# EFFECTS OF STRESS-STRAIN DATA SYNCHRONISATION ERRORS ON THE DETERMINATION OF YOUNG'S MODULUS OF HARD AND SOFT MATERIALS IN MATERIAL TESTING MACHINES

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# EFFECTS OF STRESS-STRAIN DATA SYNCHRONISATION ERRORS ON THE DETERMINATION OF YOUNG'S MODULUS OF HARD AND SOFT MATERIALS IN MATERIAL TESTING MACHINES

A. Prato[1], A. Schiavi[2], A. Facello[3], F. Mazzoleni[4], A. Germak[5]

INRiM – National Institute of Metrological Research, Turin, Italy
[1] a.prato@inrim.it, [2] a.schiavi@inrim.it, [3] a.facello@inrim.it, [4] f.mazzoleni@inrim.it, [5] a.germak@inrim.it

**Abstract:**
In this paper, the effects of stress-strain data synchronisation errors on Young's modulus of hard and soft materials in typical material testing machines are described. Seven materials, three Cu-Cr-Zr alloys and four polymers, are tested in two machines conceived for the measurement of the mechanical properties of hard and soft materials. In both machines, the synchronisation of stress and strain signals are guaranteed by the machine's internal signal processing system. By performing known temporal shifts with respect to each other, the Young's modulus is calculated. In this way, the variation of Young's modulus as a function of the temporal shift can be determined and the sensitivity coefficients, to be used in the uncertainty evaluation, derived.

**Keywords:** Stress-strain; Young's modulus; synchronisation; metals; polymers; material testing machines

## 1. INTRODUCTION

The automotive, aerospace, off-shore energy, healthcare and construction industries as well as the research community relies on material and mechanical testing to ensure the quality and safety of their products in daily use. Also, to avoid structural failures in mechanical components, such as those required by the civil engineering or aviation industry, material tests need to be done to get physical and mechanical properties of substances, such as raw materials and components under various conditions. These measurements are usually performed in material testing machines (MTMs) with tensile tests, which are performed by gradually applying a load to the material and measuring the relevant deformation, from which the well-known stress-strain curves are determined. Such procedures for metallic materials and soft materials are described and given in ISO 6982-1:2019 [1] and ISO 527:2019 series [2], respectively. These curves reveal many of the properties of a material, such as the Young's modulus, the yield strength and the ultimate tensile strength. In tensile tests, the specimen is placed in the machine between the grips used to apply the force in time and an extensometer automatically records the change in gauge length during the test. For this reason, the synchronisation of these time signals is of paramount importance to avoid incorrect results. Usually, it is guaranteed by using the same acquisition system for force and displacement signals, however, small and unavoidable differences always occur due to delays in data processing. Furthermore, when independent acquisition systems are used, synchronisation task is difficult to be accurately achieved. In any case, uncertainty due to such effect is usually disregarded in the relevant standards, thus its influence shall be evaluated. In this work, the effects of stress-strain data synchronisation on the determination of the Young's modulus of three hard and four soft materials are evaluated by using two different MTMs, each conceived for hard and soft materials, respectively. In particular, the variation of the Young's modulus as function of time delay is evaluated and the sensitivity coefficient to be used in uncertainty assessment is provided.

## 2. MATERIALS AND METHODS

Three samples of Cu-Cr-Zr alloy (1 % Cr, 0.06 % Zr, 98.4 % Cu) are tested as hard materials. Specimens 2 and 3 have been aged from different heat treatments at 480 °C and 550 °C, while specimen 1 is kept as received. The experimental procedures for the measurement of their Young's modulus, by means of engineering tensile tests at CIRA (Centro Italiano Ricerche Aerospaziali), are described. Young's modulus is determined on the basis of stress-strain measurements according to ISO 6892-1:2019 [1]. Tensile tests have been performed by using an INSTRON 4505 "stress-strain" device, shown in Figure 1. The resulting force is measured by means of a 100 kN load cell. Displacement is evaluated, from DIC technique, in several regions of the sample and the mean value is used [3]. The displacement rate is set to 0.1 mm/min.

In addition, four polymeric materials are tested: a negative photoresist epoxy-based polymer (JHS), a hexamethylene diisocyanate-based polymer (JHT), and two polyethene-based polymers (JJS and JJT). Tensile tests are carried out with a proper device specifically designed and realised at INRIM (Figure 2), which works in displacement control [4], according to ISO 527:2019 series [2]. The force is applied by a stepping motor (Orientalmotor $\alpha$-GRADE AR Series) connected to a screw by means of a reduction gear. The displacement rates can be opportunely tuned from about 1 mm/s to 0.1 µm/s. The displacement is measured by an encoder Solartron LE25/S with an accuracy of 1 µm. The resulting force is measured by means of HBM type Z3H3R 1 kN load cell, with a resolution of 5 mN.

