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EVALUATION OF THE EFFECT OF DYNAMIC VERIFICATION ON DIFFERENT TYPES OF FORCE SENSORS

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Abstract:
This study includes measurements carried out according to ASTM E467 international standard by using different loading rates also force waveform sine, in order to comprehensively investigate dynamic verification in force sensors which have two different measuring principles. It has been aimed to reveal and evaluate the effect of dynamic verification on different types of force sensors.

Keywords: influence of load rate; dynamic verification; piezoelectric force transducer; strain gauge force transducer

1. INTRODUCTION

Due to great competition and developing technology in today's industry, manufacturers want to offer higher quality and reliable products to consumers and thus increase their market share. Manufacturers apply various tests to determine the suitability of their products in usage environments. Development and manufacture of economical and more reliable products are ensured by means of material testing, which is one of these tests. Machines used in material tests work with the principle of applying and measuring the force to sensors. These sensors used in machines may also have different principles according to the method of detecting applied force. Today, strain gauge sensors are the most widely used force measuring devices and they got this name because strain gauges are used to convert mechanical deformation into electrical output. Another widely used force measuring device in the industry is piezoelectric type force sensors. Piezoelectric sensors generate an electrical signal in response to the applied force. However, while piezoelectric force transducers are only effectively used in measurement of quasi-static or dynamic loads; strain gauge force transducers are actively used in measurement of static and dynamic loads [1], [2], [3], [4], [5].

But strain gauge and piezoelectric force sensors used to make these measurements are calibrated under static conditions, but are often used to make measurements in dynamic conditions.

When literature research is conducted within the scope of scientific studies on this subject, comprehensive traceability for force metrology services is focused in [6], a procedure for dynamic force calibration using sinusoidal excitations of force transducers is described in [7], dynamic traceable and dynamic measurement of mechanical quantities are investigated in [8]. ASTM E467:2021 and ISO 4965-2:2012 are standards, defined performing verification of constant amplitude dynamic forces in an axial fatigue testing system [9], [10]. In this regard, force application in sinusoidal waveform (periodic rises and falls in force) at different loading rates for force sensors with two different measuring principles has been carried out according to ASTM E467:2021 standard. Thus, this publication aims to reveal and evaluate the effect of both static and dynamic validation on different types of force sensors.

2. DEVICE AND EQUIPMENT

Figure 1 shows the measurement system of force transducers which has been established at laboratory. In this setup, force has been generated by a Zwick Z250 type electro-mechanic material testing machine, the force to be applied by machine during dynamic verification to force sensors must be uniaxial. In this respect, a special cap and flange-mounted bottom plate are used in force sensors to ensure that the force applied in measurement is independent of bending moments and lateral forces. The testing machine has its own force application software which is called TestXpert V9.01. Since material testing machine could not reach high-frequency values during the measurement, the crosshead speed of the machine is defined and applied at 1 kN/s, 2 kN/s and 10 kN/s speeds in accordance with the dynamic force waveform sine force-time profile. Two force transducers are used in measurement, as shown in Figure 1. The piezoelectric force measuring device used as a transfer standard is a Kistler piezoelectric force transducer with a 9333A model in the measuring range (0 - 50) kN. Furthermore, this sensor has a sensitivity of -3.985 pC/N, linearity of 0.39 % (FSO) and relative expanded uncertainty of 0.11 %. On the other hand, Interface type 1120 BBA strain gauge force transducer is used in the measurement. This sensor's maximum force capacity is (0 - 100) kN, strain gauge force sensor, which is exposed to the same force and has its traceability from ISO 376:2011 standard [11]. Traceability of this force measuring device has been provided by the stepwise calibration method in the national force standard machine. In addition, strain gauge force transducer of material testing machine is also used as a transfer standard in setup. This sensor has traceability according to ISO 7500-1:2018 [12], it is used to control applied force value in calibration. It is seen a photograph of software and data acquisition modules also Zwick material testing machine measurement setup in Figure 2 and Figure 3. In order to collect data from piezoelectric force sensor Kistler type 5509AQ01 data acquisition module is used as a charge amplifier, also operating range of this device is (1 000 - 1 000 000) pC. The module has four channels; the first channel of the device is used to collect data from the piezoelectric force sensor, furthermore, Kistler type 5501A universal data acquisition module is used to collect data from strain gauge force transducer, this device has two analogue inputs, one of these inputs is used in the measurement setup. In measurements, Kistler KiStudio Lab Software Type 2910A has been used for data acquisition. In calibration, acquisition of value pairs, consisting of force and the associated output signal of calibration item, are carried out time-discretely or value-discretely. Time-discrete detection is carried out with a predetermined sampling frequency (typically N = 10 000 to 100 000 value pairs). In the value-discrete acquisition of measured values, value pairs (typically N = 100 to 500) are recorded using specified loads, in order to prevent aliasing, suitable filter settings are selected. Kistler Jbeam Software Type 8.0 has been utilised for data analysis of calibration.

