IETeasy: An open source and low-cost instrument for impulse excitation technique, applied to materials classification by acoustical and mechanical properties assessment.

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ABSTRACT

In the past twenty years, impulse excitation technique (IET) has become a widely diffused non-destructive technique in metal industry field. This success resides in its capability to determine with high precision and accuracy some elastic properties of materials, such as Young’s modulus, shear modulus and Poisson’s ratio. The technique, which is very fast and non-destructive, consists in exciting a sample by a mechanical input and registering the acoustic output that, once analyzed by Fast Fourier-Transformation (FFT), provides the resonant frequencies of the sample, with a fast data analysis procedure. The approach is thus very easy to be applied to most materials and cost and time effective. Despite these many advantages, IET is still an under exploited technique in academic research centres, that mainly rely on traditional destructive methods for the evaluation of such properties, for instance by the measurement of strain-stress curves. Commercial IET instruments, similarly to traditional ones, have costs spanning from many hundreds to thousands of dollars, limiting their diffusion in academic world but also in small companies with limited R&D or quality control expenses. Non-professional instruments can also give very precise results and can be successfully used in basic research and in quality control even if not certified as commercial ones. Moreover they can be easily customized according to specific user needs and sample features. Since no examples of low cost IET designs can still be found in the scientific literature, we fill the gap in this paper, giving instructions for a self-assembled instrument for IET analysis, with a cost in the range of 70–85 USD. Moreover, the collected calibration data are analyzed to prove that the instrument can be used for other purposes than the common elastic properties determination, but also for a fast and cheap material characterization exploiting a multivariate analysis approach. Calibration results show that IETeasy can be used in both academic and industrial field for quality control purposes as a low-cost, fast and efficient alternative to tensometers. Principal component analysis, applied in this paper for the first time to IET data analysis, was able to distinguish and classify steel from Al or Cu alloys from polymers, but also different steel grades, demonstrating its potential in massive and eventually automatic IET data analysis. Calculated mechanical properties fitted with good approximation the ranges expected for each sample.

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1. Hardware in context

In the last years of the 1990s, [1,2] Impulse Excitation Technique (IET) was proposed as an easily applicable method for the measurement of resonant frequencies of materials, which can be exploited to calculate elastic properties, such as Young's modulus, shear ratio and Poisson's coefficient. The approach can be thought of as playing a percussion instrument, which consists in generating a mechanical impulse in a sample, using a mallet or a projectile, and collecting the audible output sound-wave. The data collection can be performed by different sensors depending on the availability: microphones, accelerometers, piezoelectric sensors, or laser vibrometers. Then, data are processed usually by FFT, which converts the sound-wave signals in the time domain to spectral data in the frequency domain. In the obtained spectra, natural resonant frequencies of the samples are identified by the peak positions and, by applying Euler-Bernoulli beam theory for Free-Free boundary conditions [3], elastic properties of materials can be determined. Despite being a relatively simple approach, the accuracy of the technique is very high, and the uncertainty on the calculated moduli can be lowered to 0.1% [4]. IET is also very versatile and can be used in a wide range of temperatures (from −50 °C to 1700 °C [2]) and in presence of different gases or in vacuum, depending on which sensor is equipped on the instrument (laser vibrometers is necessary for vacuum measurements). In the 2000s, the industrial world implemented this approach in the quality control processes, while regulatory bodies [5–7] provided technical standards for IET procedures. Despite its capability to provide precise and accurate results in a very short time, IET initially remained mainly confined in the industrial world and used for quality control purposes. However, even in this field, other expensive complementary techniques had been preferred to IET, such as the ultrasounds analysis, radiography and tomography [8], which are still the most used non-destructive techniques (NDT) for quality control and certification. In the last years, many notable academic research examples began to spread in the fields of the metallurgy [9–11], geology [12] and the science of ceramic materials [13–15]. Even if IET data are rich in information content, the main application of the technique consists in the measurement of elastic properties of materials, such as Young’s modulus, shear modulus and Poisson’s coefficient [16]. In some research articles, IET is used on samples to detect and study the nature of defects [17,11], stress [18] and voids [19]. The technique can be used, not only for the elastic characteristics of a material and its damping properties, but also for material classification and qualitative analysis of samples. For these purposes, multivariate statistical analysis can cover a key role with many unexplored and promising applications, with the most common pattern recognition and classification methods (Cluster analysis, principal component analysis, linear discriminant analysis) being used for sample identification. In more complex and wider data collections, machine learning can be also used to build an automated recognition system. These applications are still scarce in the scientific literature and this can be ascribed to two concurrent causes. On one hand, many professional instruments are often rather costly, especially the portable ones and do not allow the full analysis of the collected impulses due to factory settings or for lacks of suitable algorithms. In particular, some instruments are designed to give the Young’s module of sampled materials as output, which is only one of the responses that can be extracted by a complete analysis of the impulse. Academic research requires a direct control and handling of raw data. On the other hand, despite being known as a technique that does not require a professional equipment, in scientific literature, no examples of low-cost and/or open source instruments for IET can be found. To overcome these obstacles hindering a wider diffusion in academic world, but also in small companies not able to afford a professional instrument, a self-built instrument for IET analysis (IETeasy) is presented in two different versions: one built in spruce wood and another one, identical in shape but in polylactic acid (PLA), made by 3D-Printing. The main difference between the two setups resides in their aesthetic, with the 3D-printed version being more elegant than the spruce wood one. However, the 3D-printed version, can be reproduced more easily in many identical exemplars. Some samples of different materials were then analyzed with the IETeasy and both raw and processed data are provided in an online Mendeley Data repository [20] and described in the respective data article [21]. Descriptive statistics on the collected data and a demonstration of the capability in materials recognition are provided in Section 7. Young’s moduli for these materials were calculated and compared to the expected ones reported in literature or in technical data sheets. Finally, the potentialities of principal component analysis (PCA) in fast, efficient and eventually automatic analysis of very large data set by IET spectroscopy is demonstrated, since PCA can be a con-
venient complementary or alternative approach to Fourier transform based methods, as demonstrated in crystallography field by some of us [22].

