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Ghost internal friction peaks, ghost asymmetrical peak broadening and narrowing: Misunderstandings, consequences and solution

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ABSTRACT

The effect of the 'Zero-Point Drift' (ZPD) on computed values of the logarithmic decrement from decaying harmonic oscillations is reported. It is shown that the ZPD modifies the shape of exponentially damped harmonic oscillations and leads to false values of the logarithmic decrement if computed according to the classical algorithms. This procedure can readily create ghost internal friction peaks, ghost asymmetrical peak broadening and/or narrowing. This means, that the shape, the height, and the symmetry of internal friction peaks are strongly affected by the ZPD. A solution of the problem of computing the logarithmic decrement in the presence of different ZPD is provided. It is demonstrated that the 'Optimization in Multiple Intervals' algorithm is the proper way to compute the logarithmic decrement for all damping levels in the presence of various types of Zero-Point Drift.

1. Introduction

All available classical algorithms to compute the logarithmic decrement, δ, refer by definition to free decaying exponentially damped harmonic oscillations recorded, e.g. in a resonant mechanical spectrometer. The available algorithms used to date to compute δ, *a priori* assume that the decaying harmonic oscillations are symmetrical [1–5]. This widely accepted assumption is not usually fulfilled in experimental practice. In fact, this assumption is not true particularly with deformed metals and alloys, with fatigued or irradiated materials as well as with materials undergoing phase transitions during measurements as a function of temperature and/or time, etc.

It must be admitted that for many years experimentalists working in the field of low-frequency internal friction were aware that a sample is susceptible of deployment of its center of oscillations ('self-micro-twisting'). This effect is illustrated in Figs. 1–4 and is defined as the 'Zero-Point Drift' (ZPD) [6,7]. For many different technical reasons the ZPD was not taken into consideration. This effect was generally taken as a mere inconvenience in experimentation, that is, an undesirable but inevitable experimental complication during the measurements of the logarithmic decrement. In many cases the ZPD effect was simply overlooked. Recently, the first quantitative approach to tackle the effect of the ZPD in the computations of the logarithmic decrement was reported [6]. It was demonstrated that the presence of the ZPD leads to false values of the logarithmic decrement, however, no solution was provided.

Since the influence of the ZPD on computed values of δ is surprisingly strong [6] ghost internal friction peaks may occur and false shape of internal friction peaks may be obtained. The purpose of this paper is to provide a quantitative approach to the ZPD. It will be concluded that false values of the logarithmic decrement and ghost internal friction peaks result from use of the classical algorithms to compute δ and will be clearly demonstrated that the 'Optimization in Multiple Intervals' (OMIs) algorithm [3] can be used to solve the problems caused by the Zero-Point Drift.

2. Experimental

It was originally suggested that the ZPD (Fig. 1, left column) should be detected at first and then corrected (see Fig. 3 in [6]). Both, detection and correction of the ZPD is a difficult task. Indeed, it turns out that several carefully designed and tested algorithms cannot be used for different experimental conditions and acquisition parameters. In addition, low-pass filters cannot remove the ZPD from decaying harmonic oscillations in the low- and the medium-ranges of resonant frequencies.

2.1. Computation of the logarithmic decrement

The logarithmic decrement δ can be computed according to several classical methods [1–5], where an implicit value of the *i*th

