ANALYSIS OF THE NONLINEAR REVERBERATION OF TITANIUM ALLOYS FATIGUED AT HIGH AMPLITUDE ULTRASONIC VIBRATION

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ABSTRACT. The strong amplitude dependence of material parameters of micro-inhomogeneous materials can be used to link observations of nonlinearity to micro-scale damage. We have measured the amplitude dependence of the resonance frequency and damping characteristics in the reverberation field of the fundamental eigenmode of titanium alloy samples at regular instances during dynamic fatigue loading at high strains. The analysis of the reverberation is performed in the frequency domain using classical time-windowed FFT, as well as in the time domain using analytical functions with iteratively optimised parameters over each time window. The results show a significant increase of the nonlinearity in the frequency and damping characteristics of the signals observed during the fatiguing process.

INTRODUCTION

By applying cyclic loads with amplitudes much smaller than the yield strength, microcrack nucleation may occur at microscopic imperfections within a material (at locations of brittle particles, inferior bonds or grain boundaries, etc). After nucleation, the small-scale microcracks grow into the matrix, reducing the material’s resistance, and finally coalesce with other microcracks to form a macrocrack which subsequently result in the failure of the material. Fatigue processes of this kind, in various materials, have been studied by several conventional techniques, including acoustic emission and ultrasonic measurements. Lately, the use of non-linear ultrasonic measurements has gained quite some interest since it has been proven that even very small imperfections can produce a significant increase in nonlinearity. In general, the excess nonlinearity mainly results from a strong local nonlinearity called crack-closure, i.e. an asymmetry in the local stiffness upon opening and closing cracks or moving and restoring dislocations, which causes a modulation of the quasi-linear material properties. The effects of enhanced nonlinearity may be observed in the acousto-elastic effect [1-4], in the creation of harmonic frequency components [5-10], in the intermodulation of low and high frequency components [11-13], in the reduction of the resonance frequency as function of the excitation amplitude [14-16] and in the nonlinear contribution to the damping characteristic of the material due to the excess energy loss per cycle [16-17].

One of the most striking reports, by Nagy and Adler [2,3], illustrates observations of fatigue-induced nonlinearity using a dynamic and constant strain rate controlled measurement of the acousto-elastic effect. In their experiments, the change in ultrasonic velocity in a cantilever beam specimen is analysed as function of the applied external deformation which is produced by cyclic bending the cantilever beam at typically 0.1 Hz. The frequency of the ultrasonic probe signal, used for through transmission measurements of the velocity at the location of maximum stress, is between 5 and 15 MHz. The report clearly shows that the second-order acousto-elastic parameter, expressing the quadratic dependence of the ultrasonic velocity on the instantaneous strain, is far more sensitive to early fatigue processes than all of the linear ultrasonic and mechanical material properties (linear velocity, attenuation and static modulus). Experiments were performed on plastics, metals (alloys), adhesive metals and metal matrix composites.

In this paper we describe the results of an investigation using a resonance technique to monitor the fatigue process in titanium alloys. The procedure is based on the analysis of the reverberation signal as function of the instantaneous amplitude response. First we explain the experimental method and set-up, including the choice of the sample geometry. In the discussion of the results, we confirm the expectations reported by Nagy and Adler: nonlinearity parameters are indeed far more sensitive to linear parameters.

EXPERIMENTAL METHOD AND ARRANGEMENT

In the present study, we limit our investigation to monitoring the fatigue of titanium alloys (Ti 6Al 4V, a material which is commonly used in the construction of high-power transducers). Both the fatiguing and the non-destructive monitoring of the relevant material parameters were performed in a resonant mode.

The experimental set-up used for fatiguing the samples and measuring the linear and nonlinear characteristics is shown in Figure 1. It consists of a high performance driving apparatus to excite the samples at resonance and a sensitive data acquisition system. A detailed description of this set-up can be found in [17]. The generator is equipped with a feedback system that automatically adjusts the excitation frequency to the sample’s resonant frequency. The sample is attached to the tapered end of the stepped horn which is connected to the piezoceramic sandwich.