2. Hardware description

IETeasy is an instrument very simple in its design, composed by two separate parts: a sample-holding frame and a mallet support. The first part is a frame with two taut nylon strings with diameter of 0.5mm. The strings have the task of supporting the sample and, at the same time, implementing Free-Free boundary conditions as well as possible by placing them along the nodal lines of the desired vibration mode. Inside the frame, a passing bar is placed with a centimeter scale, used to measure the distance between the two strings and guarantee that all the data collections are done in the same conditions. The centimeter scale is, not only convenient to guarantee that data are collected in the same conditions, but also to place the strings along the nodal lines. Moreover, the central bar has the task of supporting the strings, in order to avoid distortion effects that can be caused the string vibrations against flat surfaces of the frame. The mallet support consists in a xylophone mallet mounted on a wooden standing support which has the task of preventing differences in the exciting impulse strength. Being only gravity-based, the hitting strength of the mallet is always the same, which guarantees that the measurement as reproducible as possible. A USB condenser microphone connected to a PC is used as acquisition setup. The head of the microphone is positioned above the sample and directed toward its upper side, as displayed in Fig. 1. An average acquisition spans between 8 and 12s, depending on how much damped is the sound produced by the sample.

2.1. Traditional data analysis methods

The collected raw data are in the time domain and they can be used for the calculation of the damping parameter of the investigated samples, which gives an estimation of the material’s behavior in response to an induced oscillation. It has to be considered that the calculation of the acoustic insulation can not be accurate with this setup, as the air viscosity it’s usually not negligible. Vacuum chamber and a laser vibrometer (or another non-acoustic sensor) are required for a precise measurement. Traditional analysis can be carried out on both time or frequency domain. The calculation can be done by refining the damped sound wave with an exponentially damped sine function in time domain in the form [23]:

\[ s_t = Ae^{-kt}\sin(2\pi f_r t + \phi) \] (1)

where:

1. \( s_t \) is the collected sound wave in the time domain;
2. \( A \) is a scale coefficient that have to be refined;
3. \( k \) is the decrease parameter due to the damping;
4. \( t \) is the time;
5. \( f_r \) is the frequency of the fundamental flexion vibration mode;
6. \( \phi \) is the wave phase.