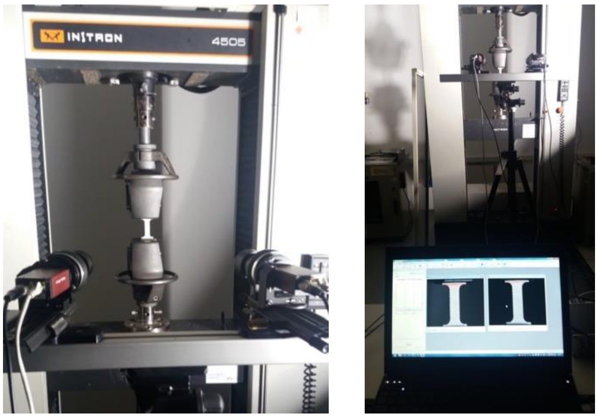


Figure 1: MTM used at CIRA and DIC technique for metallic materials

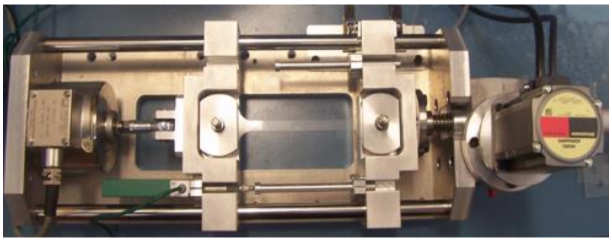

Figure 2: MTM used at INRIM for soft materials

Force and displacement signals are simultaneously acquired by the acquisition board (NI 4431) with a time step of 1 s for around 600 s at CIRA and with a time step of 0.5 s for around 250 s at INRiM. Forces (in newtons) and displacements (in metres) are then converted into stress (in pascals) and strain by dividing by the area of specimen section and by dividing by the length of the specimens, respectively, according to the relevant standards.

Young's modulus is calculated from stress-strain curves by performing a linear regression of the linear elastic region, as shown in Figure 3 and Figure 4 for CuCrZr #1 and JHS, respectively, and taking the angular coefficient of the line. Results are summarised in Table 1.

To evaluate the effect due to the synchronisation, stress-strain time signals are shifted with respect to each other with different time steps up to ±9 s and ±15 s for hard and soft materials, respectively. In this way, the Young's modulus is recalculated for each temporal shift in the same elastic region.

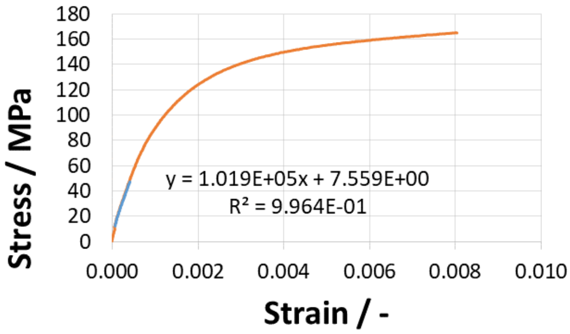


Figure 3: Stress-strain curve of CuCrZr #1. The blue line is the linear region used to calculate Young's modulus

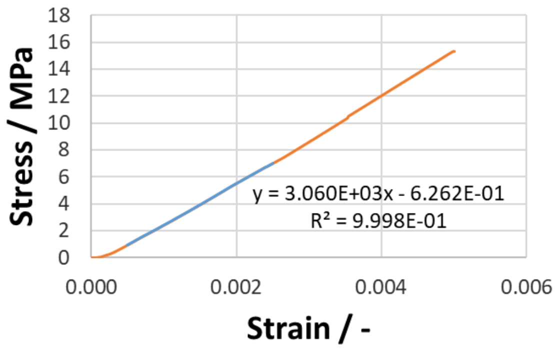


Figure 4: Stress-strain curve of JHS polymer. The blue line is the linear region used to calculate Young's modulus

Table 1: Young's modulus of the tested materials

| **Material** | **Young's Modulus *E* / GPa** |
|---|---|
| CuCrZr #1 | 101.9 |
| CuCrZr #2 | 125.4 |
| CuCrZr #3 | 110.5 |
| JHS | 3.060 |
| JHT | 0.206 7 |
| JJS | 0.327 9 |
| JJT | 0.268 5 |

## 3. RESULTS

In Figure 5 to Figure 11, the Young's modulus curve as a function of the temporal shift is depicted for all tested materials. For the hard metallic materials, the curves are not linear and show a different behaviour although a similar composition. It is worth underlying that, despite the huge temporal shifts, Young's modulus is always calculated in an elastic region of the stress-strain curve.

