lines correspond to lower and upper limits of mean static and continuous sensitivities  
 348 with associated expanded uncertainty [8].

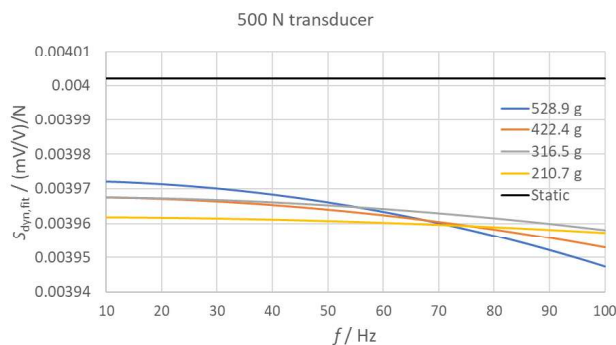
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350 Based on this comparison, the results from all three calibration regimes appear broadly compatible within  
 351 their respective uncertainty bounds. However, this compatibility is highly sensitive to the declared uncertainty  
 352 levels. If the uncertainties in dynamic and continuous calibrations were reduced to match those of static cali-  
 353 bration, compatibility would likely be compromised due to the more pronounced discrepancies. Specifically,  
 354 when using static calibration as a reference, continuous sensitivity shows closer agreement than dynamic sensi-  
 355 tivity, which diverges more as the load decreases, an observation consistent with earlier findings [12]. This  
 356 is also confirmed by comparing static and dynamic sensitivities for the other tested transducers as depicted in  
 357 Fig. 11.

358



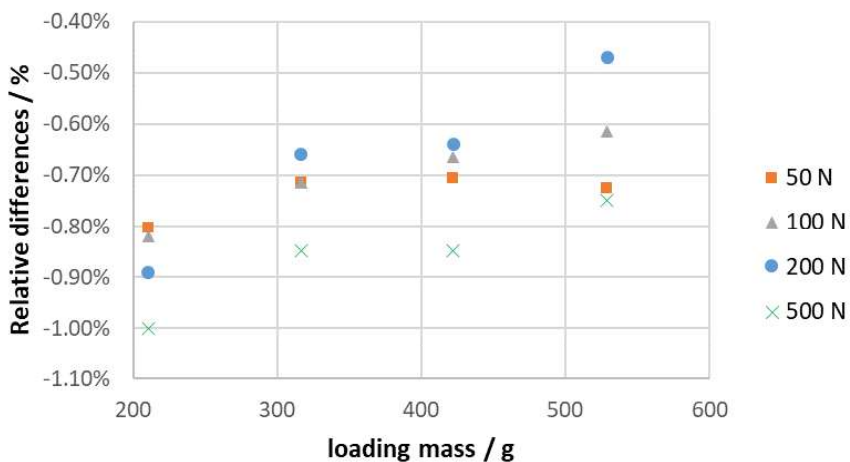
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Fig. 11. Comparison between static and dynamic calibration sensitivities up to 100 Hz for the 50 N, 100 N and 500 N transducers.

Since dynamic values are given as function of frequency, the dynamic sensitivities extrapolated at  $f=0$  Hz, i.e.,  $p_1$  values from Table 4, are also compared with static sensitivity from Table 1 in order to get a more robust comparison. For this purpose, relative differences as function of loading mass are calculated and depicted in Fig. 12 for all tested transducers.



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Fig. 12. Relative differences between dynamic sensitivity at  $f=0$  Hz, i.e.  $p_1$ , and static one for the 50 N, 100 N, 200 N and 500 N transducers.

It is found that relative differences range between -1 % and -0.5 %, decreasing at increasing loading mass for all tested transducers. This may indicate that as the applied dynamic force deviates further from the transducer's nominal capacity, the dynamic sensitivity increasingly diverges from the static value, similarly to [19]. However, since dynamic calibration cannot currently reach force levels near the transducer's nominal limit, doubts remains about the true behavior of the transducer in those regions. This raises questions about the effectiveness of the dynamic calibration approach, despite its theoretical and metrological validity. In real-

379 world applications, such as fatigue testing, transfer transducers are often subjected to dynamic loads up to full  
380 capacity [20], which dynamic calibration methods currently struggle to replicate.

381 Similar concerns apply to the interpretation of uncertainty values. The significantly higher uncertainties  
382 observed under continuous and dynamic conditions may reflect either inherent transducer limitations or limi-  
383 tations of the current calibration methodology and equipment. For these reasons, all influencing factors should  
384 be carefully considered before the broader adoption and standardization of these new calibration methods.

#### 385 **4. Conclusions**

386 This study presents a comprehensive comparison of static, continuous, and dynamic calibration methods  
387 applied to low-force strain-gauge transducers with capacities ranging from 50 N to 500 N. The static calibration  
388 results, performed according to ISO 376, showed high repeatability, minimal deviation across force steps, and  
389 low uncertainties, confirming the reliability of these transducers under standard calibration conditions.

390 Continuous calibration, carried out in compliance with DKD-R 3-9, exhibited sensitivity values comparable  
391 to static calibration, although with noticeably higher uncertainties, particularly in reversibility. These increased  
392 uncertainties were found to arise not only from the transducer's behavior under non-static loading but also from  
393 mechanical imperfections in the calibration setup, such as adapter compliance and connection misalignment.

394 Dynamic calibration, implemented following DKD-R 3-10, revealed a frequency-dependent decrease in  
395 sensitivity, as expected from theoretical models. Dynamic sensitivities were consistently lower than static ones  
396 and exhibited a stronger divergence at lower excitation forces. This divergence decreased as the applied load  
397 approached the nominal capacity of the transducer. However, due to the physical limitations of dynamic setups,  
398 such full-range loading is not achievable in practice, leading to uncertainty about the transducer's true dynamic  
399 performance near its upper limit.

400 Despite these limitations, regression modeling using Monte Carlo methods showed that extrapolated zero-  
401 frequency dynamic sensitivities ( $p_1$  values) are generally consistent with static sensitivities, particularly for  
402 larger loading masses. Nevertheless, dynamic and continuous calibration methods continue to produce higher  
403 uncertainty levels, ranging from 0.3 % to over 1 %, compared to the sub-0.05 % uncertainties typically  
404 achieved with static methods.

405 The results demonstrate broad compatibility between calibration methods within declared uncertainties.  
406 However, if the uncertainty levels in continuous and dynamic calibrations were reduced to match those of  
407 static calibration, the underlying differences in sensitivity would render the methods incompatible. This high-  
408 lights a fundamental challenge in the metrological traceability of force measurements under realistic operating  
409 conditions.

410 Ultimately, while dynamic and continuous calibration procedures are conceptually robust and supported by  
411 standardization initiatives (e.g., DKD, ComTraForce project, and ISO/TC 164/SC 1/SG 1), their practical im-

412 plementation remains limited by methodological and technical constraints. Further research is needed to im-  
413 prove system performance, reduce uncertainty contributions, and ensure traceability under dynamic loading,  
414 particularly in applications like fatigue testing, where full-range dynamic calibration is crucial.

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