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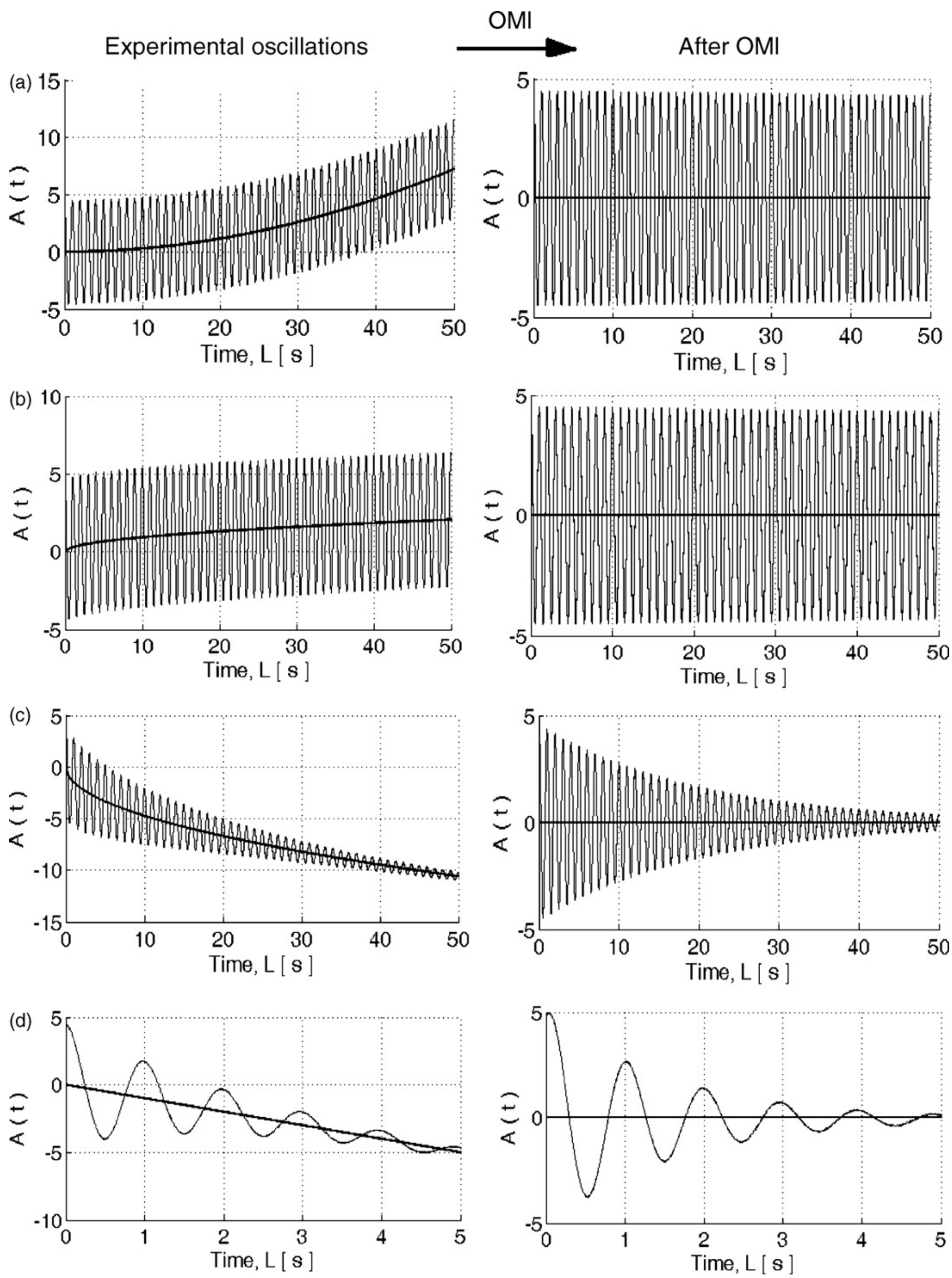

Fig. 1. Experimental free decaying oscillations biased by the ZPD (left column pictures) and oscillations calculated by the OMI algorithm (right column pictures). The center of oscillations is shown by a solid line. Positive ZPD (a and b). Negative ZPD (c and d). (a) $\delta = 0.001$, (b) $\delta = 0.001$, (c) $\delta = 0.05$ and (d) $\delta = 0.5$.

amplitude A_i or the ith area S_i under a half cycle of the oscillation must be measured. The logarithmic decrement can be computed from:

(1) the number of oscillations (NO) to decay from a given amplitude A_1 to a given amplitude A_2 (or the number of decaying oscillations in *a priori* defined span of time);
(2) the height of n successively decaying amplitudes A_i (RA) or areas S_i (RS) under a half cycle of the oscillations;
(3) the algorithm 'Optimization in Multiple Intervals' [3–5].