3. DYNAMIC VERIFICATION PROCEDURE

First of all, static verification measurement has been performed with both strain gauge and piezoelectric force sensors as required by ASTM E467:2021 standard. After reaching temperature stability in laboratory environment, piezoelectric and strain gauge force transducers have been positioned and centred in the material testing machine as seen in Figure 1. Loading has been done up to force value determined as the highest force capacity, and then return to zero force, zero the sensors and indicator force output.

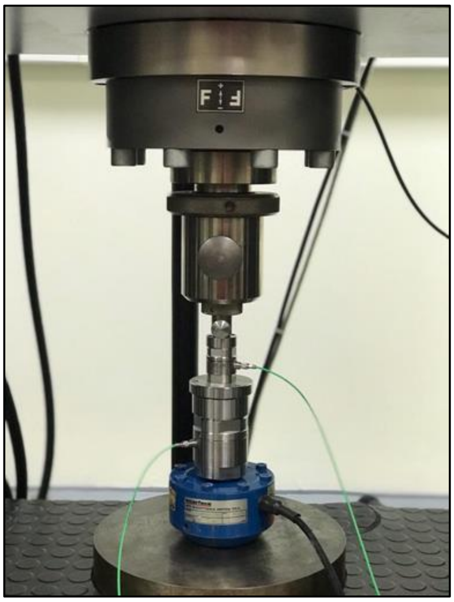

Figure 1: The positions of reference force sensors

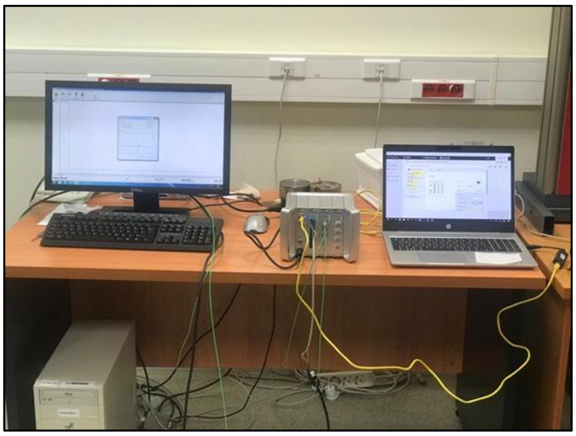

Figure 2: Data acquisition modules and software

Figure 3: Zwick material testing machine and calibration systems

This process, which is defined as preloading, has been repeated three times. First, 1 050 N force value which is 5 % more than the minimum force value of 1 000 N, then the minimum force value in measurement which is 1 000 N force, finally, 950 N force value which is 5 % less than the minimum force value of 1 000 N force has been applied to strain gauge, piezoelectric force sensor and force transducer of testing machine in compression force application direction of the machine.

During all these processes, force value on indicator of force transducer of testing machine, force values read from both strain gauge and piezoelectric force sensor have been recorded and then error values have been calculated.