Often, such refinements are not easy to perform due to the superposition of several modes. The time domain data are then processed by FFT to transform the signal in the frequency domain and extract the resonant frequencies, which can be used for qualitative analysis or to calculate the mechanical properties, or even to determine if a sample has structural defects. For mechanical properties, on rectangular samples (the ones for which this instrument is designed), Young’s modulus \((E)\) of rectangular samples can be calculated as [5,7,6]:

![Fig. 1. One of the wooden self-built version of IETeasy instrument.](image)
\[ E = 0.9465 \left( \frac{m^2 f_r^2}{w} \right) \left( \frac{l}{t} \right)^2 C \]  

Where:

1. \( m \) is the mass in kilograms of the sample;
2. \( f_r \) is the frequency of the fundamental flexion vibration mode;
3. \( w \) is the width in metres of the sample;
4. \( l \) is the length in metres of the sample;
5. \( t \) is the thickness in metres of the sample;
6. \( C \) is the correction factor defined as:

\[ C = 1 + 6.585 \left( \frac{t}{l} \right)^2 \]  

The correction factor should be used only when \( l/t \geq 20 \).

2.2. Multivariate data analysis as a fast and efficient approach to IET data

Multivariate analysis allows a precise qualitative analysis and, differently from traditional data analysis, can be performed for classification purposes on both time domain and FFT-processed frequency data. In other fields, it resulted a very efficient alternative or complementary technique to FFT based method, as demonstrated by some of us in crystallography [22,24]. One of the main advantages of using a multivariate approach consists in the reduction of dimensionality, in which useful information is extracted from a large set of variables and rewritten in a few “easy to interpret” variables. More important is its capability of easily, fastly and very efficiently analysing very large dataset also in an automatic fashion. In this paper we demonstrated PCA huge potentialities in IETeasy data analysis, and in general, on IET data. Consequently, a fast data analysis coupled to a tool that can produce a huge amount of data in a short time is suitable for on-line analysis (i.e. waste disposal centres). Of course no direct advantage is evident in the small training set used in this paper, but PCA can be easily applied to thousands of data set in a few time and also in an automatic fashion, differently from traditional analysis methods, using mostly (or only) the fundamental frequency. An example of this approach is given in Section 7.3 with the principal component analysis applied to the validation of the data. Also, by measuring series of samples with the same size and shape, it is possible to determine whether defectivity or deviation from conformity is present in a sample or not, making an automatic version of this instrument a good candidate for an on-line quality control.

- Mechanical properties can be determined with high precision and accuracy on materials of different natures;
- Classification analysis can be performed by using both time domain and frequency domain data. Samples can be very well distinguished in the corresponding classes with a highly precise approach;
- By calculating the damping coefficient, a rough estimation of the acoustic insulation of the material can be performed. The use of a vacuum chamber and a laser vibrometer might improve the precision of the calculation, but such approach is beyond the scope of the present contribution.

3. Design files

For the wood version of the IETeasy, detailed building instructions and illustrations are reported in Section 5, therefore no design files were produced. For the 3D-Printed version of the instrument, the required .stl files can be found as Supplementary material of the present article. All files are detailed in the following table.

3.1. Design files summary

| Design filename | File type | Open source license | Location of the file |
|-----------------|-----------|---------------------|----------------------|
| angle a         | stl 3D file | CC BY-NC-ND 4.0  | Available within the repository |
| angle b         | stl 3D file | CC BY-NC-ND 4.0  | Available within the repository |
| base a          | stl 3D file | CC BY-NC-ND 4.0  | Available within the repository |
| base b          | stl 3D file | CC BY-NC-ND 4.0  | Available within the repository |
| central bar     | stl 3D file | CC BY-NC-ND 4.0  | Available within the repository |
| canti           | stl 3D file | CC BY-NC-ND 4.0  | Available within the repository |
| pin a           | stl 3D file | CC BY-NC-ND 4.0  | Available within the repository |
| pin b           | stl 3D file | CC BY-NC-ND 4.0  | Available within the repository |
4. Bill of materials

4.1. Bill of the wood structure

| Designator          | Number | Cost per unit currency | Total cost | Source of materials | Material type |
|---------------------|--------|------------------------|------------|---------------------|---------------|
| Wood strip 40 mm × 40 mm × 1 m | 3      | 4.04 USD per piece     | 12.12 USD  | Leroy Merlin        | Spruce wood   |
| Wood strip 20 mm × 20 mm × 1 m | 1      | 2.49 USD per piece     | 2.49 USD   | Leroy Merlin        | Spruce wood   |
| Vinyl glue          | 1      | 2.40 USD per 225 g     | 2.40 USD   | Leroy Merlin        | Vinyl glue    |
| Wood screw 6 mm × 4 mm | 7      | 14.70 USD per kg       | 0.25 USD   | Leroy Merlin        | Bronzed steel |