The measurement of NO, RA and RS can be made considering the positive or the negative part of the envelope. The RA and RS values can include only the positive values ($RA^{[+]}$, $RS^{[+]}$), only the negative values ($RA^{[-]}$, $RS^{[-]}$) or the absolute values of both positive and negative amplitudes ($RA^{[+,-]}$) or areas ($RS^{[+,-]}$) [2].

Another classical algorithm named the averaged logarithmic decrement of amplitudes (AvA) or areas (AvS) [2,3] is neglected in this work because it was already shown that the OMI algorithm always yields better results as compared to the AvA and the AvS [3–5].

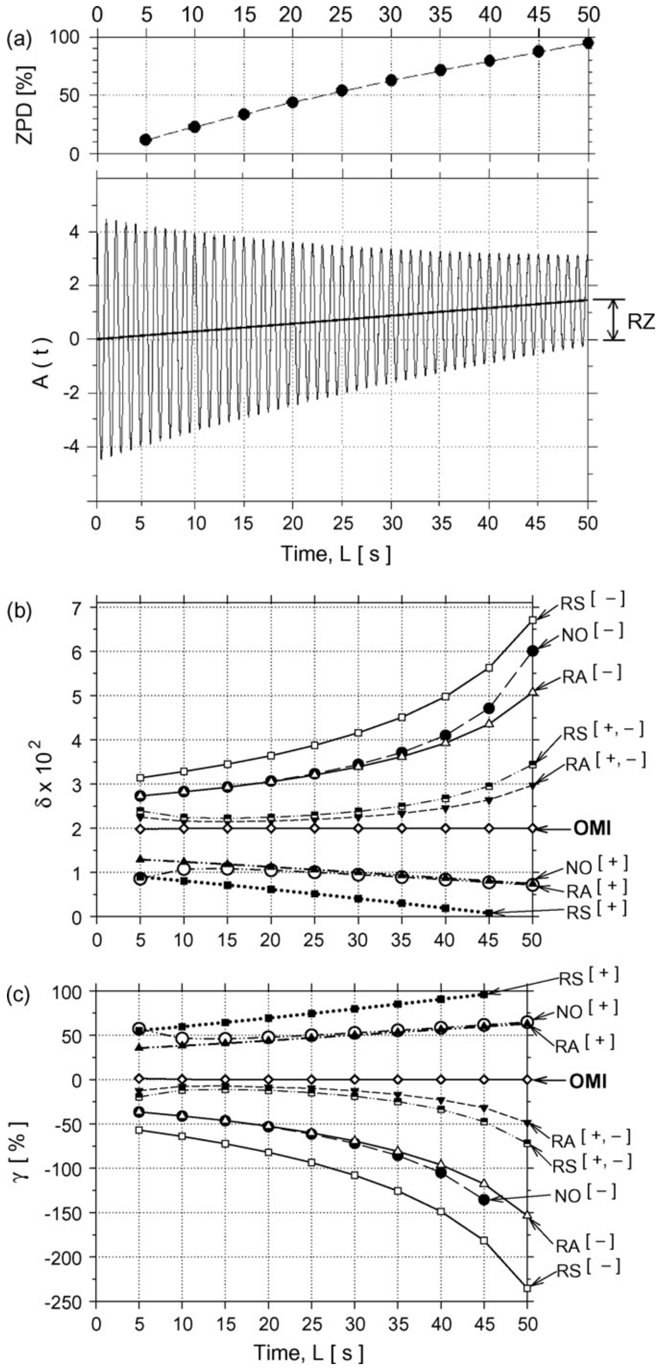

Fig. 2. Comparison between the logarithmic decrement δ, computed according to the OMI algorithm and the classical algorithms in the presence of linear positive ZPD. (a) Exponentially decaying harmonic oscillations ($\delta = 0.02$) biased by positive linear ZPD (resonant frequency $f_o = 1$ Hz, sampling frequency $f_s = 3$ kHz, S/N = 38 dB). (b) Logarithmic decrement δ, and (c) relative error γ, computed according to the OMI and classical algorithms for different length of time L: OMI (—◇—); NO$^{[+]}$ (-··-○-··-), NO$^{[-]}$ (— —●— -): number of oscillations from positive or negative envelope; RA$^{[+]}$ (-·-▲-·-), RS$^{[+]}$ (■■■): regression of positive