Impulse excitation technique and its application for identification of material damping: an overview

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Abstract. The recent work presents an overview of the papers devoted to the application of Impulse Excitation Technique (IET) for the measurement of internal friction in different materials. IET is an advanced method to measure such materials’ characteristics as Dynamic Young’s and Share Moduli, Dynamic Poisson’s Ratio, Damping, to investigate the deformation behavior, softening phenomena and relaxation mechanisms and phase transformations in different materials. The experimental studies can be performed at both, room and high temperatures. Due to its simplicity, low cost, high accuracy and reproducibility it may take the leading position among the other non-destructive testing methods and techniques.

1. Introduction
Traditionally, in engineering literature many materials have been considering as purely elastic. Such an assumption was adopted in order to simplify engineering calculations. However, in the reality there are very few materials which possess a fully elastic behavior. The majority of them beside elastic component has a viscous one and therefore are called “viscoelastic” materials. In order to deeply understand the nature and the degree of viscoelasticity of a material, the phenomenon of damping, or internal friction is being studied. There are several ways in literature to give a definition to internal friction or damping. Blatner et al. [1] introduced the most general definition of it as a dissipation of energy in a material, which was different from the meaning of the traditional term of “friction” to represent the resistance against motion. Referring to cyclic loading of the material, authors define the specific damping capacity $\varphi = \Delta W/W$, or the loss factor $\Delta W/2\pi W$, and the quality factor $Q = 2\pi W/\Delta W$, where $W$ is the maximum elastic energy stored during one cycle, and $\Delta W$ is the corresponding energy absorption during that cycle. Postnikov [2] introduced the internal friction itself as $\varphi = \Delta W/2\pi W$. However, this is not the only definition of internal friction.

By considering a viscoelastic solid under a cyclic applied stress or strain, the sinusoidally varying stress $\sigma^*$ and strain $\varepsilon^*$, respectively, could be expressed as follows

$$\sigma^* = \sigma_0 e^{i\omega t},$$

and

$$\varepsilon^* = \varepsilon_0 e^{i(\omega t - \varphi)} = (\varepsilon^* - i\varepsilon^*)e^{i\omega t},$$

and the complex modulus $E^*(\omega)$ could be written as
where $\varphi$ is the phase lag between stress and strain, $\omega$ is the frequency of vibrations, $E'$ is the Storage Modulus, $E''$ is the Loss Modulus. In such a situation, the internal friction $Q^{-1}$ could be defined as [1-2]:

$$Q^{-1} = \frac{\Delta W}{2\pi W} = \tan \varphi = \frac{E''}{E'}.$$  

Moreover, Oeser [3] derived a similar formula when the shear stress or strain was applied, given as follows

$$G' = G' + iG''; \quad Q^{-1} = \frac{G''}{G'},$$  

2. Measurement of damping

There are several ways to measure internal friction in different materials. Pavlova et al. [4] measured the damping as a logarithmical decay of the vibrations of an inverted torsion pendulum

$$Q^{-1} = \left(\frac{1}{\pi n}\right) \ln A_i/A_{i+n},$$

where $A_i$ and $A_{i+n}$ are the amplitudes of the $i$th and $(i+n)$th vibrations, respectively.

Both Postnikov [2] and Meshkov [5] proposed a torsional pendulum to measure internal friction in metals (see figure 1). The device allowed one to measure the internal friction and shear modulus under free and forced vibrations of samples of circle and square cross-section with the area range from 0.4 to 4 mm$^2$ and length of 100 mm under the temperatures varying from 20 °C to 1000 °C. Amplitude of the relative deformation was varied from 2·10$^{-6}$ to 2·10$^{-4}$, frequency from 20 to 200 Hz. The device was consisted of an inverted pendulum, tubular electric furnace, thermoregulator, optical system and section for generating forced vibrations of the sample and for determining the resonance frequency.

As is shown in figure 1 [2], the section to generate the forced vibrations of the sample and to determine the resonance frequency includes the sound generator with the additional device 13 for the smooth frequency regulation and the micro ammeter for alternating current 14 with the high-resistant rheostat 15. When the harmonic voltage from the generator 16 is applied to the frame, it generates the forced torsional oscillations of the sample. The amplitude of the oscillations was measured on the scale 12. At the moment of resonance $Q^{-1} = \frac{I}{\varphi_0\omega^2}$, where $I$ is the current in the frame, $\omega_0$ is the resonance frequency, and $\varphi_0$ is the resonance amplitude of the sample end deformation [2].

