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Utilizing Hilbert–Huang transform in detection some of mechanical properties of the refractory metals

Arshed Abdulhamed Mohammed^{a,b,*}, Sallehuiddin Mohamed Haris^b, Mohd Zaki Nuawi^b^a Department of Mechanical Engineering, College of Engineering, Diyala University, Iraq^b Department of Mechanical and Materials Engineering, Faculty of Engineering and Built Environment, University Kebangsaan Malaysia, UKM, 43600 UKM Bangi, Selangor Darul Ehsan, Malaysia

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ABSTRACT

This study is one of the first to report on the use of Hilbert–Huang transform (HHT) to determine the modulus of elasticity of a material, which is one of the most important properties of metals. In addition, this study involves an analytical study of the process of transfer of energy, which was represented in the form of intrinsic mode functions (IMFs). Moreover, the distribution of IMFs within the time-frequency-plane was determined by testing eight test specimens. Five test specimens were refractory materials, namely, Ti, Ti6Al4V, Zr, Nb, and Ta, and the other three were non-refractory materials, namely, Al, Brass, and ST4340. The new setup was composed of Mg and involves the use of two piezoelectric transducers, which were used as the emitter and receiver. The setup was designed and implemented in this research based on Mg usage to test the metals. First, a new relationship was derived between the pressure transmission coefficient (PTC) of the transmitted wave (through the emitter–water–test specimen–Mg to the receiver) and the corresponding values of the product of the density (ρ) and the modulus of elasticity (E) for the same test specimen. Another relationship was established between the PTCs and the total energy transmitted at high frequencies. This energy indicates the summation of IMFs that have high frequencies (THIMFs), higher than 10 kHz, can determine E better than TOF for most test specimens. To verify this results, with regard to the second conclusion, a new simulation for this setup was carried out using Simulink in MATLAB. Twelve theoretical tests were done, for high acoustic impedance metals, like Hf, Mo, WNiFe and W in addition to test the same group which was tested experimentally. The results of theoretical tests supported the experimental results except for Nb. Most of the conclusions were obtained through practical results and analytical studies. The results proved that THIMFs can determine the change in the microstructure of the alloys when the ratio of their constituent elements was changed.

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1. Introduction

Over the past decade, the use of refractory metals and their alloys in many applications, such as in high-energy physics, civil engineering [1], and nuclear power industry [2], has been increasing. Special studies have focused on the properties of

* Corresponding author. Department of Mechanical Engineering, College of Engineering, Diyala University, Iraq. Tel.: +96 47819023530; fax: +60 389259659.

E-mail address: arshad_ald@yahoo.com (A.A. Mohammed).

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Table 1

The characteristics of some refractory metals and their alloys (Ti6Al4V, Ti, Zr, Nb, Ta) while Al, Brass and Steel4340 are non-refractory metals.

material	(ν)	C_L	ρ	Z	E_S	E_D	R_D (%)	$E_S \times \rho$
Name (TS)		(m/s)	(kg/m ³)	(Kg/m ² s)*10 ⁶	(Gpa)	(Gpa)		GPa × kg/m ³
Magnesium(Mg)	0.35	5740	1738	9.97612	45	35.679209	79.28713	78210
Aluminum (AL)	0.35	6350	2699	17.13865	70	67.809728	96.87104	188,930
Ti-6Al-4V	0.342	5800	4430	25.694	114	96.044703	84.24974	468,520
Titanium (Ti)	0.345	6100	4450	27.145	120	105.40528	87.837732	534,000
Zirconium (Zr)	0.38	4262	6506	27.728572	97	63.130552	65.083044	631,082
Niobium (Nb)	0.397	3480	8570	29.8236	104	49.531973	47.626897	891,280
Brass	0.34	4430	8520	37.7436	100	108.63203	91.367972	852,000
Steel 4340 (St)	0.28	5850	7800	45.63	206	208.80288	98.639379	1,606,800
Tantalum (Ta)	0.342	3400	16654	56.6236	185.7	124.07666	66.81565	3,092,648

these materials, such as [3–7]. Acoustic tests are usually employed to determine the mechanical properties of these metals. The use of acoustic testing to determine material properties has been rapidly developing, and these properties depend on the time of flight (TOF) of the wave [8] which depends on Eq. (1) in calculation the modulus of elasticity (E_{TOF})

