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EFFECTS OF FORCE APPLICATION RATE ON TRANSDUCER PERFORMANCE

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Abstract:
This paper compares static and continuous performance characteristics of a force transducer, determining the effect of force application rate, force application principle, and filter settings on the observed differences. It also develops a methodology for identifying and correcting possible non-synchronisation between instrument channels.

Keywords: force transducer; continuous calibration; materials testing; traceability

1. INTRODUCTION

Most materials test results are critically dependent upon the magnitudes of the forces applied during the test. For this reason, the forces applied by the testing machine need to be traceable and this is generally achieved by machine calibration using force transducers which have themselves been calibrated in a force standard machine. These two calibration exercises follow quasistatic force-time profiles specified in the relevant standards [1], [2], but these profiles differ both from each other and from the profile generated during the materials test itself. This difference in profiles introduces an uncertainty component associated with the value of the applied test force due to the non-ideal time-dependent characteristics of both the testing machine and the force transducer used for its calibration.

Ideally, the testing machine would be calibrated using the same force-time profile as it employs during tests, and the transducer would also have been calibrated using this profile. This would have the dual benefit of eliminating uncertainty contributions due to the difference in profiles and reducing the time taken to perform the two calibrations. The two major downsides associated with this approach are:

1. Force standard machines are not generally capable of producing the required profiles – an intermediate reference standard transducer with validated time-dependent characteristics would be required;

2. Synchronisation of the force transducer readings with both the reference standard transducer and the testing machine would be required, possibly involving additional expenditure on instrumentation.

The work described in this paper investigates the differences between the calibration results of a force transducer when calibrated either statically within a deadweight force standard machine or continuously against a reference standard transducer, over a range of different force application rates and filter settings.

2. EQUIPMENT

This section describes the hardware and software used during the investigation.

2.1. Force Machines

Two different force machines were used for this work – a 20 kN deadweight force standard machine (DWM) and a 25 kN servohydraulic materials testing machine (MTM). All work was performed in compression to minimise the effects of potential misalignments.

20 kN DWM

This machine generates forces in 0.5 kN increments up to 5 kN and then in 1 kN increments up to 20 kN. Any required force can be applied (or removed) in a single step by driving downwards (or upwards) the scalepan and any weights suspended from it, at a manually-variable speed. The expanded uncertainty of any generated force is 0.001 %.

25 kN Servohydraulic MTM

An Instron 8872 servohydraulic MTM (with an expanded uncertainty of force generation of 0.22 %), controlled by Instron's WaveMatrix software, was used to conduct additional testing after the work in the DWM was complete. The ability of this machine to consistently generate pre-defined force-time profiles proved very useful.

2.2. Force Transducers

Two strain gauge force transducers (the standard type used within uniaxial testing traceability) were employed for this work; one being designated the reference standard (REF) and the other the unit under test (UUT) – details are given in Table 1. The two transducers were physically connected using adaptors screwed into and onto their threaded ends (see Figure 1, in which REF is shown above UUT).

Table 1: Transducer information

ID	Manufacturer	Model	Capacity
REF	Revere	USP1-5-A	22 kN
UUT	Interface	1610AJH	22 kN

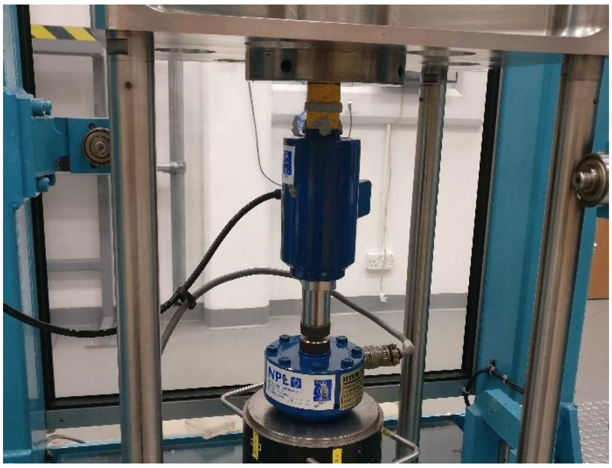

Figure 1: The two transducers in the 20 kN machine

2.3. Instrumentation and Software

Each force transducer was connected to an HBM ML38B card housed within an MGCplus chassis, with the data being acquired, nominally synchronously, via a Visual Basic application running on an attached laptop computer.