Then, a load of 5 250 N, which is 5 % more than the highest force value of 5 000 N, then 5 000 N, which is determined as the highest force value, and finally 4 750 N, which is 5 % less than the highest force value, has been applied to all sensors in the compression direction. The same procedure has been performed on all sensors for the maximum force values of 10 000 N and 20 000 N, then force values read from all indicators have been recorded and then error values have been calculated.

Then, dynamic verification measurement has been performed with both strain gauge and piezoelectric force sensors as required by ASTM E467:2021 standard. In dynamic verification of force sensors with both different measurement principles, 500 readings per second have been taken, and measurement time has been arranged as 60 s and a sinusoidal force-time profile has been applied.

First, a load of 5 000 N has been applied to the force sensors positioned on the machine with a crosshead speed of 1 kN/s of the testing machine. Later force values at peak and valley points in sinusoidal force-time profile have been recorded for all force sensors and then peak error and valley error in measurement have been calculated. The measurement has been completed by defining the crosshead speed of the machine as 2 kN/s, then 10 kN/s, and then applying a load of 5 000 N to force sensors positioned on the machine. Then, the force values at peak and valley points of sinusoidal force-time profile have been recorded for all force sensors, and then peak error and valley error in measurement have been calculated.

In respect to 1 kN/s, 2 kN/s and 10 kN/s crosshead speeds in the material testing machine, procedure described in the above paragraph has been repeated by applying a load of 10 000 N and 20 000 N to all sensors in compression direction, respectively. Then, force values at peak and valley points of sinusoidal force-time profile have been recorded for all force sensors, and measurements have been completed with calculation of peak and valley error.

Two separate mathematical equations have been created by considering two different methods for the uncertainty approach modelled in this publication. First of these, uncertainty in static force measurements was calculated by using the equation detailed in Annex C of ISO 7500-1 standard and included in equations (1) and (2) (k = 2.0).

$$U = k \times u_{\mathrm{c}} \quad (1)$$

$$u_{\mathrm{c}} = \sqrt{u_{\mathrm{rep}}^2 + u_{\mathrm{res}}^2 + u_{\mathrm{cal}}^2 + u_{\mathrm{drift}}^2 + u_{\mathrm{temp}}^2 + u_{\mathrm{approx}}^2} \quad (2)$$

- u_{rep} is the standard uncertainty related to repeatability,
- u_{res} is the standard uncertainty related to resolution,
- u_{cal} is the standard uncertainty regarding calibration values from reference force transducers certificate,
- u_{drift} is the standard uncertainty related to drift of reference force transducers,
- u_{temp} is the standard uncertainty related to temperature deviation of reference force transducers,
- u_{approx} is the standard uncertainty related to linear approximation to the polynomial curve of reference force transducers.

In addition, the uncertainty approach, which is modelled by using the parameters expressed in equations (3) and (4), has been applied in dynamic force measurements (k = 2.0).

$$U = k \times u_{\mathrm{c}} \quad (3)$$

$$u_{\mathrm{c}} = \sqrt{u_{\mathrm{rep}}^2 + u_{\mathrm{res}}^2 + u_{\mathrm{hyst}}^2 + u_{\mathrm{cal}}^2 + u_{\mathrm{drift}}^2 + u_{\mathrm{temp}}^2 + u_{\mathrm{ind\text{-}volt}}^2 + u_{\mathrm{long\text{-}term}}^2 + u_{\mathrm{supply\ volt}}^2} \quad (4)$$

- u_{rep} is the standard uncertainty related to repeatability
- u_{res} is the standard uncertainty related to resolution
- u_{hyst} is the standard uncertainty related to hysteresis
- u_{cal} is the standard uncertainty regarding calibration values from reference force transducers certificate
- u_{drift} is the standard uncertainty related to drift of reference force transducers
- u_{temp} is the standard uncertainty related to temperature deviation of reference force transducers
- $u_{\mathrm{ind\text{-}volt}}$ is the standard uncertainty related to indicator voltage deviation
- $u_{\mathrm{long\text{-}term}}$ is the standard uncertainty related to long term stability of indicator
- $u_{\mathrm{supply\ volt}}$ is the standard uncertainty related to supply voltage deviation of measurement system

4. MEASUREMENT RESULT

Static and dynamic verification measurement results, which are performed as a requirement of ASTM E467:2021 standard by using piezoelectric and strain gauge force sensors with different force capacities, are given from Table 1 to Table 5, respectively. Error values calculated as a result of evaluation of these data are also included in these tables.