In order to obtain damping, the shear modulus must be calculated first, using the natural frequency

$$\omega_1 = \sqrt{\frac{G(\omega_0)k}{I}},$$

where $k=\pi d^4/32L$ for a round straight rod with the diameter $d$ and length $L$, $I$ is the moment of inertia of the attached mass. The natural frequency can be determined from the period of free vibrations following a perturbation or by tuning the frequency in a driven (forced) system.

Lakes [6] considered that the damping value of $\tan \delta$ was small and was calculated from the full width $\Delta \omega$ of the resonance curve at the half-maximum amplitude: $\frac{\Delta \omega}{\omega_1} = \sqrt{3} \tan \delta$. For small $\delta$, $Q^{-1} \approx \tan \delta$. Considering a driven system, it was possible to make measurements away from the
resonant peak. In this case, for a lumped system of one degree of freedom, the phase angle between torque and angular displacement was given by: \( \tan \varphi = \frac{\tan \delta}{1 - (\omega / \omega_r)^2} \) [6].

Figure 1. Scheme of the apparatus for measuring G during free and forced vibrations: 1 - nylon thread, 2 – frame, 3 – rod, 4 – reducer, 5, 7 – split terminals, 6 – sample, 8 – magnet, 9 – weight, 10 – oven, 11 – thermoregulator, 12 – optical system, 13 – device for smooth frequency regulation, 14 – micro ammeter, 15 – rheostat, 16 – generator [2].

Lakes [6] reviewed different kinds of torsion pendulums, where the inverted pendulum, driven subresonant torsion pendulum and driven high-temperature subresonant torsion pendulum are presented.

Recently, some devices have been suggested, which are able to directly measure internal friction of different materials. Huang et al. [7] used DTM-II-J Dynamic Elastic Modulus Damping Internal Friction Analyzer produced by Hunan Zhenhua Analysis Instrument Co. Ltd., China. The device utilized the bending resonance method according to GB/T13665-2007 [8].

The principle of bending resonance method is shown in figure 2. The frequency is raised up until the strain amplitude reached half of the resonance value, which corresponded to frequency of \( \omega_2 \) and period of \( T_2 \). While the frequency was reduced until the strain amplitude reached half of the resonance value, this frequency was denoted as \( \omega_1 \), and period as \( T_1 \). Therefore, \( \Delta \omega \) is the difference value of \( \omega_2 - \omega_1 \), \( \Delta T \) was the difference value of \( T_2 - T_1 \), \( \omega_r \) was the resonance frequency and \( T_r \) was the resonance period [7]. Then the damping was calculated as

\[
Q^{-1} = \frac{\Delta \omega}{\sqrt{3} \omega_r} = \frac{\omega_r - \omega_1}{\sqrt{3} \omega_r},
\]

or,

\[
Q^{-1} = T_r \frac{\Delta T}{\sqrt{3} T_2 T_1} = T_r \frac{T_2 - T_1}{\sqrt{3} T_2 T_1}.
\]

An advanced method to measure not only material’s damping and the components of its Complex Moduli, but also to investigate its rheological properties is being widely used in modern science. The method is called Dynamic Mechanical Analysis. Liu and Oliphant [9] implemented the Dynamic Mechanical Analyzer (DMA 2980) produced by TA Instruments to measure the Storage Modulus of bovine gel, 10%-by-volume and 15%-by-volume. The same apparatus was used by Deng et al. [10] in order to measure temperature-dependent elastic moduli of two cured epoxy systems and two silica–epoxy nanocomposites. It was remarkable that DMA 2980 could directly measure the Storage
modulus, Loss modulus and Internal friction of the materials. However, the maximal size of the specimens for all DMA instruments is very limited.