In order to achieve high strains, the samples are designed as prismatic bars with stepped profiles [17-18] and slightly rounded transitions (see Figure 1). Their size is adjusted to match their first flexural resonance mode with the transducer’s resonance frequency as closely as possible (typical size is 4 by 1 cm with stepped height of 0.25 cm, 1 cm, 0.25 cm). The theoretical strain profile of such samples in the first flexural resonance mode is shown in Figure 2 [17]. Typical resonant modes for different samples range from 21 to 23 kHz. The Modal Damping Ratio ($\xi = 1/(2Q)$, with Q the quality factor) is approximately 0.0005 for intact samples. Steady state resonances are usually attained after 3Q cycles, i.e. after 3000 cycles.

The data acquisition system consists of a He-Ne laser vibrometer providing non-intrusive measurements of the out-of-plane particle velocity in the range of 10 microns/s up to 10 m/s for frequencies of up to 1.5 Mhz. The vibrometer picks up the signal at one of the thin edges (position of highest velocity) and is connected to an oscilloscope and a computer to store and analyse the signals.

As mentioned before, the same experimental set-up is used to induce fatigue in the samples and to monitor the linear and nonlinear characteristics.

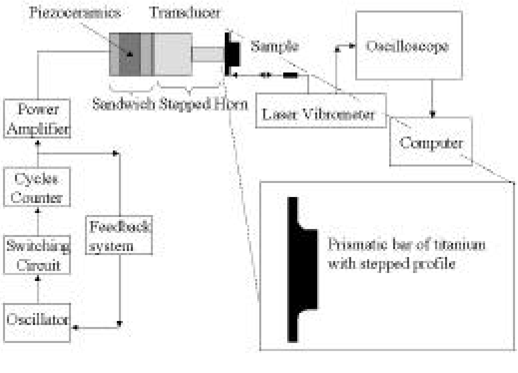

Figure 1: Experimental set-up for fatiguing the samples in the first flexural mode. The same driver is used in combination with a data acquisition system to measure the linear and nonlinear characteristics. Insert: geometry of the samples.

Fatiguing The Sample

In order to fatigue the samples, bursts of 0.2s with an off-interval of 3s were used. The operation frequency is continuously adjusted by the feedback loop system of the generator, taking into account the geometrical specifications of the sample and the excitation level. The latter is very important since the resonance frequency may depend on the applied excitation, especially when microstructural damage has occurred. To induce fatigue, the samples were driven at a voltage of 40-60V, corresponding to a peak stress value of about 300 MPa (3.25 nanostrain). It is important to note that this value is considerably smaller than the yield stress which can be deduced from static fracture analysis. The samples were subjected to resonances at these amplitudes for up to five million cycles (approximately 1250 bursts). The burst length and the off-time in between bursts was chosen so that sample heating was minimized [17].

Probing The Linear And Nonlinear Characteristics

The technique used in this study to monitor the linear and nonlinear characteristics of the sample is an extension of the simple ring-down measurement for a resonant mode. First, we subject the sample to a sinusoidal excitation at its resonance frequency using the same excitation apparatus as in the case of the fatigue loading. However, the voltage is reduced to 10V, corresponding to a peak stress of about 90 MPa. The feedback loop accounts for the adjustment of the driving frequency at this excitation level. The electrical signal is a burst of 0.2s. The velocity response of the sample is captured by the data acquisition system and the decreasing sinusoidal signal at the turn-off of the excitation burst is analysed. For a material with linear characteristics, the characteristic decay of the amplitude with time is a measure of the MDR ξ, and the dominant frequency in the decaying signal corresponds exactly to the resonance frequency of the sample *f*. Indeed, if the damping of the structure is of a linear viscous type, the captured signal has the form of an exponentially decaying sine function:

$$s(t)=V_0 e^{-\xi \omega t}\sin(\omega t-\varphi) \tag{1}$$

where V_0 is the initial (steady state) amplitude, φ the phase, ω the angular frequency containing the response frequency *f* ($2\pi f = \omega$), and ξ the MDR.