In the light of these results, variation in error values calculated as a result of the static verification of strain gauge force sensor is in the range of 0.19 % to 0.49 %. In contrast, this variation is in the range of 0.76 % to 1.17 % in the piezoelectric force sensor.

On the other hand, the variation in peak error values calculated as a result of dynamic verification of strain gauge force sensor is in the range of 0.07 % to 0.23 %. However, this variation is in the range of 0.99 % to 1.20 % in the piezoelectric force sensor.

The variation in valley error values, which are included in the same tables and calculated as a result of dynamic verification, is in the range of 0.01 % to 0.08 % for the strain gauge force sensor. Whereas, this variation is in the range of 0.04 % to 0.28 % in the piezoelectric force sensor.

However, in static force measurements, a maximum relative uncertainty of 0.16 % has been calculated for the strain gauge force sensor, while the result of this calculation has been obtained as a maximum of 0.76 % for the piezoelectric force transducer.

In dynamic force measurements, the maximum uncertainty value for strain gauge force transducer has been calculated as 0.86 %, while this value has been found as maximum 1.2 % for piezoelectric force sensor.

Table 1: Static verification data of strain gauge force sensor according to ASTM E467:2021

Applied Force		**Indicated Force**	**Dynamometer Force**	**Error**	
Detail	**N**	**N**	**N**	**N**	**%**
minimum force + 5 %	1 050	1 054	1 052	2	0.19
minimum force value	1 000	1 020	1 017	3	0.29
minimum force - 5 %	950	954	951	3	0.32
maximum force + 5 %	5 250	5 260	5 252	8	0.15
maximum force value	5 000	5 016	5 010	6	0.12
maximum force - 5 %	4 750	4 754	4 748	6	0.13
maximum force + 5 %	10 500	10 524	10 483	41	0.39
maximum force value	10 000	10 024	9 990	34	0.34
maximum force - 5 %	9 500	9 518	9 490	28	0.30
maximum force + 5 %	21 000	20 991	20 914	77	0.37
maximum force value	20 000	20 023	19 945	78	0.39
maximum force - 5 %	19 000	19 151	19 058	93	0.49

Table 2: Static verification data of piezoelectric force sensor according to ASTM E467:2021

Applied Force		**Indicated Force**	**Dynamometer Force**	**Error**	
Detail	**N**	**N**	**N**	**N**	**%**
minimum force + 5 %	1 050	1 054	1 046	8	0.76
minimum force value	1 000	1 020	1 011	9	0.89
minimum force - 5 %	950	954	946	8	0.85
maximum force + 5 %	5 250	5 260	5 210	50	0.96
maximum force value	5 000	5 016	4 967	49	0.99
maximum force - 5 %	4 750	4 754	4 706	48	1.02
maximum force + 5 %	10 500	10 524	10 408	116	1.11
maximum force value	10 000	10 024	9 912	112	1.13
maximum force - 5 %	9 500	9 518	9 408	110	1.17
maximum force + 5 %	21 000	20 991	20 823	168	0.81
maximum force value	20 000	20 023	19 856	167	0.84
maximum force - 5 %	19 000	19 151	18 967	184	0.97

Table 3: Dynamic verification data of strain gauge force sensor according to ASTM E467:2021