3. TESTS

This section details the tests that were performed and analyses their results.

3.1. Measurements in the 20 kN DWM

Static Calibrations

With the transducers centralised in the 20 kN DWM and no disturbance of them between runs, a static calibration to 20 kN in 2 kN increments was performed. This calibration comprised four runs; two incremental only then two incremental and decremental, with dwell periods of 30 s at each force. The calibration was then repeated with each transducer connected to the other ML38B card – UUT was connected to card 1 in calibration A and to card 2 in calibration B.

The outputs from the two transducers were logged every second throughout the calibrations, with the transducer deflections then being derived by subtracting the output at the initial zero force from the output under load. The transducer sensitivity for each incremental and decremental force was calculated by dividing the mean deflection obtained just before a change of force by the applied force – these sensitivities are shown as calibration factors (CF) for incremental (Inc) and decremental (Dec) forces for the two calibrations (A and B) in Figure 2.

It is clear from these results that there is a large difference in sensitivity between the two transducers, that both exhibit significant hysteresis, and that there is no significant difference between the sensitivity values derived from the two different cards.

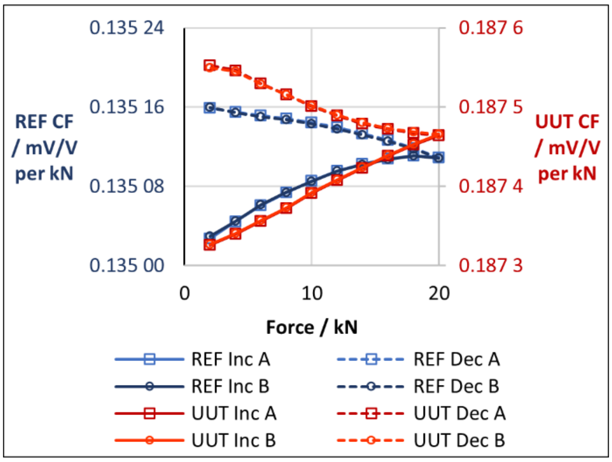

Figure 2: Static calibration sensitivities

For each transducer, separate least-squares third-order fits were derived for incremental and decremental sensitivities.

Continuous Measurements

With the full 20 kN weightstack loaded onto the scalepan, this force was applied to both transducers at six mean loading rates, based on the time period from 1 kN to 19 kN, ranging from to 500 N·s^{-1} to 32 kN·s^{-1}. After application and a 30 s dwell period, the force was removed at the same nominal rate.

This procedure was repeated at two further orientations of the transducers within the machine (rotated to 120° and 240°) and also with UUT on top of REF. It was also repeated for incremental forces only with the transducers connected to the opposite ML38B card to ensure the outputs were being acquired synchronously. Finally, the work was repeated using a range of different filter settings ranging from 0.5 Hz Bessel to 10 Hz Butterworth.

Throughout the calibration runs, the transducer outputs were acquired at a rate of 75 Hz. During post-processing, after deflections had been calculated by subtracting the output at the initial zero force, an estimate of the applied force at each sample time was determined from REF's deflection and its static calibration coefficients, switching from the incremental coefficients to the decremental coefficients halfway through the 30 s dwell period at 20 kN. From this force value and UUT's deflection, a sensitivity for UUT was determined and plotted as a function of force, then contrasted with its statically-determined sensitivity.

Data synchronisation: Pairs of slow and fast incremental runs were performed with the two transducers connected to each ML38B card in turn, the two combinations being designated C and D, using a 1.5 Hz Bessel filter, with the resultant UUT sensitivities being plotted in Figure 3.

