EXPERIMENTAL ANALYSIS OF THE NONLINEAR BEHAVIOUR OF FATIGUED METALLIC SAMPLES

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ABSTRACT

The nonlinear behaviour of intact and fatigued metallic bars flexurally and/or extensionally vibrating has been studied by means of a new experimental procedure for ultrasonic fatigue damage initiation and detection. The procedure is based on the measurement of the vibration velocity of stepped bar samples vibrating at their first resonant mode for different excitation levels. The reverberation of the vibration velocity signal, picked-up by a laser vibrometer, is automatically acquired and analysed by classical FFT methods. The tests have been done with samples of titanium and aluminium alloys. The fatigue of the material is produced by using the driving signal at high excitation levels in the same experimental set-up developed for detection. Two types of experimental studies have been carried out: determination of the fatigue stress at high frequency and comparison between the nonlinear behaviour of intact and fatigued samples. The results show a notable increase of the nonlinear characteristics of the fatigued samples with respect to the original intact samples. In particular, the variation of the third harmonic becomes very relevant.

INTRODUCTION

The problem of the high frequency (sonic or ultrasonic) fatigue strength of metals has not been very much investigated even if it is an important and useful topic in the aeronautic, aerospatial, and energy industries. In the last years, the use of nonlinear methods for investigating the formation and evolution of microdamage within a material has notably increased (see for example [2, 3]). The interest of using these tools in the analysis and prediction of fatigue has also been shown [4, 5].

We have developed an experimental system to produce and analyze ultrasonic fatigue in metals [1]. In this study we use it to analyze the nonlinear behaviour of the materials before and after fatiguing. We compare the nonlinear elastic behaviour of intact and fatigued samples of titanium alloys commonly used in the aeronautic and aerospatial industries.
This paper describes the experimental system as well as the procedure for the dynamic nonlinear characterization of the material. Experimental results are presented and commented.