In materials which exhibit nonlinear behaviour, the resonant frequency and damping characteristics depend on the internal strain amplitudes [14-16]. Using a time-windowed analysis it is possible to quantify the effect of the nonlinearity on both resonance frequency and modal damping ratio as a function of the instantaneous amplitude in the reverberation signal. This can be done in the frequency domain using a discrete Fourier analysis (DFT) on the time-windowed (and zero-padded) signal, or in the time domain by using the Resonant Frequency and Damping Analyzer (RFDA). As described in Ref.[19], the RFDA performs an iterative algorithm of curve fitting the measured signal in the time domain to Eq.(1), and identifies the 4 parameters in Eq.(1) for each time window. Next, we express the resonance frequency *f* and the MDR ξ as function of the mean velocity amplitude in the time window:

$$f(\mathrm{V}) = f_0\,(1-\alpha_1 V+\ldots) \tag{2}$$

$$\xi(\mathrm{V}) = \xi_0\,(1+\alpha_2 V+\ldots) \tag{3}$$

from which we can obtain the linear as well as the nonlinear sample characteristics, i.e., the low amplitude (linear) resonance frequency and MDR f_0 and ξ_0, and the first order relative changes in the linear parameters represented by α_1 and α_2.

Since we only intend to demonstrate the power of nonlinear techniques as a sensitive tool for non-destructive evaluation in the early stage development of microdamage, we do not care too much about the true definition of the nonlinearity parameters. Following prior investigations [13,14,20,21], we may refer to studies of the effect of mesoscale hysteretic stress-strain relations on the macroscopic nonlinear behaviour of a material. These studies indeed show in a first approximation that nonlinear hysteretic state relations result in a linear reduction of the resonant frequency with strain amplitude and that the attenuation increases with a “nonlinear” contribution (proportional to the amplitude) due to hysteretic damping. These first order approximations are reflected in the expressions (2) and (3). However, other effects may

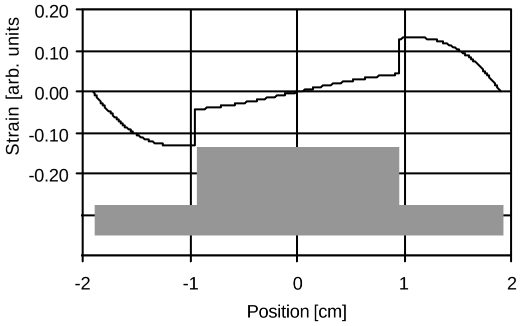

Figure 2: Strain profile of prismatic bars with stepped profiles.

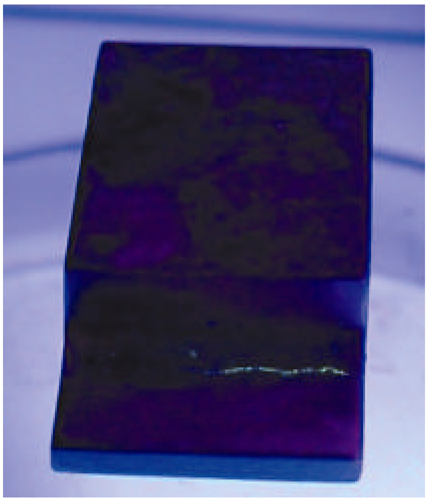

Figure 3: Visualisation of a macrocrack developed at failure in a prismatic titanium bar with stepped profiles.

complicate the interpretation. When a structure is forced to vibrate for a certain period at a given amplitude, the microstructure of the medium can be affected by long term relaxation phenomena, which may influence the behaviour at lower amplitudes (so called slow dynamics) [22,23]. This certainly complicates the interpretation of the time-windowed analysis of the measurements. Nevertheless, for the purpose of this study, it is not necessary to go into further details.