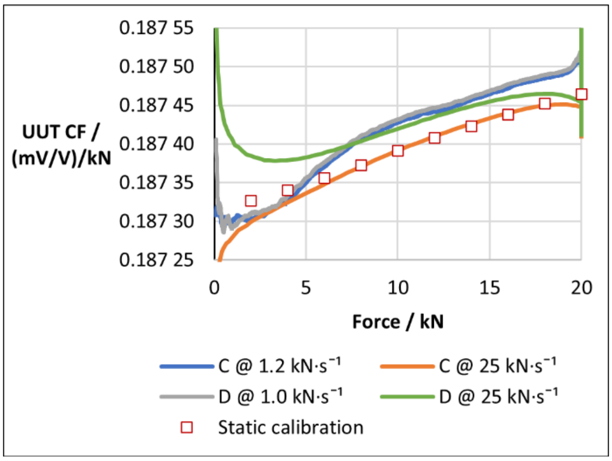

Figure 3: UUT sensitivity with no time offset

As expected, at the slower force application rates, there is no significant difference between the derived UUT sensitivity characteristic. However, at the faster application rate of 25 kN·s^{-1}, a significant difference can be seen, suggesting that the data acquisition from the two channels is not perfectly synchronous, as identical results would have been obtained if it were. Introducing a simulated time offset of 25 µs (selected by eye to bring the two faster traces as close together as possible) between the two channels within the data analysis resulted in the plots shown in Figure 4.

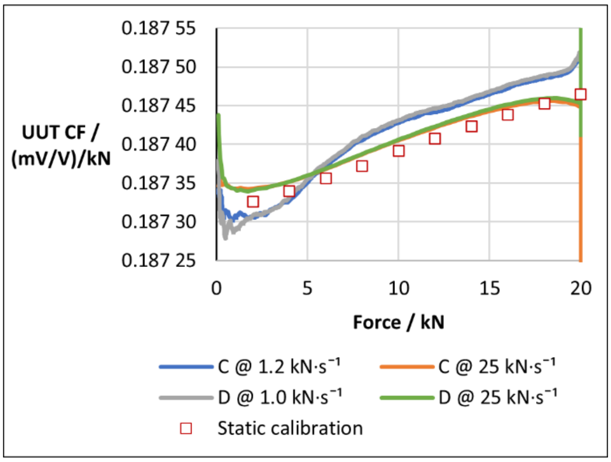

Figure 4: UUT sensitivity with 25 µs time offset

The introduction of this offset has had minimal effect on the slower force traces but has successfully overlaid the 25 kN·s^{-1} ones, suggesting that there is a time offset between data capture from the two cards of approximately 25 µs. Repeated similar testing, not further reported here, confirmed that this offset remained stable and repeatable. As this was the case, all results were corrected in the post-test data analysis for a time offset of this magnitude.

Effects of force rate: Typical UUT sensitivity results as a function of force application rate are shown in Figure 5. These tests were performed with REF located above UUT and employed a 1.5 Hz Bessel filter. The tests were repeated with the transducers rotated in the machine and with UUT located above REF – in all cases, similar results were obtained.

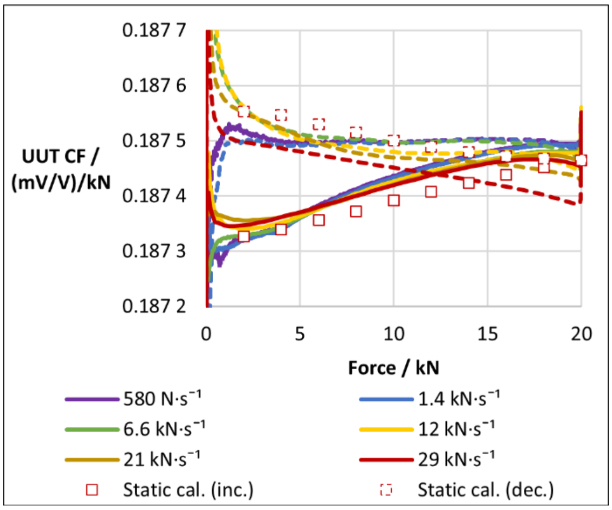

Figure 5: Effect of force rate on UUT sensitivity (solid lines: incremental loading, dashed lines: decremental loading)

An alternative way of presenting these results is shown in Figure 6, in which the relative difference from the cubic fit to UUT's static sensitivity is plotted as a function of force.