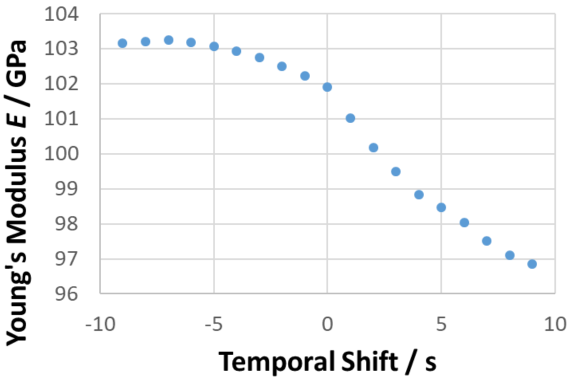


Figure 5: CuCrZr #1 Young's modulus as function of the temporal shift

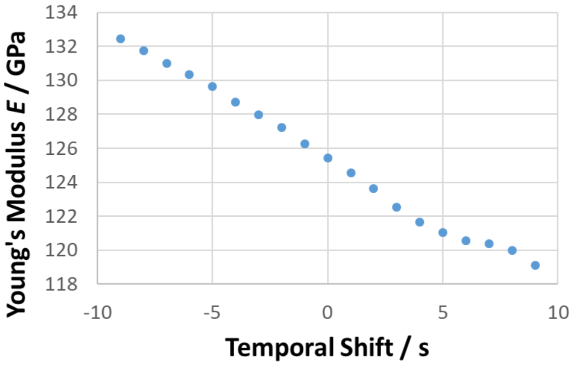


Figure 6: CuCrZr #2 Young's modulus as function of the temporal shift

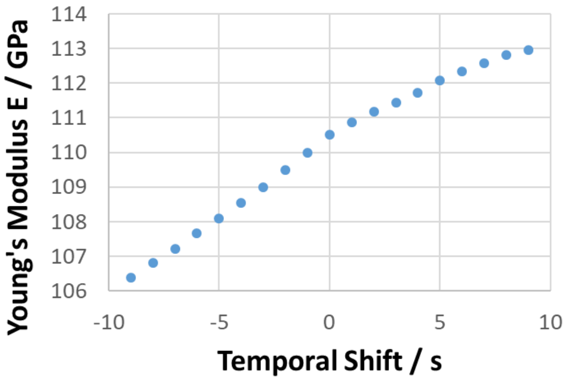


Figure 7: CuCrZr #3 Young's modulus as function of the temporal shift

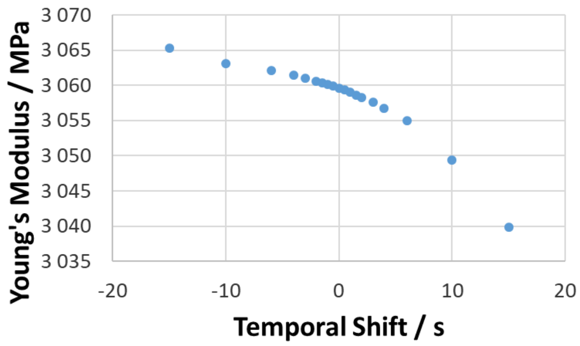


Figure 8: JHS Young's modulus as function of the temporal shift

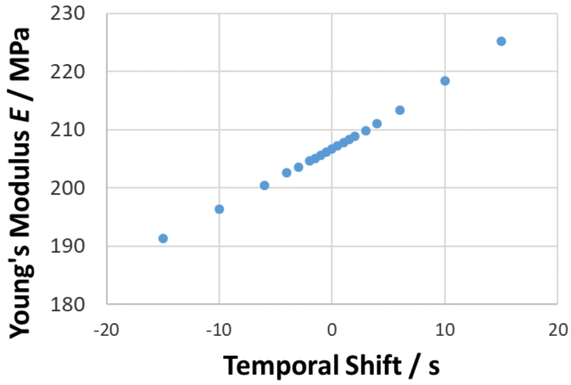


Figure 9: JHT Young's modulus as function of the temporal shift

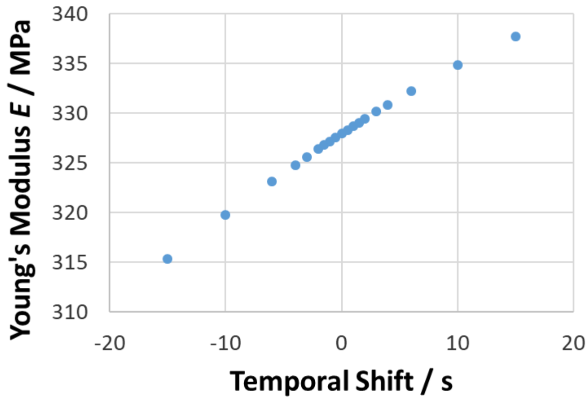


Figure 10: JJS Young's modulus as function of the temporal shift

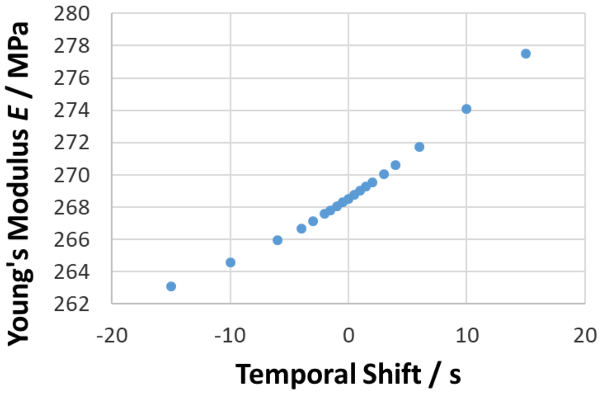


Figure 11: JJT Young's modulus as function of the temporal shift

## 4. SENSITIVITY COEFFICIENTS AND UNCERTAINTY BUDGET

By performing a linear fit of the Young's modulus/temporal shift curves, the sensitivity coefficient in MPa/s can be evaluated. In Table 2, the sensitivity coefficients of these curves for the tested materials are summarised. Such coefficients can be used in the Young's modulus uncertainty evaluation to propagate the uncertainty due to synchronisation errors. It can be found a quite dispersion of results for the hard metallic materials despite their similar composition, whereas, for soft materials, sensitivity coefficients are similar.

Table 2: Young's modulus sensitivity coefficient associated with synchronisation

| Material | Sensitivity coefficient $c_{synch}$ / MPa/s |
|---|---|
| CuCrZr #1 | -586 |
| CuCrZr #2 | -779 |
| CuCrZr #3 | 380 |
| JHS | -0.759 |
| JHT | 1.11 |
| JJS | 0.749 |
| JJT | 0.480 |

In this way, the metrological model for the evaluation of the uncertainty associated with Young's modulus can be written as equation (1).

$$E = \frac{\partial\left(\frac{F}{A}\right)}{\partial\left(\frac{L_0}{l}\right)} + c_{synch}\Delta t \qquad (1)$$

where $F$ is the measured tensile force (in N), $A$ is the area of the specimen's section (in m$^2$), $L_0$ is the initial length of the sample (in m), $l$ is the occurring deformation length (in m), $c_{synch}$ is the sensitivity coefficient due to the synchronisation error (in Pa/s) and $\Delta t$ is the temporal shift between force and displacement signals (in s), which is nominally equal to 0.