4.2. Bill of the 3D-Printed structure

| Designator          | Number | Cost per unit currency | Total cost | Source of materials | Material type         |
|---------------------|--------|------------------------|------------|---------------------|-----------------------|
| angle a             | 2      | 35.69 USD per kg       | 11.64 USD  | Aliexpress          | PLA filament, $\phi = 1.75$ mm |
| angle b             | 2      | 35.69 USD per kg       | 11.64 USD  | Aliexpress          | PLA filament, $\phi = 1.75$ mm |
| base a              | 1      | 35.69 USD per kg       | 4.39 USD   | Aliexpress          | PLA filament, $\phi = 1.75$ mm |
| base b              | 1      | 35.69 USD per kg       | 2.74 USD   | Aliexpress          | PLA filament, $\phi = 1.75$ mm |
| central bar         | 1      | 35.69 USD per kg       | 1.64 USD   | Aliexpress          | PLA filament, $\phi = 1.75$ mm |
| canti               | 1      | 35.69 USD per kg       | 0.36 USD   | Aliexpress          | PLA filament, $\phi = 1.75$ mm |
| pin a               | 3      | 35.69 USD per kg       | 0.86 USD   | Aliexpress          | PLA filament, $\phi = 1.75$ mm |
| pin a               | 4      | 35.69 USD per kg       | 0.22 USD   | Aliexpress          | PLA filament, $\phi = 1.75$ mm |

For the 3D-printed version of the frame and the mallet support, the required total estimated time is of $\approx 100$ h of machine time. For an average 3D-printer, the electric consumption is about 70W for an hour, using a heated bed temperature of 60°C and an hotend temperature of 205°C. Therefore, the costs of the 3D-printing process can not be ignored and are estimated as 50 USD, depending on the cost of 1 kWh and common maintenance costs.

4.3. Bill of the essentials

| Designator          | Number | Cost per unit currency | Total cost | Source of materials | Material type |
|---------------------|--------|------------------------|------------|---------------------|---------------|
| Nylon wire 0.5 mm × 100 m | 1      | 5.91 USD per 100 m     | 5.91 USD   | Leroy Merlin        | Nylon         |
| Electrician clamp   | 2      | 2.77 USD 12 pieces     | 0.46 USD   | Amazon              | Plastic and brass clamps |
| Xylophone mallet    | 1      | 9.15 USD 4 pieces      | 2.29 USD   | Amazon              | Wood mallet   |
| USB condenser microphone | 1 | 40.23 USD per piece | 40.23 USD | Amazon              | Composite     |
| Flat hinge 25 mm    | 1      | 2.59 USD per piece     | 2.59 USD   | Amazon              | Steel         |

5. Build instructions

The dimensions and materials of the instrument have been arbitrarily chosen by the authors, based on the size of the samples that are usually analyzed in the laboratory work scale. Other materials and sizes can be chosen as needed. In particular, the mallet support is an optional component of the instrument as it was observed in the testing phase that even freehand data impulses have excellent reproducibility on the position of the resonant frequencies. Mallet support has been incorporated into the basic design of the instrument as it helps standardize the intensities of spectral signals, which would otherwise be subject to high variability.

5.1. Frame and sample-holding strings

In this section, the "made in wood" IETeasy building instructions are reported. Concerning the corresponding PLA 3D-Printed version, the single pieces have unequivocal interlocks, thus no specific instructions are needed for assembling the PLA frame and the mallet support. Once the PLA frame is built, the operations for mounting the wires are the same of the wood version, therefore only instructions from point 4 onward are required for the 3D-Printed IETeasy version.
1. Two square stripes of spruce wood, one larger with section size of 4 cm, and one smaller with section size of 2 cm were cut to obtain the four frame pieces and the passing central bar that will hold the wires in tension as showed in Fig. 2(a). The larger strips are cut 40 cm in length, while the smaller strip is cut 32 cm long.

2. To avoid wood fissuring along its natural venatures, pre-holes for wood screws were made on the four corners before screwing together the four strips of the frame as shown in Fig. 2(b). The pre-holes were made using a battery drill with a 3.5 mm in diameter drill bit. The central bar was fixed with wood screws inserted in pre-holes as shown in Fig. 2(c). Every surface irregularity can be removed by using sandpaper for a better aesthetic result.