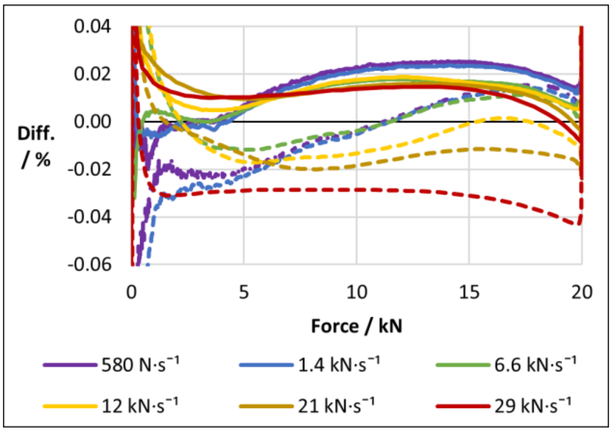

Figure 6: Effect of force rate on difference from static calibration sensitivity (solid lines: incremental loading, dashed lines: decremental loading)

A number of conclusions can be drawn from these two figures:

- for incremental forces, the UUT sensitivity is a function of the force application rate although, in the force range above 6 kN, faster application rates give sensitivities closer to UUT's static values;

- the force rate-induced variation between the incremental sensitivities is less than 0.02 % for virtually the complete force range;
- there is a greater spread in decremental sensitivities but all differences from the static values are still within ±0.05 % across the whole calibration range from 2 kN to 20 kN.

The reason that the slow force application sensitivities do not, as might be expected, agree with the static sensitivities could be that the loading conditions in the two cases are not identical. During the static calibration, the scalepan and selected weights are freely suspended from the ball-seating unit placed centrally on the upper transducer; during the continuous calibration, the scalepan is again making contact with this unit but it is also constrained by its own kinematic supports as it is being driven either downwards to increase the force on the transducers or upwards to reduce it. This additional constraint on the scalepan will be introducing a different amount of bending into the transducers than that which is present during their static calibration – and all force transducers are sensitive to such bending to a greater or lesser extent.

Similarly, the decremental sensitivities are likely to be affected by the transition from a pure deadweight of 20 kN being suspended from the transducers to the condition in which the scalepan is being partially supported by the machine framework. As the scalepan supports rise to meet the scalepan, there will be a dynamic force imparted upon it when contact is made and it will take some time for any vibrations to die down and for the kinematic locations to be correctly oriented – it should be remembered that, at the higher force rates, the complete force is removed in under 0.7 s. Figure 7 shows how much more smoothly the decremental unloading starts at slower force removal rates.

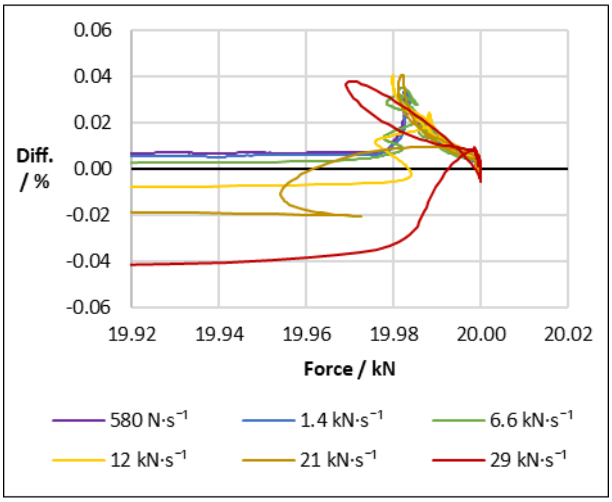

Figure 7: Effect of force removal rate on decremental differences from static sensitivities

<u>Effects of filtering</u>: To determine whether the ML38B filter selection had any significant effect, a similar set of loading rates was applied using filters of varying cut-off frequency and type (Butterworth and Bessel), but no significant effects were apparent. Figure 8 and Figure 9 show the results from the two extremes of the frequency range.