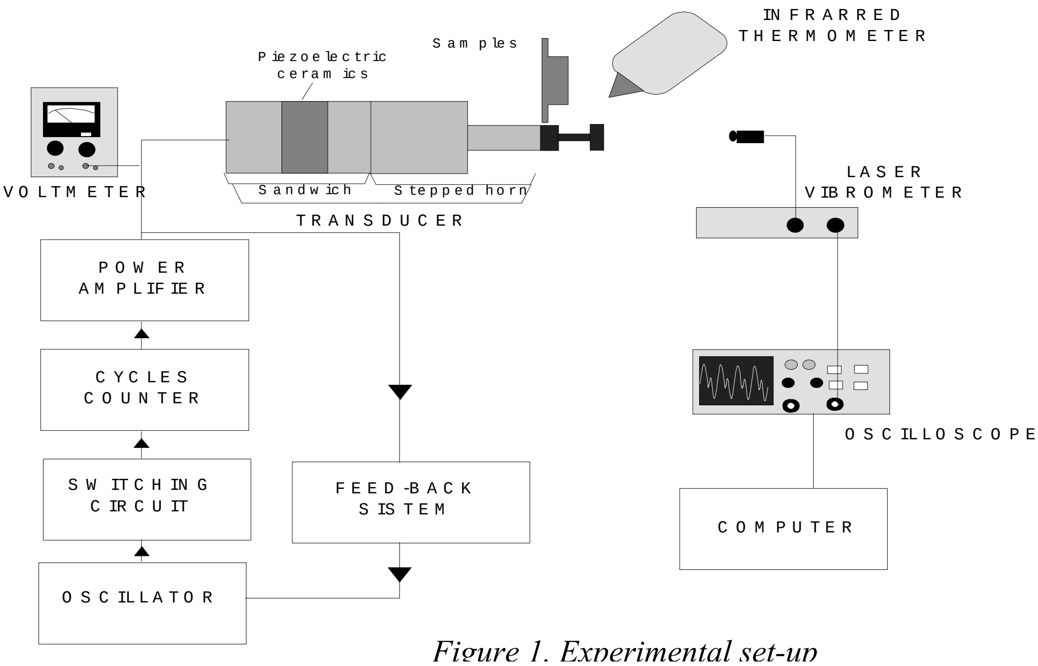

Figure 1. Experimental set-up

Sample	Maximum stress	Number of cycles
3PT1	394 MPa	$\approx 10^5$
3PT2	270 MPa	$1.6\times10^7 < NC < 1.16\times10^8$
3PT3	270 MPa	$1.6\times10^7 < NC < 1.16\times10^8$
3PT6	300 MPa	9×10^7
3PT8	375 MPa	
P1	318 MPa	$\approx 10^5$
P3	345 MPa	$\approx 10^5$
P4	285 MPa	$\approx 10^5$
P5	316 MPa	$\approx 10^5$
P6	387 MPa	$\approx 10^5$
P8	450 MPa	$\approx 10^5$

Table I. Fatigue failure stresses

EXPERIMENTAL SET-UP

The experimental set-up used for fatiguing and monitoring the samples is shown in Figure 1 [1]. It is basically constituted by an excitation system to drive the samples at resonance and a data acquisition system. The excitation system consists of a specially designed electronic generator and a piezoelectric transducer. The electronic generator to drive the transducer incorporates a feed-back system to automatically adjust the excitation frequency to the resonance frequency of the transducer. The electronic generator also includes a switching circuit for the production of periodic interruptions in the excitation signal to keep constant the temperature of the sample. This circuit establishes and counts the number and length of the bursts exciting the samples. In this way the number of applied cycles is controlled. The driving transducer is a resonant system at about 22 *kHz* constituted by two half-wave resonant elements: a piezoelectric sandwich and a stepped horn (Figure 1).

Two types of samples were designed and constructed to produce flexural and extensional standing waves. The samples are designed following two basic requirements: their first resonance mode have to match the transducer's resonance frequency and, in addition, they have to achieve high strains in certain sections while they are driven at linear range strains in other section. To that purpose the adequate sample geometry is cylindrical stepped rod for extensional waves and prismatic stepped bars for flexural waves (Fig. 1). The strain distributions for two extensionally vibrating resonant samples of stepped and uniform shape are compared in Figure 2. The strong increase of the strain in the central thinner section of the stepped sample allows to have a nonlinear behaviour in this part while keeping the excitation working in its linear range. The calculation of the (linear) stress distribution in the samples was carried out by using a commercial finite elements code. The obtained stress values in Pa for a micron of displacement at the transducer driving point are shown in Figure 3 for the two types of samples.

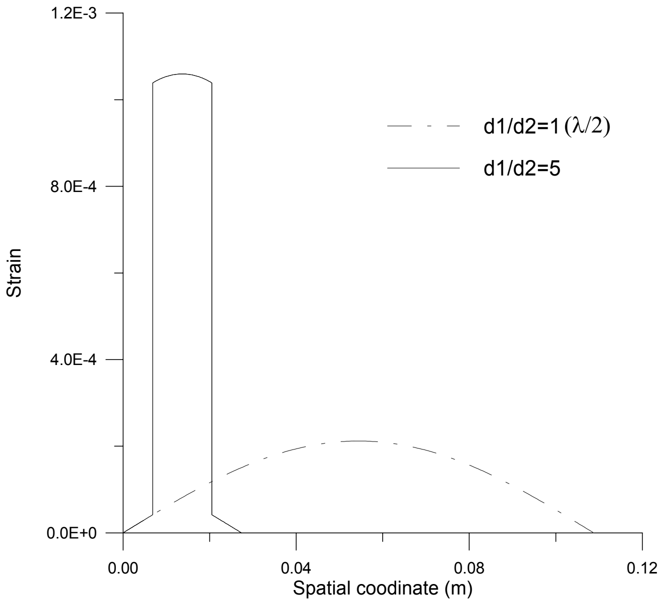

Figure 2 Strain distribution for two resonant samples extensionally vibrating: a stepped sample with a diameters relationship of 5 and a λ/2 uniform sample.

The data acquisition system consists of a He-Ne laser vibrometer providing non-intrusive measurements of the particle velocity in the range of 10 microns/s up to 10 m/s for frequencies up to 1.5 MHz with an accuracy of 2 microns/s. The temperature of the sample was monitored at the nodal section by using an infrared thermometer.