Oeser [11] used the visco-analyzer to determine viscoelastic properties of bitumen, where the device could be operated in both of the shear and tension-compression modes. In the first case, a ring-shaped material sample was placed between a hollow cylinder and a solid steel piston. The cylinder remained stationary during the cyclic loading applied by the piston. The force applied to the piston was recorded by a load cell (see figure 3).

| Figure 2. Principle of bending resonance method [7]. | Figure 3. Visco-analyzer: shear mode [11]. |
|--------------------------------------------------------------------------------------------------------|

When the tension-compression mode was generated, the visco-analyzer required a cylindrical material probe to be placed between a stationary base and a solid steel piston. Similar to the shear mode, the cylindrical piston moved up and down harmonically and the force was measured and recorded [11]. When the time lag between force and displacement was measured, and the time lag \( \Delta t \) and the duration \( T_s \) were known, the phase lag \( \delta \) could be determined as \( \delta = \frac{\Delta t}{T_s} 2\pi \).

Eventually, the Storage Modulus \( E' \) and Loss modulus \( E'' \) were defined according to the following formulae:

\[
E' = \frac{\sigma_0}{\varepsilon_0} \cos \delta, \\
E'' = \frac{\sigma_0}{\varepsilon_0} \sin \delta, \tag{10}
\]

where \( \sigma_0 \) is the peak normal stress and \( \varepsilon_0 \) is the peak normal strain. Similarly, for the shear mode

\[
G' = \frac{\tau_0}{\gamma_0} \cos \delta, \\
G'' = \frac{\tau_0}{\gamma_0} \sin \delta, \tag{11}
\]

where \( \tau_0 \) and \( \gamma_0 \) are, respectively, the peak shear stress and strain.
Muller et al. [12] proposed a torsional apparatus which applied a small sinusoidal torque to a sample of cylindrical shape. The harmonic torque was generated by a pair of electro-magnets, which was connected to a synthesizer via a power amplifier. The angular deformation of the sample was measured. The capacitive signal had been detected and amplified. When the function $G'(\omega,T)$ is known, $G'$ and $G''$ could be obtained from $G' = G' + iG'' = \left| G' \right| \cos \phi + i \left| G'' \right| \sin \phi$ [12].

3. Impulse Excitation Technique (IET)

The Impulse Excitation Technique appears in literature in 1937 [13], when Forster developed the first modern IET to identify the stiffness of materials [14]. At that time some technological restrictions in determining resonant frequencies slowed down the technique development, however, later, further evolution of data acquisition systems and computational capacities of the computers allowed this technique to take place in modern industry and science. In 1988, Heritage et al. used IET for dynamic flexural measurements at the temperature range between 25 and 300°C [15]. At that time, very few results of high-temperature measurements are reported.

The method is based on the following. After a small impact is applied to a sample, it starts vibrating. The impact force applied to the specimen does not affect the measurements, however, it must be sufficient to start the vibration, but not too high to avoid the falling down of the sample from the supports. There are different ways to excite the sample manually or automatically. It is important to notice that the impact applied to the sample must be ballistic [16].

There are well defined modes for simple shapes of specimens, such as rectangular bars, cylindrical rods and discs. For each mode the location of the nodes is known. The supports must be placed in the nodes of the sample to avoid the influence of the supports on vibrations (see figure 4). The support location plays a key role in the damping test. If the supporting points are not coinciding with the nodes, the damping will be substantially increased. In such a situation, the damping is determined not by the material, but by the test set-up [17].

The signal could be detected by one of three transducers depending on the experimental circumstances: Piezo sensor (contact), Microphone (non-contact), and Laser vibrometer (non-contact).

For each vibration mode, there is a specific optimal location of the transducer. Mechanical vibration of the sample is detected by the transducer and after its converting, the electrical signal is sent to a computer. For each vibration signal, the RFDA software calculates the specified number of frequencies, which can be set up by the user, and the corresponding damping values [16].

In the first step, the time signal is subjected to pre-processing, in order to remove transition phenomena at the beginning and noise at the end of the signal. In this step the useful signal is extracted. A Fast Fourier Transformation (FFT) is applied to this signal to provide the starting condition for the extraction algorithm. The FFT defines dominating frequencies in a signal, which are shown by high peaks in the FFT-graph. The pre-determined number of highest frequency peaks is analyzed by software. Software calculates both the damping and frequency order for each single frequency. The frequency order is the rank of the frequency in amplitude of the FFT-peak (the first order of the frequency has the highest amplitude, etc.) [16]. By using the Impulse Excitation
Technique (IET), the damping is calculated as $Q^{-1} = \frac{k}{\pi \omega}$, where $k$ is the Loss factor, $\omega_0$ is the resonant frequency [15-16]. IET has several advantages, which is a nondestructive technique and can be applied at high temperatures and in aggressive atmospheres.