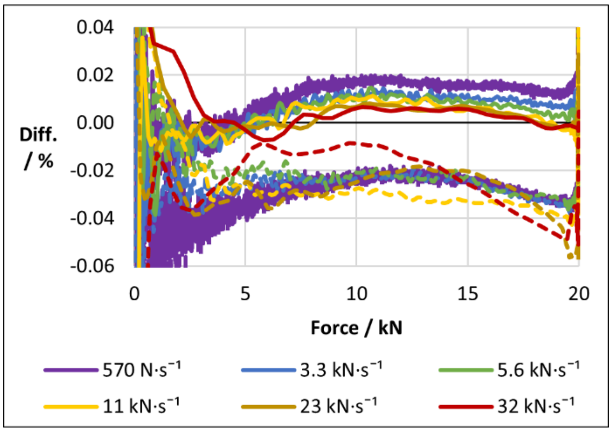

Figure 8: Difference from static calibration sensitivity – 10 Hz Butterworth filter (solid lines: incremental loading, dashed lines: decremental loading)

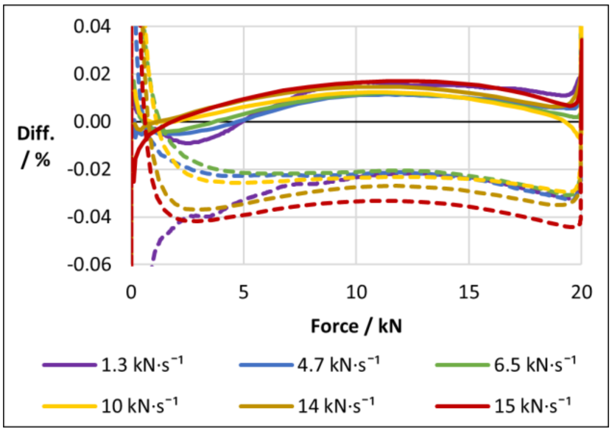

Figure 9: Difference from static calibration sensitivity – 0.5 Hz Bessel filter (solid lines: incremental loading, dashed lines: decremental loading)

It is clear that the decremental characteristics displayed in these two figures differ from those shown in Figure 6 – it is likely that this difference results from mechanical misalignment effects, as the transducers had been removed from and then replaced in the machine between tests. A repeat of the 1.5 Hz Bessel filter tests gave the initial decremental differences shown in Figure 10, clearly different from those shown in Figure 7.

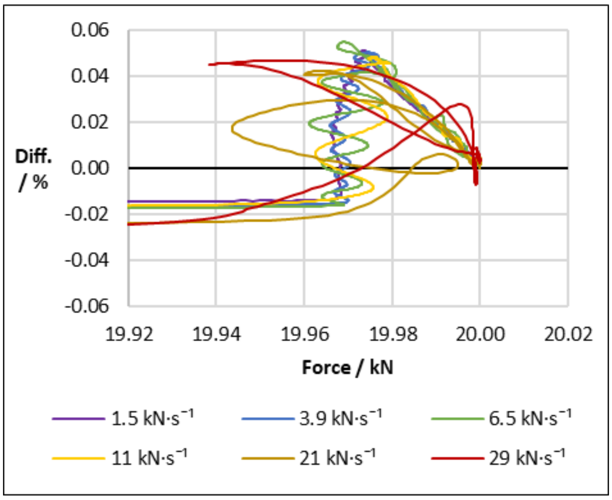

Figure 10: Effect of force removal rate on decremental differences from static sensitivities

3.2. Measurements in the 25 kN MTM

The two transducers are shown located within the 25 kN MTM in Figure 11. Above them can be seen the machine's load cell, which is used to control the applied force, attached to the end of the hydraulic ram.

Figure 11: The two transducers in the 25 kN machine

Incremental and decremental ramp loading tests were performed at rates from 700 N·s^{-1} to 30 kN·s^{-1}, with a 30 s dwell at the maximum force of 20 kN. The resulting UUT calibration factors and relative differences from its static sensitivity, as determined in the 20 kN DWM, are plotted against force in Figure 12 and Figure 13 respectively.