amplitudes or surfaces; RA$^{[-]}$ (—△—), RS$^{[-]}$ (—□—): regression of negative amplitudes or surfaces; RA$^{[+,-]}$ (— —▼— —), RS$^{[+,-]}$ (-··-■-··-): absolute values of both positive and negative amplitudes or areas.

Finally, it is to be mentioned that the Fourier and Hilbert transforms [2,9] can also be used to compute the logarithmic decrement [2]. These algorithms are neglected in this work because it has already been demonstrated that the properly optimized classical and OMI algorithms yield better results as compared to the algorithms based on integral transforms (this result is clearly visible for low damping levels).

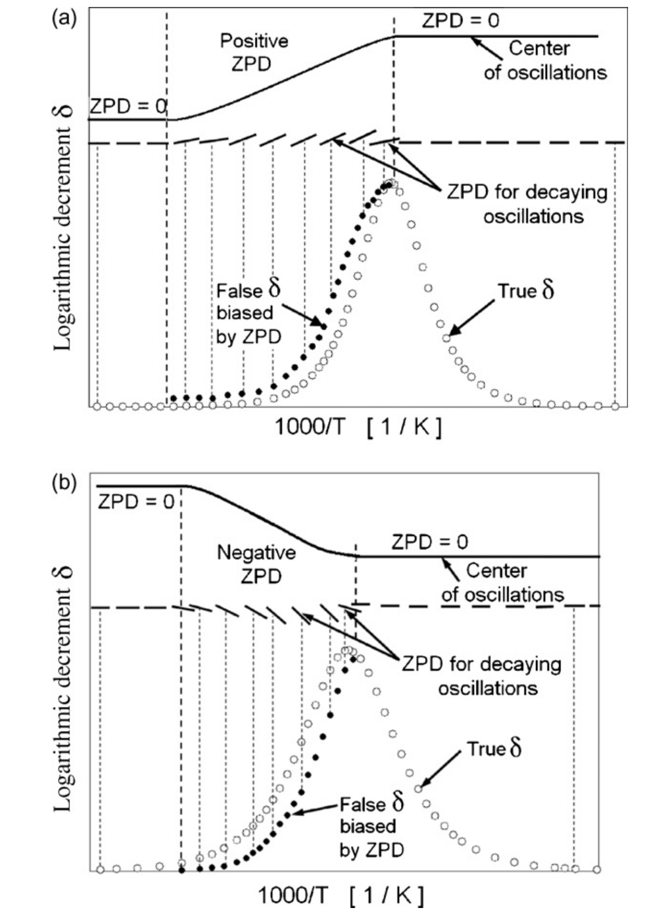

Fig. 3. Schematic illustrating how false values of the logarithmic decrement computed from the classical algorithms affect the shape of internal friction peaks. (a) Asymmetrical peak broadening resulting from positive ZPD and the RA algorithm. (b) Asymmetrical peak narrowing resulting from negative ZPD and the RA algorithm.

2.2. The Zero-Point Drift

The 'relative zero' (RZ) (Fig. 2a) of damped harmonic oscillations remains constant during the free decay of symmetrical oscillations. Any variation of the RZ value during free decaying oscillations is equivalent to the ZPD (see Fig. 1 (solid lines in the left column) and