By applying the law of uncertainty propagation, the uncertainty contribution due to the synchronisation error, $u^2_{synch}(E)$ is given by equation (2).

$$u^2_{synch}(E) = {c_{synch}}^2 \cdot u^2(\Delta t) \qquad (2)$$

To evaluate the impact of such uncertainty contribution on the overall uncertainty, as an example, supposing a tolerance of ±1 s associated with the temporal shift $\Delta t$ between the force and displacement signals (thus an associated uncertainty $u(\Delta t)$ of 0.577 s) and using equation (2), the relative uncertainty $u_{synch}(E)/E$ of Young's modulus due to synchronisation error of the tested materials is given in Table 3. Although in many cases such uncertainty is negligible due to small uncertainties associated with $\Delta t$ in particular when the same and synchronous acquisition system is adopted for both force and displacement signals, in this example, it is in the order of few parts in $10^{-3}$ compared to the typical Young's modulus relative uncertainty which is around 1 % to 2 % [5], therefore, although small, it is not that negligible and shall be considered, in particular when independent acquisition systems are adopted.

## 5. SUMMARY

In this work, the effects due to synchronisation errors of stress-strain signals in the determination of Young's modulus of hard and soft materials using typical material testing machines are shown. Three Cu-Cr-Zr alloys and four polymers are tested. Young's modulus variations as a function of the temporal shifts are described and the relevant sensitivity coefficients are calculated to be used in the uncertainty assessment.

Table 3: Relative uncertainty of Young's modulus associated with synchronisation

| Material | Relative uncertainty $u_{synch}(E)/E$ |
|---|---|
| CuCrZr #1 | $3.3 \times 10^{-3}$ |
| CuCrZr #2 | $3.8 \times 10^{-3}$ |
| CuCrZr #3 | $2.0 \times 10^{-3}$ |
| JHS | $1.4 \times 10^{-4}$ |
| JHT | $3.1 \times 10^{-3}$ |
| JJS | $1.3 \times 10^{-3}$ |
| JJT | $1.0 \times 10^{-3}$ |

## 6. ACKNOWLEDGEMENTS

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