The vibration signal is automatically acquired and treated by a PC.
To fatigue the samples, bursts of between 0.1 and 1 second with intervals of several seconds were applied to produce the peak stress values indicated in Table I. To monitor the nonlinear behaviour of intact and fatigued samples the velocity response of the sample is captured and the reverberation of the signal at the turn-off of the excitation burst is studied by using a time-windowed analysis. A detailed description of the method is done in reference [5].

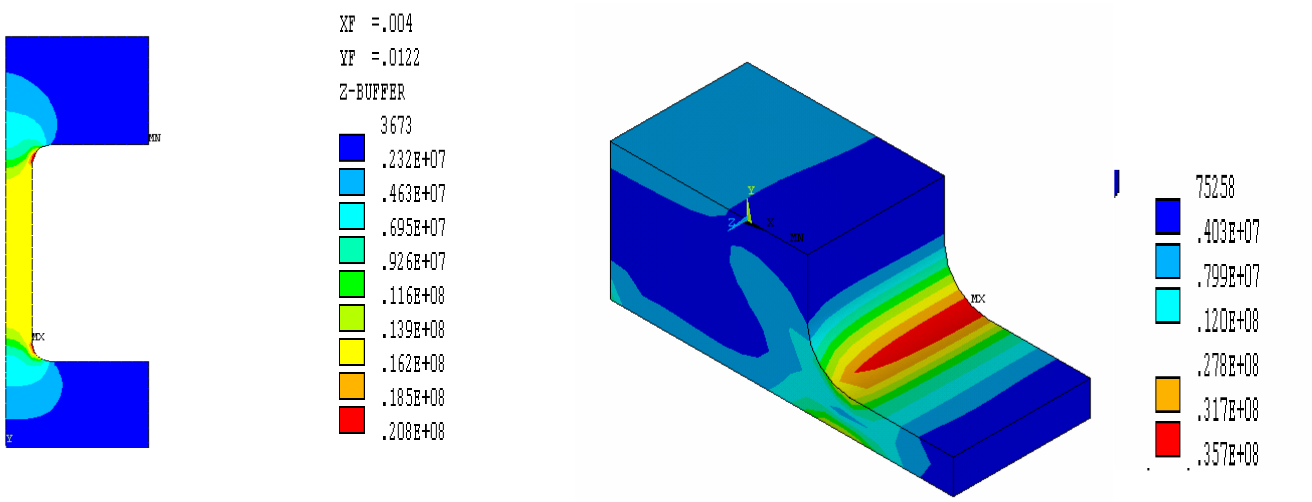

Figure 3. Linear FEM calculation of the stress distribution in the used samples

RESULTS AND CONCLUSIONS

Experiments have been carried out on titanium alloy samples (Ti 6Al 4V). The ultrasonic fatigue strength was measured in extensionally vibrating samples. The results are shown in Table I. It is to be noticed the high dispersion of maximum stress values as well as these values are rather smaller than the yield stress value deduced from static analysis. It is also to be underlined that the dynamic values of the fatigue strength are much lower than the static values which are of the order of 720 *MPa*.

Figures 4 and 5 show some experimental results referred to the nonlinear behaviour of Ti 6Al 4V samples. These results were obtained by analysing the reverberation signals picked-up from the excited intact and fatigued samples. Figure 4 shows the evolution of the second harmonic amplitude (relative to the fundamental amplitude) with the signal amplitude for fatigued and intact samples. It can be easily deduced that the nonlinearity parameter of the material is of about five times higher for the fatigued samples than for the intact samples. The second harmonic for fatigued and intact samples follows a parabolic path which become a straight line when divided by the fundamental, as shown in Figure 4. Figure 5 shows the evolution of the amplitude of the third harmonic relative to the fundamental amplitude. For intact samples the third harmonic follows a cubic behaviour, as predicted by the classical nonlinear elasticity theory, while for the fatigued samples a parabolic behaviour is found. In the figure, third harmonic is related to the fundamental and the resulting paths are fitted by straight lines. It is evident that fatigued samples present a strong nonlinear elastic behaviour including hysteresis.