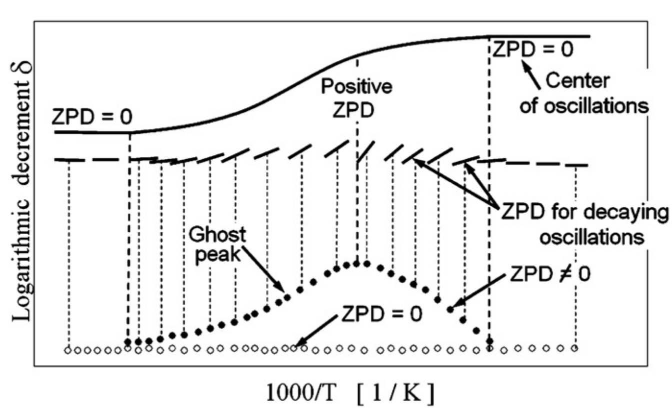

Fig. 4. A ghost internal friction peak (black points) induced by the presence of the ZPD and the use of the classical algorithms. True values of the flat background damping (open points).

Fig. 2a). The variation of the ZPD shown in Fig. 2a is given by

$$\mathrm{ZPD}\,(\%) = \frac{(A(Ideal)_L - A(ZPD)_L)}{A(Ideal)_L} \times 100,$$

where $A(Ideal)_L$ denotes the amplitude of exponentially damped harmonic oscillations at time L (here ZPD = 0 for symmetrical oscillations) and $A(ZPD)_L$ is the amplitude of the same signal biased by ZPD (see the upper part of Fig. 2a) at the same time L. It is easy to show that the ZPD (and the RZ) evolves as a function of L during free decaying oscillations biased by the ZPD (Figs. 1 and 2a).

3. Experimental results

Fig. 1 illustrates that the OMI algorithm can be successfully used to eliminate the effect of various ZPD (linear, parabolic, and 3rd order) which strongly modify decaying oscillations (left column pictures). It should also be noted that the ZPD can be positive 'anticlockwise self-micro-twisting' (Fig. 1a and b), negative 'clockwise self-micro-twisting' (Fig. 1c and d), or it can change sign during the experimentation time. It must be emphasized that the OMI algorithm returns purely decaying harmonic oscillations (right column pictures in Fig. 1), which are now suitable for the computation of the logarithmic decrement δ.

Fig. 2a shows typical decaying oscillations ($\delta = 0.02$) biased by the linear ZPD. This figure does not show the noise acquired by the A/D data acquisition board. The effect of a signal-to-noise ratio, S/N = 38 dB, is taken into consideration in the computation of the logarithmic decrement according to all the tested algorithms. In all investigated cases each extra quantization bit reduces the level of the quantization noise by roughly 6 dB [3]. The excellent efficiency of the OMI algorithm remains the same with small variation in the relative error, γ, for different S/N ratios (from S/N = 30 to 50 dB).

The values of the logarithmic decrement computed from the oscillations shown in Fig. 2a according to the OMI algorithm and the classical algorithms ($RA^{[+]}$, $RA^{[-]}$, $RA^{[+,-]}$, $NO^{[+]}$, $NO^{[-]}$, $RS^{[+]}$, $RS^{[-]}$, $RS^{[+,-]}$) are shown in Fig. 2b as a function of the acquisition time L. The variation of the estimated relative error is shown in Fig. 2c. As shown in Fig. 2b the computed values of the logarithmic decrement can be too high or too low as compared to the true one, $\delta = 0.02$. In fact, only the OMI yields time independent values of δ (horizontal line in Fig. 2b) with negligibly low relative error γ [3–5]. Whether the false values are too high or too low depends on the algorithm used for the computation and on the sign of the ZPD. The level of false values of δ depends on the length of the acquired signal L (see Fig. 2b). Similar conclusions are obtained for very low ($\delta = 0.00005$) and very high damping levels ($\delta = 0.5$). In all the investigated cases the OMI returns symmetrical exponentially decaying harmonic oscillations and yields the best estimate of the logarithmic decrement δ.

In general, the RS algorithm yields better results as compared to the RA algorithm [2–5]. This conclusion is true under the condition that the ZPD does not occur. In experimental practice, however, whenever the ZPD occurs the use of the RS algorithm automatically leads to higher false values of the logarithmic decrement δ as compared to the RA algorithm (see Fig. 2b and c).