It is clear that the better control of the loading rate and the more consistent loading conditions result in smoother, more homogeneous traces than those seen in Figure 5 and Figure 6.

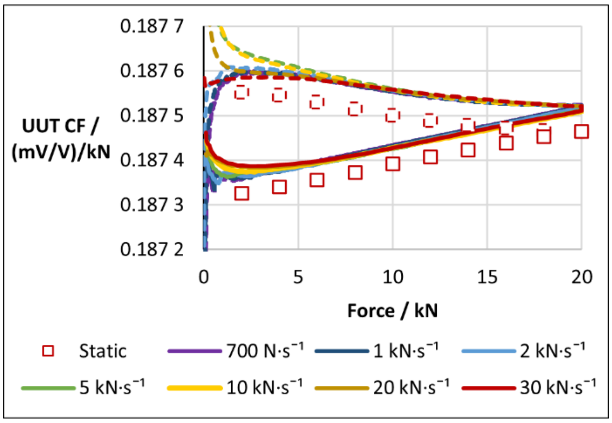

Figure 12: Effect of force rate on UUT sensitivity (solid lines: incremental loading, dashed lines: decremental loading)

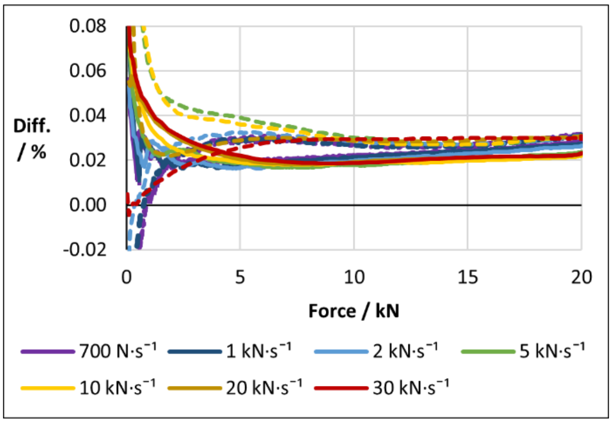

Figure 13: Effect of force rate on difference from static calibration sensitivity (solid lines: incremental loading, dashed lines: decremental loading)

An alternative method to analyse the data is to look at the ratio between the deflections of the two transducers under different loading profiles. The 25 kN MTM was operated to generate a similar force-time profile to that employed during the static calibration of the transducers in the 20 kN DWM, shown in Figure 14 together with the ratio of the transducer deflections. The stability of this ratio, a measure of the relative creep of the two transducers, throughout a selection of the nineteen 30 s dwell periods is shown in Figure 15.