Traditionally Impulse Excitation Technique was used to test relatively small samples of ceramics, glasses, metals, etc. In 1997, Roebben et al. [16] presented an apparatus to measure dynamic elastic moduli and internal friction of different materials, so called Resonant Frequency and Damping Analyzer (RFDA). Produced by Integrated Materials Control Engineering (IMCE) the equipment measures materials’ damping by means of the impulse excitation technique. It was noted that the type of the support can substantially affect the measurements. The authors compared Pt-wire suspension with Polymer-foam support. It has been found that the first case shows much less values of $Q^{-1}$ rather than the second one. Later, this effect was partially investigated by Popov et al. [18], when the original nylon wire support was replaced by the one with steel wires, which was able to perform measurements with much heavier specimens. After multiple tests of a standard ceramic sample it was shown that both, nylon and steel wire support systems show now any significant difference in the results.

Filipak Vanin et al. [19] applied IET for investigation of dynamic moduli of cement pastes modified by cellulose nanocrystals. The samples were simply hooked on nylon bands at the nodal points corresponding to each vibrational mode so that the effect of simply supported samples has been achieved.

In 2000, Roeben et al. [20] performed IET tests with simultaneous determination of multiple resonant frequencies. Namely, the two furnaces of different characteristics were connected to RFDA to conduct the measurements in different materials at high temperatures. Later, in 2002-2003, the authors conducted certain studies on the application of IET at high temperatures [21-22].

Rojas et al. [23] studied glass fiber and epoxy resin composites evaluating its Dynamic Young’s Modulus and Loss Tangent by the Impulse Excitation Technique.

Voiconi et al. [24] studied elastic and damping properties of ductile aluminum foam (AlMg1Si0.6) using the Resonant Frequency and Damping Analyzer. It has been found that internal friction of the foam decreases with the increase of its relative density.

Sankawar et al. [25] have shown that by means of the IET it is possible to investigate the deformation behavior, softening phenomena, relaxation mechanisms and “in-situ” monitoring of the damage evolution in hard metals and composites. When performing the test under high temperatures, the technique allows one to study temperature dependencies of the parameters of measurements [26-29].

In 2016-2017, Impulse Excitation Technique has been applied for identification of the fractional parameter for concrete [30-31], which was considered to be a viscoelastic material and its properties were described by the fractional-derivative models. The order of the fractional derivative, or so called fractional parameter, is an important material characteristic, which is able to describe the microstructural changes in the material. Experimental device RFDA Basic allowed the authors to measure internal friction, as well as the components of the complex elastic modulus. Using the internal friction test data, the vector diagrams have been constructed. The fractional parameter has been found directly from the vector diagrams. According to the experimental results, within the concrete age interval between 3 and 182 days the average value of the fractional parameter has decreased by 276.33%, i.e. by more than two times. This phenomenon could be explained by the microstructural changes of concrete during its hardening: viscosity is substantially decreasing, while the elastic properties take on the dominating position. This method can be used for investigation of microstructural changes in different materials, such as polymer and rubber concretes, plastics, ceramics, etc.

4. Conclusions
In conclusion it should be noted that the Impulse Excitation Technique (IET) is an advanced method to measure such material characteristics as Dynamic Young’s and Shar Moduli, Dynamic Poisson’s Ratio, Damping, to investigate the deformation behavior, softening phenomena and relaxation
mechanisms and phase transformations in different materials. The experimental studies can be performed at both, room and high temperatures. Moreover, IET allows one to define the fractional parameter and to study microstructural changes of different materials. Due to its simplicity, low cost, high accuracy and reproducibility the Impulse Excitation technique may take the leading position among the other non-destructive testing methods and techniques.