Thus, the complete measurement procedure is as follows: To fatigue the sample, the test structure is excited at high excitation amplitude for a sequence of short bursts (typically 50 bursts of 0.2s) by means of the special generator-transducer combination. After such a sequence, a reverberation measurement at low excitation level (again using a burst of 0.2s) is performed and the response, picked up by the laser vibrometer, is stored and analysed for several time windows both in frequency and in time domain. This allows to extract the linear and nonlinear parameters of interest according to Eq.(2) and (3). Subsequently, the sample is subjected to a new sequence of fatiguing cycles, which is then again followed by a low excitation reverberation measurement and analysis. The sequence of fatigue cycles is repeated till complete failure, i.e., the development of a macrocrack at the sharp transition between the thin and thick part of the sample (see Figure 3).

RESULTS

After each sequence of fatigue, we extracted the values for the linear resonance frequency f_0, the linear MDR x_0, and the nonlinear parameters α_1 and α_2 representing the first order dependence of frequency and damping on amplitude. Doing so, we are able to monitor the changes of each of these parameters during the fatigue process. When significant changes were noted, the length of the fatigue sequence was shortened in order to follow the process in more detail. In Figure 4, we have visualized the overall behaviour of the nonlinear parameter α_1 (deduced from the amplitude dependence of the frequency in the reverberation signal, Eq.(2)) and the linear parameters. All measured parameters are normalised to their initial values to display relative changes only. It is clear that the changes in nonlinearity are far more significant than the changes in the linear properties. For better visibility, the relative small changes of the linear parameters are shown in Figure 4 (right) on a magnified scale. Close to failure the nonlinearity has increased by a factor 20, whereas the MDR increased only by a factor 1.5 and the linear frequency decreased by only 2%. In order to appreciate the sensitivity of the nonlinear parameter, a detail of the data for early stages during the fatigue process is displayed in Figure 5. We note that the nonlinearity starts to increase well before any of the linear parameters would indicate the deterioration of the material. At about 2 million cycles in the fatigue process,

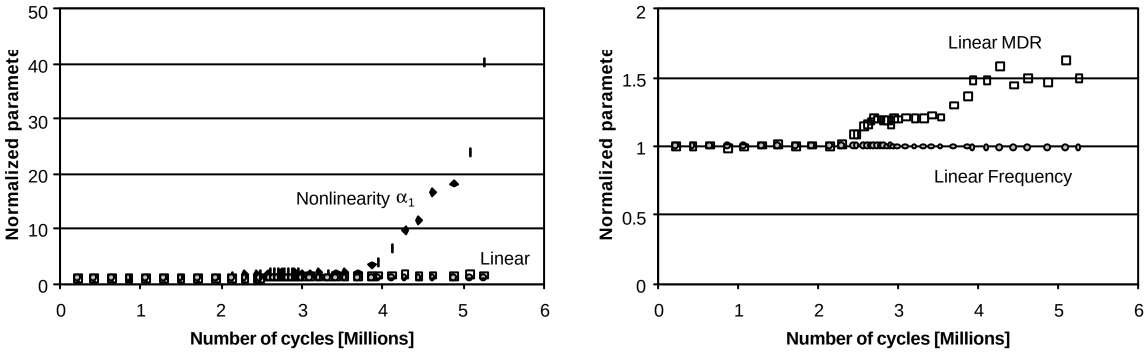

Figure 4: Variation of the linear (f_0 and x_0) and nonlinear (α_1) parameters with fatigue in titanium prismatic bars