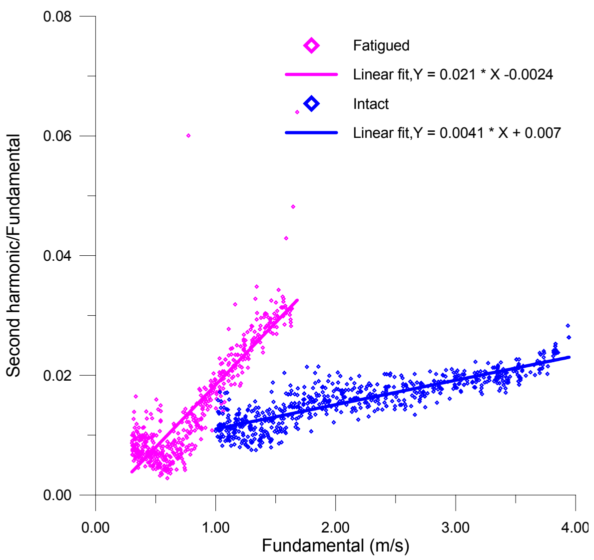

Figure 4. Second harmonic evolution for fatigued and intact samples

This result is in agreement with the theories about the phenomenology of the fatigue process [7]. If for the third harmonic we define a nonlinearity parameter given by the slope of the straight lines of Fig. 5, we will see that this parameter is 15 times higher for the fatigued samples To characterise the changes in the linear behaviour of the material we look at the fundamental frequency of the system, which has to be proportional to the changes in the second order elastic constants. The changes of the fundamental frequency in the fatigued samples with respect to intact samples, result to be of about 2% while the changes in the nonlinear parameters are as high as 500% and 1500%.

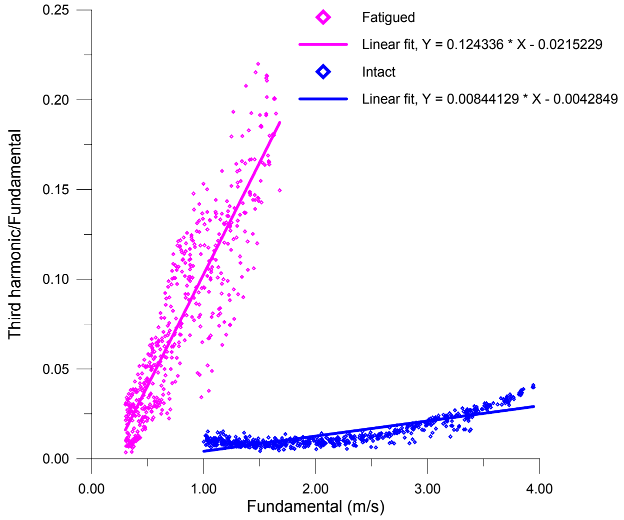

Figure 5. Third harmonic evolution for fatigued and intact samples

Figure 6 shows a comparison of the second and third harmonic in the fatigued samples of Figure 4 and 5. We can see that the third harmonic becomes much more important than the second one. This behaviour can not been explained from a classical nonlinear elasticity theory.

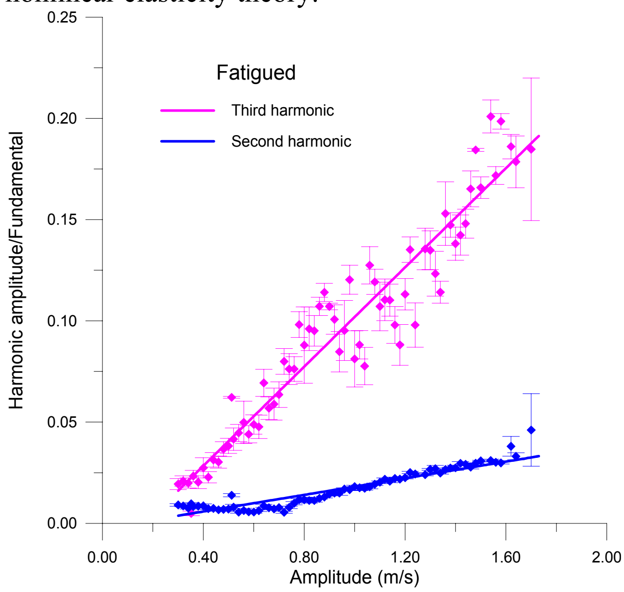

Figure 6. Second and third harmonic evolution for fatigued samples

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