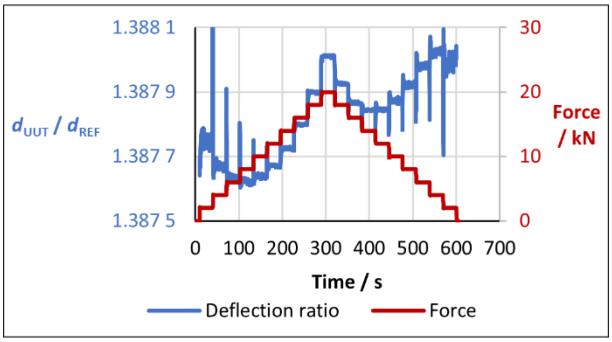

Figure 14: Force-time profile and deflection ratios

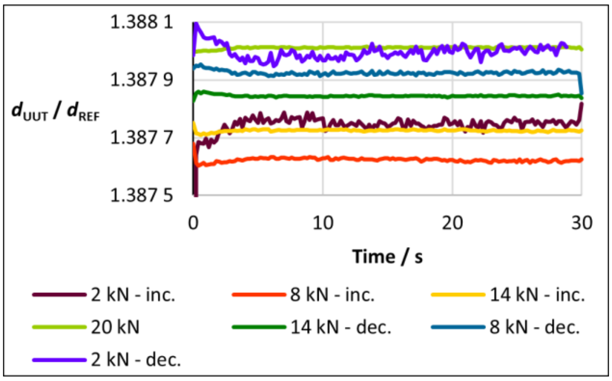

Figure 15: Stability of transducer deflection ratio

The deflection ratio traces obtained in the previous ramp tests are shown in Figure 16, together with the static deflection ratio values, as determined at the end of each 30 s dwell period in this test, designated “Static (MTM)”. Also shown are the transducers’ deflection ratios from their static calibrations in the 20 kN DWM, designated “Static (DWM)”. Differences from fits to the MTM static values are plotted in Figure 17. The results suggest that, for this pair of transducers and at each force, it should be possible to estimate UUT’s deflection after 30 s from REF’s deflection at 30 s and from any of the ramp force test results, to within 0.02 %.

The results also suggest that the differences (in most cases less than 0.01 %) resulting from the wide range of testing speeds used are small in comparison to the differences (up to 0.04 %) resulting from the transducers’ mechanical alignment.

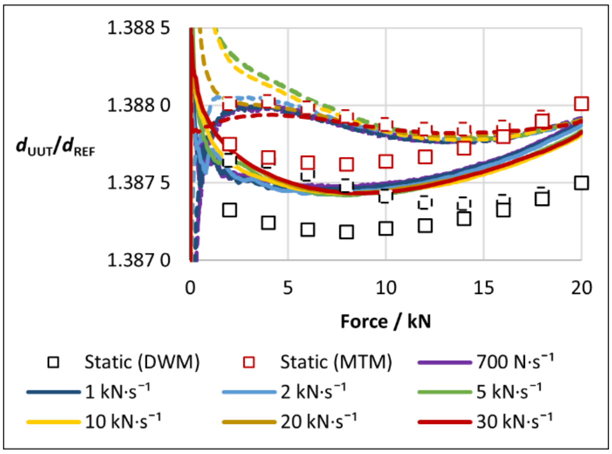

Figure 16: Transducer deflection ratios from static and ramp testing (solid lines: incremental loading, dashed lines: decremental loading)

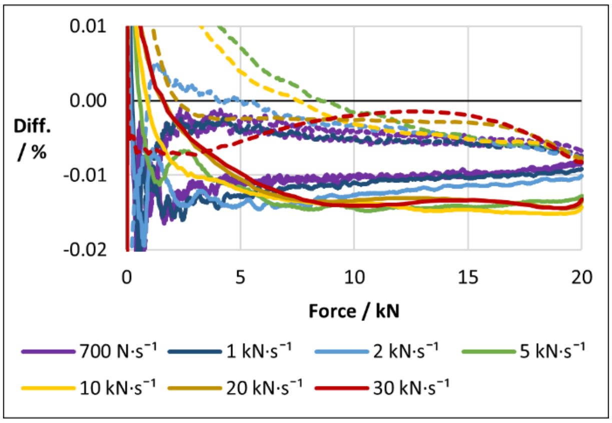

Figure 17: Deflection ratio differences from MTM static values (solid lines: incremental loading, dashed lines: decremental loading)

4. CONCLUSIONS

A sequence of tests with the appropriate variation of parameters for both loading and data processing can in fact characterise the behaviour of the pair of transducers in question.

The use of calibration machines employing the deadweight principle to generate continuous force profiles must undergo a careful a priori evaluation, especially with regard to repeatability in the control of applied force and unknown inertial and mechanical effects. Standard materials testing machines are likely to have better control of the force application rate and the more consistent loading conditions should result in smoother and more homogeneous traces.

Relative continuous creep and hysteresis are mandatory parameters to be further analysed in future studies.

5. REFERENCES

[1] ISO 376, “Calibration of force-proving instruments used for the verification of uniaxial testing machines”, International Organization for Standardization, 2011.

[2] ISO 7500-1, “Tension/compression testing machines – Calibration and verification of the force-measuring system”, International Organization for Standardization, 2018.

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