3. On the central bar a centimetre scale was glued (Fig. 2(d)) in order to have a reference of the distance between the sample-holding wires. It is not important that the centimetre scale is positioned at the beginning of the central bar, because it’s unlikely that wires will be separated more than 20 centimetres due to possible collisions between the sample and the frame. If wanted, rubber feet can be attached to the lower part of the frame to keep all the instrument suspended from the underneath table for a better aesthetic result. As spruce wood is soft, the wire can indent the surface, metal plaque can be added to preserve the structure as displayed in Fig. 1.

4. Two pieces of 1 m each of nylon wire with diameter 0.5 mm was cut to make the sample holder. The wires are passed around both the central bar and the opposite side of the frame, as shown in Fig. 2(f). In the version showed in Fig. 2, wires are passed through two holes at the desired measurement distance. Optionally, the wires can be kept in tension using two steel springs, as shown in Fig. 1, which let wires to be custom-positioned at each measurement.

5. The two wires are then taut and kept in position by using electrician clamps. The wire tension can be checked by using a guitar tuner. In this case, an A4 note was used to accord the wires, but this specific note is not necessary to obtain reproducible measurement: the important check is conversely having both wires equally taut and giving the same note, in order to avoid undesired damping effects on the sample.

5.2. Mallet support

Similarly to what stated for the frame, the 3D-Printed version of the mallet support does not require instructions as interlocks are unequivocal. Only flat hinge and mallet instructions have to be read, from the following point 3 onward.

1. Three pieces 12 cm long and 4 cm wide are glued together using vinyl glue in order to obtain a squared piece that will act as the base of the mallet support. Once the glue is set, surface irregularities can be removed by using sandpaper (Fig. 3(a)).

2. A strip 25 cm long and 4 cm wide and a strip 7 cm long and 2 cm wide are cut and will be used as stand part and mallet support respectively.

3. A pre-hole is made at the center of the base and a strip in order to fix by using a screw the 25 cm long piece as shown in Fig. 3(b). To avoid rotations of the vertical part, applying some glue is suggested.

4. A hole 1 cm deep, with a diameter slightly smaller than the one of the mallet strip is made on the flat part of the support as displayed in Fig. 3(c). The piece is fixed to the vertical mallet support with the hinge in order to have a semicircular movement toward the bottom. The mallet is glued and fixed in the proper hole as shown in Fig. 3(d).

5. A rubber band is used to keep the mallet suspended after the impulse is given. There is no particular indication about the rubber band, because it has to be evaluated by the user depending on the setup positioning. The authors used a standard commercial rubber band with a section of 1 mm × 5 mm and a diameter of 42 mm.

Fig. 2. Visual building instructions of the sample-holding frame.
6. Operation instructions

- Place the instrument on a flat stable surface, with the microphone positioned as shown in Fig. 4. Check the distances between the frame and the mallet support and be sure that the mallet can hit the sample correctly once positioned.
- Connect the USB microphone to the PC used to record the impulse. Open the recording software and check that the USB microphone is default input device and that the audio signal is correctly read by the PC. In this paper, Audacity 2.4.2 [25] was used to manage sound sampling.

Fig. 3. Visual building instructions of the mallet support.

Fig. 4. Acquisition setup. The sample is positioned on the sample-holding strings and the mallet is released, giving the mechanical excitation to the material. The produced sound wave is collected by the microphone positioned over the sample and then is processed for further analyses.
• Check the correct distancing between the sample-holding strings. In this paper, standard distance is 5 cm as samples are about 10 cm long.
• Place the sample on the supporting strings and check that the microphone is correctly positioned over it as shown in Fig. 4.
• Start recording and, after few seconds, release the mallet.
• Stop recording after 5–6 s after the impulse production, when the damping is finished.

7. Validation and characterization

The IETeasy hardware was tested initially in its different components and with different purposes: at first, the uncertainty due to the microphone was tested (Subsection 7.1) by collecting notes generated at given frequencies. Then, real-world samples of fifteen different materials were measured by using IETeasy ten times each, in order to obtain descriptive statistics on the natural resonant frequencies of the materials, using an traditional univariate approach (Subsection 7.2). In this section, Young’s moduli had been calculated and compared to the tabulated values on the corresponding technical data sheets for each material. In Subsection 7.3, the whole frequency spectra were analyzed with a multivariate approach by using Principal Component Analysis (PCA) to demonstrate its capability in their classification and the potentialities of such an approach when dealing with thousand data files. For the validation of the hardware construction procedure, two different IETeasy instruments were built by two different users (NM and ML) and then massively used, thus suggesting that multiple IETeasy can easily be assembled and used for materials analysis and classification with good reproducibility.