Speed	Reference Peak Force	Indicated Peak Force	Peak Force Error		Reference Valley Force	Indicated Valley Force	Valley Force Error	
kN/s	N	N	N	%	N	N	N	%
1	5 040	5 049	9	0.23	1 017	1 020	3	0.08
2	5 042	5 050	8	0.20	1 016	1 018	2	0.05
10	5 044	5 051	7	0.18	1 015	1 017	2	0.05
1	10 040	10 048	8	0.09	1 012	1 015	3	0.03
2	10 035	10 046	11	0.12	1 010	1 013	3	0.03
10	10 035	10 045	10	0.11	1 011	1 013	2	0.02
1	20 032	20 045	13	0.07	1 007	1 008	1	0.01
2	20 030	20 048	18	0.09	1 007	1 011	4	0.02
10	20 029	20 053	24	0.13	1 009	1 012	3	0.02

Table 4: Parameters of dynamic verification for both strain gauge and piezoelectric force sensor

Speed kN/s	Sample Rate s^{-1}	Test Duration s	Wave Shape
1	500	60	sine
2			
10			

Table 5: Dynamic verification data of piezoelectric force sensor according to ASTM E467:2021

Speed	Reference Peak Force	Indicated Peak Force	Peak Force Error		Reference Valley Force	Indicated Valley Force	Valley Force Error	
kN/s	N	N	N	%	N	N	N	%
1	5 005	5 049	44	1.10	1 009	1 020	11	0.28
2	5 008	5 050	42	1.05	1 008	1 018	10	0.25
10	5 003	5 051	48	1.20	1 007	1 017	10	0.25
1	9 949	10 048	99	1.10	1 006	1 015	9	0.10
2	9 951	10 046	95	1.06	1 004	1 013	9	0.10
10	9 955	10 045	90	1.00	1 003	1 013	10	0.11
1	19 856	20 045	189	0.99	1 000	1 008	8	0.04
2	19 850	20 048	198	1.04	999	1 011	12	0.06
10	19 852	20 053	201	1.06	1 001	1 012	11	0.06

5. CONCLUSION

This study includes the measurements in which two different force sensors with strain gauge and piezoelectric measurement principles are used as reference force transducer and the evaluation of these measurement results according to the ASTM E467 standard. The measurements have been carried out at different dynamic speeds and related force measurement ranges. As defined in ASTM E467, firstly static force measurements and then dynamic force measurements have been carried out.

Zwick material testing machine has been evaluated according to the measurement results of both reference sensors. For both reference sensors (piezoelectric and strain gauge), accuracy error has been determined according to the relative relationship between the force value of the reference sensor and indicated force value from the testing machine in both static and dynamic measurements. It has been investigated whether this error value is below 1 % for static force measurements and then for dynamic force measurements as defined in ASTM E467.

At the end of measurement, static accuracy error values have been calculated under 0.49 % for strain gauge force sensor. On the other hand, static accuracy error values have been calculated above 1 % for piezoelectric sensor. This is because of the values of piezoelectric sensors are less stable than strain gauge sensors in static measurements.

In dynamic measurements, data with strain gauge sensors have been calculated to be below 1 % for peak values. It has been found that data obtained from measurements made with strain gauge force sensor and calculated error values are within tolerance concerning to ASTM E467:2021 standard. In addition, since the response time of the piezoelectric sensor to the applied force is much faster than the strain gauge sensor, it has been observed that the accuracy error values at the peak value are above 1 %.

Interpretation to be drawn from measurement results is that in force measurement of piezoelectric force transducers, especially drift of charge amplifier should be considered for decreasing measurement error values and uncertainty. On the other hand, nonlinearity behaviour is the other criteria for increasing the measurement error values and uncertainty of the piezoelectric force sensor. However, when the metrological performance of the piezoelectric force sensor is to be evaluated, it is always necessary to consider the entire measurement chain, including the force transducer, cable and charge amplifier. Additionally, piezoelectric force sensors have directional cross sensitivities that affect measurement repeatability at different mounting positions, due to the design and anisotropic properties of piezoelectric material.

In this research, it is aimed to reveal and evaluate the effect of dynamic validation on different types of force sensors. In the future, it is thought that it will be appropriate to produce a theoretical model using different dynamic test machines and sensors with different measuring principles.

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