3.1. Ghost asymmetrical peak broadening and narrowing

Detrimental effect of the ZPD on the shape of an internal friction peak is illustrated in Fig. 3. Fig. 3a shows false asymmetrical peak broadening (black points) created by the use of the classical algorithms to compute δ in the presence of the positive 'anticlockwise self-micro-twisting' ZPD. In contrast, Fig. 3b illustrates false asymmetrical peak narrowing caused by the negative 'clockwise self-micro-twisting' ZPD. False values of internal friction are always observed whenever decaying oscillations are affected by the ZPD and the classical algorithms are used to compute the logarithmic decrement δ.

The evolution of the ZPD during the entire mechanical loss experiments is illustrated in the upper parts of Fig. 3. Middle parts of Fig. 3 demonstrate the evolution of the ZPD [6] during acquisition of the signal to compute a single value of the logarithmic decrement. Lower parts of Fig. 3 show false (black points) and true (white points) values of δ resulting from the presence of the ZPD. It is concluded that a false peak shape always coincides with the occurrence of the ZPD. For this reason, the peak shape may be affected on the left, on the right or on both sides of an internal friction peak.

3.2. Ghost internal friction peaks

The point we would like to emphasize is that the use of the classical algorithms to compute the logarithmic decrement in the presence of the ZPD generates a purely artificial peak named a 'ghost internal friction peak'. Indeed, such ghost peaks can be 'experimentally observed' although the true values of the logarithmic decrement represent a flat background. This situation is shown in Fig. 4. The shape of a ghost peak is determined by the evolution of the ZPD during mechanical loss measurements. Fig. 4 reflects true experimental situations that are observed, e.g. in the temperature range from 200 to 300 K after: (1) low-temperature in situ deformation of metallic samples in a torsion pendulum and (2) after low-temperature electron and neutron irradiation of metallic samples. A number of other experimental artifacts induced by the presence of the ZPD will be reported elsewhere. A critical assessment of old experimental data is desirable especially with respect to the Hasiguti peaks, Bordoni peaks observed in freshly deformed samples and phase transformation peaks.

4. Discussion and conclusions

The presence of the ZPD is ubiquitous and well known, but the effect of the ZPD on the computation of the logarithmic decrement δ was not considered and not reported in the literature until 2006 [6]. Experimentalists were rather accustomed to deploy a detector of oscillations to follow oscillations of the self-micro-twisting samples. But it is clear that the continuous deployment of the center of free decaying oscillations was always neglected. This paper shows that the ZPD modifies the shape of exponentially damped harmonic oscillations and leads to false values of the logarithmic decrement computed according to the classical algorithms. Negligence of the fact that damped harmonic oscillations biased by the ZPD are not suitable for classical computations of the logarithmic decrement generated a number of false experimental data reported in the literature and yield unreliable theoretical explanations of mechanical loss spectra. In our opinion, many experimental data published in the literature suffer from the ZPD effect. To the best of our knowledge, the ZPD was carefully considered only in studies of the Snoek–Köster (SK) relaxation in Fe–C alloys [8–10]. Although this approach to the ZPD effect was qualitative [8] it has lead to an important conclusion that the 'reliable' SK peak – the so-called stable SK peak – can only be used for further calculations of the relaxation parameters if the ZPD is absent during the entire process of the measurement of the SK peak as a function of temperature. At that time, it was only anticipated [8–10] that the ZPD might have led to wrong values of the logarithmic decrement.

It is worthwhile to reiterate that the presence of the ZPD observed during mechanical loss measurements and the use of the classical algorithms to compute the logarithmic decrement inevitably leads to false values of the logarithmic decrement. Consequently, ghost internal friction peaks and false shapes of internal friction peaks (asymmetrical peak broadening and peak narrowing, peak height modification, artificial sub-peaks) can be observed. The OMI algorithm is the unique algorithm to compute the logarithmic decrement in the presence of the ZPD for low-, medium- and high-damping levels.

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