7.1. Microphone distortion

The accuracy of the microphone was tested by putting it in front of a speaker and generating sound waves corresponding to the seven notes on nine octaves, from \(A_0\) to \(B_8\). Then, those sounds were recorded and processed with FFT to transform the time-domain signals in frequency-domain signals. In Table 1, the generated frequencies and the acquired ones are reported.

As can be seen in Table 1, the errors relative to the acquisition setup are very small and affecting the last one or two significant figures, therefore it can be assumed that the intrinsic overall error is less than the 0.01%, with respect to the measurement itself.

7.2. Characteristic resonant frequencies

Samples of different materials (metals and polymers), were then measured with ten repetitions each, and the collected data were processed by FFT to further analyses reported in Tables 2 and 3. Details on both the samples and the data collection and FFT algorithm are given in the related data article [21]. Obtained spectra were analyzed with the `pick.peaks` function of the ChemometricsWithR package in R, in order to extract the principal resonant frequencies. The results are very precise for alloys but then become more noisy for polymers, as their internal structure is very different, not only due to the long polymeric chains that have more degree of freedom, and a consequent less efficient phononic propagation, but also because of their amorphous structure, which causes an internal damping effect. When plotting the original sound-waves, it can be noticed that the acquisition time of polymers is far shorter than those from the alloys, simply because of the different damping of the materials.

By looking at the descriptive statistics in Table 4, calculated on the resonant frequencies of Tables 2 and 3, it can be observed that alloys samples best perform as reproducibility of the method, with a coefficient of variation of \(10^{-3} - 10^{-4}\) percent. Polymers, due to their molecular structures, characterized by long interconnected chains and amorphous (or less crystalline) phases, have a greater variation coefficient, about 100 times greater than the ones obtained for metals. Despite this, the coefficient of variation of this material is still very low, being only 0.56%.

| Octave | \(C_{\text{read}}\) | \(C_{\text{gen}}\) | \(D_{\text{read}}\) | \(D_{\text{gen}}\) | \(E_{\text{read}}\) | \(E_{\text{gen}}\) | \(F_{\text{read}}\) | \(F_{\text{gen}}\) | \(G_{\text{read}}\) | \(G_{\text{gen}}\) | \(A_{\text{read}}\) | \(A_{\text{gen}}\) | \(B_{\text{read}}\) | \(B_{\text{gen}}\) |
|--------|-------------------|-------------------|-------------------|-------------------|-------------------|-------------------|-------------------|-------------------|-------------------|-------------------|-------------------|-------------------|-------------------|-------------------|
| 0      | 32.705            | 32.703            | 36.722            | 36.708            | 41.209            | 41.203            | 43.639            | 43.654            | 49.014            | 48.999            | 55.006            | 55.000            | 61.727            | 61.735            |
| 1      | 65.405            | 65.406            | 73.416            | 73.416            | 82.435            | 82.407            | 87.336            | 87.307            | 97.999            | 97.999            | 110.02            | 110.00            | 123.47            | 123.47            |
| 2      | 130.88            | 130.81            | 146.84            | 146.83            | 164.79            | 164.81            | 174.60            | 174.61            | 196.02            | 196.00            | 220.00            | 220.00            | 246.95            | 246.94            |
| 3      | 261.70            | 261.63            | 293.75            | 293.67            | 329.65            | 329.63            | 349.32            | 349.23            | 392.03            | 392.00            | 440.05            | 440.00            | 493.88            | 493.88            |
| 4      | 523.28            | 523.25            | 587.41            | 587.33            | 659.30            | 659.23            | 698.49            | 698.46            | 784.04            | 783.99            | 880.14            | 880.00            | 987.92            | 987.77            |
| 5      | 1046.6            | 1046.5            | 1174.8            | 1174.7            | 1318.6            | 1318.5            | 1397.0            | 1396.9            | 1568.1            | 1568.0            | 1760.3            | 1760.0            | 1975.7            | 1975.5            |
| 6      | 2093.2            | 2093.0            | 2349.6            | 2349.3            | 2637.4            | 2637.0            | 2794.2            | 2793.8            | 3136.4            | 3136.0            | 3520.4            | 3520.0            | 3951.6            | 3951.0            |
| 7      | 4186.5            | 4186.0            | 4699.2            | 4698.6            | 5274.7            | 5274.0            | 5588.3            | 5587.7            | 6272.6            | 6271.9            | 7040.8            | 7240.0            | 7903.1            | 7902.1            |
Young's moduli of the analyzed materials were determined using Eq. 2. All calculated values are compared to the corresponding average values in Table 5. The reported tabulated values are taken from literature [26] or from specialized websites, as no experimental data were reported in technical data sheets given by the supplier. Stainless steel reported values that are about 30 GPa lower than the expected value, while for other materials the difference between the calculated and the expected data is very low.