References

[1] Blanter M, Golovin I, Neuhausser H and Sinning H-R 2007 Internal Friction in Metallic Materials vol 90 ed R Hull, J Parisi, R M Osgood and H Warlimont (Springer Berlin Heidelberg) p 539

[2] Postnikov V S 1974 Internal Friction in Metals (Moscow: Metallurgia) p 352 (In Russian)

[3] Oeser M 2011 Visco-Elastic Modeling of Virgin and Asphalt Binders Computer Methods for Geomechanics: Frontiers and Applications pp 313-9

[4] Pavlova T, Golovin I, Sinning H-R, Golovin S and Siemers C 2006 Intermetallics 14 1238–44

[5] Meshkov S I 1974 Viscoelastic Properties of Metals (Moscow: Metallurgia) p 193 (In Russian)

[6] Lakes R 2004 Rev. Sci. Instrum. 75 797–810

[7] Huang W, Zhan H, Xu L, Xu Z and Zeng J 2009 Acta Metallurgica Sinica (English Letters) 22 211–8

[8] GB/T 13665-2007 2007 Test Method for Damping Capacity of Metallic Damping Materials – Torsion Pendulum Method and Bending Vibration Method (Standardization Administration of China)

[9] Liu H and Oliphant T 2003 Proc. IEEE Symposium on Ultrasonics (Honolulu) vol 1(IEEE) pp 933–6

[10] Deng S, Hou M and Ye L 2007 Polym. Test. 26 pp 803-13

[11] Oeser M and Pellinien T 2012 Comput. Geotech. 42 pp 145-56

[12] Muller K, Bagdassarov N, James M, Schmeling H and Deubener J 2003 J. Non. Cryst. Solids 319 44–56

[13] Forster F 1937 Z Metallkd. 29 109–15 (in German)

[14] Brebels A and Bolen B 2015 The e-Journal of Nondestructive Testing 20

[15] Heritage K, Frisby C and Wolfenden A 1988 Rev. Sci. Instrum. 59 p 973

[16] Roebben G, Bollen B, Brebels A, Van Humbeeck J, and Van der Biest O 1997 Rev. Sci. Instrum. 68 p 4511

[17] RFDA Basic v.1.1 Manual, IMCE N.V.

[18] Popov I, Chang T P, Shitikova M and Rossikhin Yu 2016 Proc. 2016 Int. Con. Inf. Manag. Eng. Ind. Appl. (Phuket) vol 1 (DesTech Publications Inc.)

[19] Filipak Vanin D V, Andrade V D, Fiorentin T A, Souza Recouvreux D O, Carminatti C A and Al-Qureshi H A 2020 Mater. Chem. Phys. 239 1–6

[20] Roebben G, Basu B, Vleugels G, Van Humbeeck J and Van der Biest O 2000 J. Alloys Compounds 310 284–7

[21] Roebben G, Duan R G, Sciti D and Van der Biest O 2002 J. Eur. Ceram. Soc. 22 2501–9

[22] Roebben G, Basu B, Vleugels J and Van der Biest O 2003 J. Eur. Ceram. Soc. 23 481–9

[23] Rojas J A, Ribeiro B, Rezende M C 2020 Influence of serrated edge and rectangular strips of MWCNT buckypaper on the electromagnetic properties of glass fiber/epoxy resin composites Carbon 160 317–327

[24] Voiconi T, Marsavina L, Linul E and Kovacik J 2014 Proc. XIIIth Youth Symp. on Exp. Sol. Mech. (Decin) vol 1 pp 141-4

[25] Swarnakar A K, Giménez S, Salehi S, Vleugels J and Van der Biest O 2007 Key Eng. Mater. 333 235–8

[26] Swarnakar A K, Donzel L, Vleugels J and Van der Biest O 2009 J. Eur. Ceram. Soc. 29 2991–8

[27] Jung I and De Cooman B C 2012 Solid State Phenom. 184 209–14

[28] Gregorová E, Pabst W, Diblíková P and Nečina V 2018 Ceram. Int. 44 8363–73
[29] Gregorová E, Nečina V, Hříbalová S and Pabst W (In Press) J. Eur. Ceram. Soc. DOI: 10.1016/j.jeurceramsoc.2019.12.064.
[30] Popov I 2016 *Theoretical and Experimental Analyses of the Impact Response of Concrete Beams Considering Internal Friction PHD Thesis* (Taipei: National Taiwan University of Science and Technology)
[31] Popov I, Rossikhin Yu A and Shitikova M V 2020 Experimental Identification of the Fractional Parameter for a Viscoelastic Model of Concrete at Its Different Ages Based on the Impulse Excitation Technique *Advances in Rotor Dynamics, Control, and Structural Health Monitoring*, Dutta et al (Eds.), (Springer Nature)

**Acknowledgments**
This research has been supported by RFBR Grant #20-38-70143.