$$E_{TOF} = \frac{C_L^2 \rho (1 + \nu)(1 - 2\nu)}{(1 - \nu)} \quad (1)$$

where ν , ρ and C_L are Poisson ratio, the density and the longitudinal velocity of the wave of the test specimen, respectively. However, the use of this testing method on refractory metals is difficult because the calculated properties are different from those obtained from loaded and un-loaded tests (tensile and acoustic tests), as shown in Table 1. Eq. (2) shows the percentage of convergence (R_D) between modulus of elasticity calculated from tensile tests (E_S) [static modulus of elasticity, according to Eurocode1 [9]] and the modulus of elasticity calculated from acoustic tests (E_{TOF}) [dynamic modulus of elasticity according to [9,10]]. Where the values of E_S measured according to ASTM standards (American society for testing and materials).

$$R_{D1} = 100 - \sqrt{\left(\frac{E_S - E_{TOF}}{E_S}\right)^2} \times 100 \quad (2)$$

The other property in Table 1, which is the acoustic impedance (Z), $Z = \rho \times C_L$. All these properties, in Table 1, were collected from authorized sources in materials and ultrasonic applications [11–14].

Arshed in his thesis [15] explained that there is main reason stands behind these difference in the results. This reason connects between the origin of Eq. (1), which is the development equation of motion of wave in isotropic media (Navier governing equation) as shown in Eq. (3) [16], and some of refractory metals properties

$$(\psi + \mu)u_{j,j} + \mu u_{j,j} + \rho f_i = \rho \ddot{u}_i \quad (i, j = 1, 2, 3) \text{ (Navier governing equation)} \quad (3)$$

where ψ and μ are Lamé constants and u is the displacement of particles. Eq. (1) was derived base on neglected the term of ρf_i which represents the body force [17], where the body force is forces that acts throughout the volume of a body which are gravity, magnetic and electrostatic attraction [18]. In fact body forces can be neglected for normal materials (non-refractory metals) [17] such as Al, steel and brass etc, therefore it can be seen the acceptable correspond between E_S and E_{TOF} for these metals in Table 1. While this simplification is un-acceptable for the materials have electrostatic force like Ti, Zr, Nb, and Ta. The electrostatic force (ESF) can be determined from the electric potential energy, this energy associated with the configuration of a particular inside the metal and this energy depend on two things first, the amount of electric charge (Q) that this particle has and its relative position to other electrically charged objects (electric field (EF)), therefore $ESF = Q \times EF$ [19,20] pointed out the intensity and values of the electrostatic of Zr-Silicate for different amounts of this material. Also [21] referred to the electrostatic properties of Ta₂O₅, TiO₂, ZrO₂. As well [22,23] proved this properties for Ti, likewise [24] for Nb. In addition, it is well known that the piezoelectric materials are materials which have ability to convert the mechanical energy to electric energy and that means the particles of piezoelectric elements have an electrostatic force [25,26], and it is well known that Ti and Zr are the essential elements in PZT (lead zirconium titanate with the chemical formula $Pb[Zr_xTi_{1-x}]O_3$ $0 \leq x \leq 1$), which is regarded one of the most famous materials in producing piezoelectric elements. Ta is also regarded one of the elements entering in manufacturing piezoelectric elements [27,28]. Therefore the results of E_S and E_{TOF} are not identical for Ti, Zr, Nb, and Ta as shown in Table 1.

The use of energy in calculating for the mechanical properties of materials is rather new [29]. A study [30] used the Cambridge serial total energy package for geometry optimizations and elastic constants calculations. The present research offers new insights into the correlation between the pressure transmission coefficient (PTC) of signal and the total energy calculated using the Hilbert–Huang transform (HHT). This energy was calculated by obtaining the summation of intrinsic mode functions (IMF) of the transmitted wave between the test specimen of various metals, especially refractory metals and magnesium, which are usually used as the control metal in all tests. In addition, this research presents an analytical study of the amount of energy transmitted from water-test specimen-Mg and its distribution within their frequency levels by using HHT. The main reason why HHT was performed in this study are as follows: (a) it is an advanced signal analysis method

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