As a final note on the reproducibility during IETeasy usage and on the stability of the whole hardware and its components, it must be pointed out that the two built instruments were massively used in preliminary analyses and in the campaign to obtain the data described in the Data in Brief article [21]. Hundreds measurements were carried out and resulted reproducible within time, without progressive drifts in the measurements and without changes in the experimental error, also comparing data by the two above-mentioned different instruments.

### 7.3. Multivariate analysis

PCA is a common method for pattern recognition analysis, which is often used to explore relationships between samples and variables. A detailed description of the method applied to xy data and the interpretation of its results is reported in a
performed on Group 2 and 3 are reported. Results of the analysis of Group 3 are very similar to the previous ones, with a
matically analyzed to identify sample not conform to a defined standard and/or outliers. In Fig. 6 the results of the analysis
approach can be without effort extended to the analysis of thousand of data and, in a quality control vision, the result auto-
ter have very little distances one from another, while they have greater distances between one group and another. This
are highlighted by the four blue squares along the diagonal of the matrix, which represent that the ten elements of each clus-
our groups of data with increasingly difficulty in sample recognition and classification:

- Group 1 – full mixture: AISI 304 steel, aluminum 6082, copper and Teflon. This group is the most heterogeneous and sim-
ples to analyze, as the analyzed materials are very different one from another, with large differences in both number of
peaks, intensities and peak broadening; the target is recognizing polymer from pure metals and alloys.
- Group 2 – Fe-based metals: AISI 304 steel, AISI 316 steel, C45E steel, Fe37 drawn, X150 steel. All these materials are iron-
based alloys and have very similar compositions, that vary only for the ligands; the target is to distinguish the different
steel grades.
- Group 3: nylon 6, high-density polyethylene (HDPE), pom-c and Teflon. All the analyzed materials are polymer-based.
Even if the molecular structures are very different one from another, three of these samples (HDPE, pom-c and Teflon)
have the fundamental resonant frequency in a range of 300Hz, with a noisy spectrum and broader peaks, if compared to
the other analyzed materials; the target is to distinguish the polymers.

Before proceeding with the analysis, the only pre-processing that was carried out on the data was a normalization to
reduce scale effects that could affect the analysis, as described on RootProf documentation [42]. As well, the range of fre-
cuencies that were analyzed spans from 0 Hz to 8000 Hz. No other pre-treatments were used in order to analyze the data
with a blind approach, without using prior knowledge on the systems. However, along with the interpretation of the results,
detailed suggestions on how to better analyze the results are given. The results of the analysis for the first group of samples
can be observed in Fig. 5. The scree plot (Fig. 5(a)) shows that the first three principal components, the ones that the software
considers reliable, explain the 62% of the total variance of the system. The explained variance in this situation can be
increased by reducing the range of analysis and the variables in which no signals are present. Three PCs were selected by
the algorithm also because the software automatically recognized four groups of samples very different one from the other.
In this situation, PCA positions the clusters on the vertices of an n-dimensional solid, for the representation of which n – 1
dimensions are required. Therefore, in this case, the four groups are on the vertices of a tetrahedron in a three dimensional
space. In Fig. 5(b) and (c) this is confirmed by the projections of the samples in the principal component space (Score plot):
PC1, PC2 and PC3 can be seen as the new x,y, and z axis, and the position of the samples are the projection of a tetrahedron
on the two PC1-PC2 and PC1-PC3 planes. The four clusters are highlighted by the four coloured circles on the score plot, which are
calculated by the software by using a hierarchical clusterization approach (Euclidean distances with group average
method). In Fig. 5(d) is reported a colour map that represents the distances between the samples. The four different clusters
are highlighted by the four blue squares along the diagonal of the matrix, which represent that the ten elements of each cluster
have very little distances one from another, while they have greater distances between one group and another. This
approach can be without effort extended to the analysis of thousand of data and, in a quality control vision, the result automatic-
ly analyzed to identify sample not conform to a defined standard and/or outliers. In Fig. 6 the results of the analysis
performed on Group 2 and 3 are reported. Results of the analysis of Group 3 are very similar to the previous ones, with a