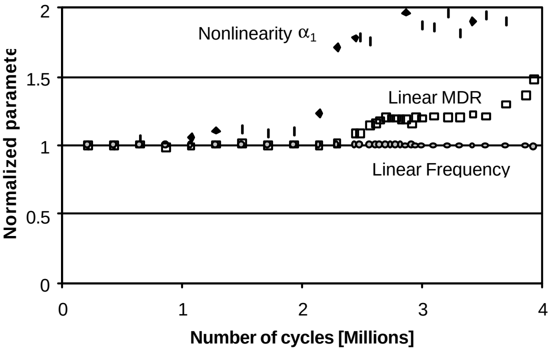

Figure 5: Detail of the variation of the linear and nonlinear parameters in titanium prismatic bars at early stages of the fatiguing process

possibly at the formation of the first concentration of microcracks, a significant increase of the nonlinearity can be noted. The linear parameters show a delayed and less drastic change. At 4 million cycles (Figure 4 left), we assume that the microcracks start to coalesce and form a macrocrack which grows upon further fatigue loading until complete failure occurs. The nonlinear parameter increases dramatically. The changes in MDR and to a lesser extend also in resonance frequency also reflect the ultimate road to failure.

In Figure 6 we compare the relative changes in nonlinearity α_1 obtained from the amplitude dependence of the frequency in the reverberation signal with the relative changes in the nonlinear parameter α_2 obtained from the amplitude dependence of the damping. The overall behaviour is quite similar. However, the nonlinearity coefficient α_2 appeared to be negative for a nearly intact sample, and changes its sign during the fatigue life of the specimen. Exactly at the formation of the first concentration of microcracks, α_2 becomes positive, indicating the enhanced contribution to damping due to the hysteretic stress-strain behaviour at the micro- and mesoscale. (Note that the relative value for α_2 in Figure 6 becomes negative at this point since it has been normalised to its initial value which is negative.) A similar observation was reported by Nagy [3] for a FM355 adhesive layer. In general, we have found that it is easier to measure α_1 in stead of α_2 using the time-domain analysis because of the large error due to resolution problems when measuring α_2 at the low amplitude responses in the tail of the reverberation signal.

CONCLUSIONS

We investigated the acoustic nonlinearity during the fatigue life of titanium samples and compared the relative changes to measurements of the linear material properties. Fatiguing was induced by dynamic loading at high strains. The linear and nonlinear parameters were deduced

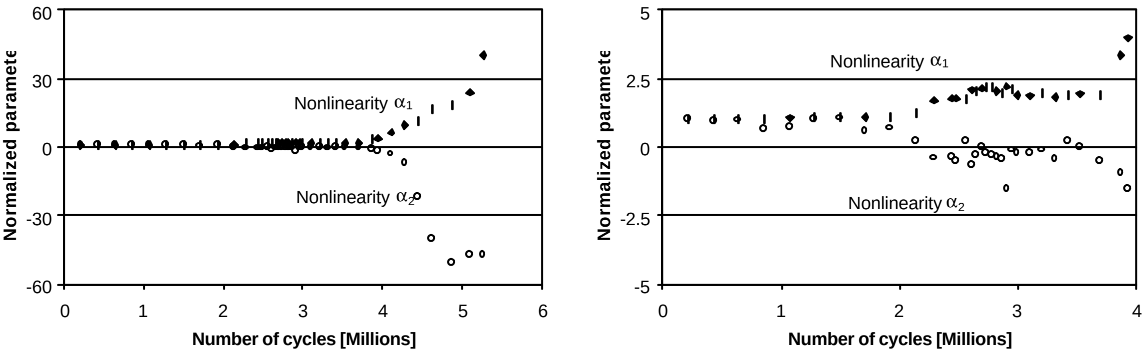

Figure 6: Variation of the two nonlinear parameters a_1 and a_2 in titanium prismatic bars during the fatiguing process (left: up to failure; right: detail of the early stage of fatigue). The values are normalised to their initial values. a_1 is always positive. a_2 is initially negative and changes its sign at the formation of the first concentration of microcracks.

from measurements of the time-windowed reverberation signals at low excitation using traditional DFT and the RFDA time-domain reconstruction. The results show that nonlinear parameters are much more sensitive to deterioration of the sample and that they supply indication of variation much earlier in the fatiguing process compared to linear properties. Since the measurement technique is quite simple and fast, we expect that this technique could be applied to evaluate microdamage nucleation in a wide range of applications.

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