| Sample          | Calculated Young's modulus | Tabulated Young's modulus |
|-----------------|----------------------------|---------------------------|
| AISI 304 steel  | 166 GPa                    | 193 GPa [26]              |
| AISI 316 steel  | 170 GPa                    | 193 GPa [26]              |
| Aluminum 6082   | 69 GPa                     | 67.0 GPa to 70.0 GPa [27,28]|
| B10 bronze      | 92.5 GPa                   | 90 GPa to 110 GPa [29]    |
| B12 bronze      | 93.9 GPa                   | 90 GPa to 110 GPa [30]    |
| BrAl alloy      | 119 Gpa                    | 125 Gpa [31]              |
| C45E steel      | 184 Gpa                    | 190 Gpa [32]              |
| Copper          | 132 Gpa                    | 118 Gpa to 132 Gpa [33]   |
| CW614           | 107 GPa                    | 105 Gpa [34]              |
| Fe37 drawn      | 201 Gpa                    | 200 Gpa [35]              |
| HDPE            | 2.16 GPa                   | 0.65 GPa to 4.30 GPa [36] |
| Nylon 6         | 4.08 Gpa                   | 1.30 Gpa to 4.20 Gpa [37] |
| Pom-C           | 4.29 Gpa                   | 0.59 Gpa to 11.7 Gpa [38] |
| Teflon          | 1.19 Gpa                   | 0.39 Gpa to 2.25 Gpa [39] |
| X150 steel      | 181 Gpa                    | 190 Gpa [40]              |
number of significant principal components which is equal to the number of samples minus one for a total explained variance of 54%. In the score plot of Fig. 6(a), samples 10–19 and samples 20–29 seem superimposed because of the projection of the data in a two-dimensional spaces, but by looking at Fig. 6(b), the two sample groups are well separated. The analysis on Group 3 samples, despite the noisy spectra recorded on the polymeric samples (showing broad peaks) gave satisfactory results, and the samples can be distinguished one from another, as shown in Fig. 6(d). The cumulative explained variance of the significant principal components is 48%. This value is rather smaller than previous three groups and is due to the noisy data. However, it must be noted that the raw data were analyzed and the explained variance (and thus the amount of extracted information, can be increased by pre-processing spectral data using pre-treatments and variable selection, commonly used in chemometrics.

• The IETeasy data collection is non-destructive, reproducible and accurate, making it suited for mechanical properties analysis. As shown at the beginning of this section, the coefficient of variation is very low (≈ 0.001% on metals and ≈ 1% on polymers), demonstrating that the approach is excellent for the measurement of the properties of the materials and their classification.

• The PCA-cluster analysis, used for the first time on IET data, demonstrated that the instrument is suitable for in situ and ex situ qualitative analyses. The instrument, combined with any software for multivariate analysis is capable to recognize and classify different kinds of materials, spanning from hard materials such as alloys to soft ones such as polymers. many other materials, also of biological origin can be analyzed with the same approach.
Ellipses in score plots of Figs. 5 and 6 can be used to identify anomalies, as samples falling inside the ellipses are identified as “conform” and samples not included are “doubt” or “defective”. This approach can be further investigated as a perspective of the present work, in the quality control philosophy of detecting problems (i.e. all samples not falling within the ellipses of Figs. 5 and 6) and thus reducing scraps.

Data collected by IETeasy can be used for classification purposes even with different methods, that can be based on Linear Discriminant Analysis which uses the single frequencies or exploiting a machine learning approach that takes as an input the whole sound profiles or the frequency spectra of the samples.

The power of multivariate approach of PCA applied to the whole spectra analysis, demonstrated in the present paper, can be winning when handling hundreds to thousands (or even more) data file, a typical situation in quality control procedures; moreover PCA allows obtaining more information with a reduced uncertainty with respect to traditional OVAT approaches, in a much shorter time, and eventually also in an automatic way; samples not conform to a defined standard can be easily (an also automatically) identified.

**Authors' contribution**

The instrument in Figure 1 was assembled by NM during his bachelor thesis under the guidance of ML. A second instrument was built by ML. Data collection was performed by NM and ML. Multivariate analysis was carried out by NM and ML. All the authors participated to data interpretation, edited the manuscript and approved its final version.
Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.ohx.2021.e00231.

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