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INSTRUMENTATION OF ULTRASONIC HIGH-FREQUENCY MACHINE TO ESTIMATE APPLIED STRESS IN MIDDLE SECTION OF SPECIMEN

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ABSTRACT

The objective of this paper is to describe the instrumentation of a new developed ultrasonic fatigue testing machine at 20 kHz working frequency and compare the possible solutions to estimate the stress applied in the middle section of the specimen. Stress is estimated by measuring the displacement on bottom of the specimen and their strain on middle section.

The monitoring of the displacement, considered here in the bottom face of the specimen, is carried out using a high resolution laser, the strain using a strain gauge in middle of specimen and field temperature using a pyrometer and thermographic camera.

A LabVIEW routine is used to control the initial parameters of the transducer, such as the frequency reset, the frequency seek, the load amplitude and to record data of all sensors. To manage and process the data, a data acquisition device working at 400 kHz from National Instruments is used.

Keywords Very high cycle fatigue (VHCF); strain; displacement; stress

1. INTRODUCTION

The fatigue of metallic materials was first discussed more than 170 years ago, the first published results, dating back to 1837 by Wilhelm Albert and to this point many researchers have dedicated to this area. Beginning in 1860, Wöhler published the results of fatigue tests with railway axles, and was the first to present quantitative results. In 1870 he presented a final report called "Wöhler's laws", where he concludes that cyclic stress range is more important than peak stress and introduces the concept of endurance limit.

Many significant contributions were made along years, Irwin, Paris and others develop the fracture mechanics, and in 1970's fatigue analysis became an established engineering tool in many industrial applications.

With the continuous effort of the transportation industry trying to achieve higher speeds, modern equipments such as new aircrafts, high speed railways and fuel efficient engines are expected to have longer life cycles. Trying to cope with such expectations with the use of high performance materials, must be lives up to 10E9 cycles are required. In order to perform fatigue tests for such high number of cycles in a useful time period, new strategies are being developed. One of the most promising among them is the use of ultrasonic fatigue testing machines that can perform tests at frequencies up to 30 kHz. This technique was developed and introduced originally by Mason in 1950, an ultrasonic fatigue testing machine with 20 kHz as working frequency was presented in scientific community. In the attempt to reach higher frequencies Girard presents in 1959 a testing machine with 92 kHz as testing frequency

but, at that time, some questions unanswered were made about the results; the technology available didn't guarantee a convincing correlation between results and experiments. Stanzl-Tschegg in Austria and Bathias in France continue to develop strategies in ultrasonic fatigue testing machines in 1967.

The ultrasonic setup is based on an controller that supplies adequate electric power pulse trains to a piezoelectric transducer; this transducer converts this electric energy into mechanical motion (vibration); an ultrasonic tuned horn, working in a resonance condition, amplifies the vibration coming from the transducer and transmit it to the specimen test; all the chain is set in order to obtain the required strain amplitude in the middle section of the specimen.

The development of new sensors and the analytical and computational calculations allow an accurate determination of applied stresses, is possible to measure the maximum stress directly in middle section by strain gauge sensor or relate that with displacement in extremity of the specimen by analytical solution.

The so-called very high cycle fatigue regime is now an established technology in what concerns the lay-out of ultrasonic fatigue machines, but the accurate measurement of the parameters that influence fatigue life (stress, displacement, temperature, etc...) at ultrasonic frequencies is still a matter of concern and continuous development in the scientific community.

2. ULTRASONIC FATIGUE CONCEPTS

An ultrasonic fatigue test differs from the conventional fatigue in the type of vibration. In ultrasonic test seek to reproduce free vibration working in natural frequency of the specimen. In conventional test we work away natural frequencies and specimen is in forced vibration. In order to perform ultrasonic test, it is needed to design natural frequency specimen to the same machine work frequency.

2.1 Analytical specimen with variable section
Under longitudinal resonance [1-5], the specimen behavior must satisfy the differential Eq. (1), determined by the equilibrium of forces.

$$\frac{\partial^2 u(x,t)}{\partial x^2} + P(x)\frac{\partial u(x,t)}{\partial x} = \frac{1}{C^2}\frac{\partial^2 u(x,t)}{\partial t^2} \tag{1}$$

where $C = \sqrt{\dfrac{E_d}{\rho}}$ is the velocity wave propagation and $P = \dfrac{S'(x)}{S(x)}$ the ratio of cross section.
Solution takes the form:

$$u(x,t) = U(x)\sin(\omega t) \tag{2}$$

where ω is the resonance frequency in rad/s, the amplitude of vibration U(x) at each point along the specimen can be easily obtained:

$$U''(x) + P(x)U'(x) = -\frac{\omega^2}{C^2}U(x) \tag{3}$$

To obtain solution of Eq. 3, we need to define the different parts of specimen, see Fig. 1, by a cylindrical part and a profile of hyperbolic cosine for reduced section:

$$\begin{aligned} y(x) &= R_2, \quad L_2 < |x| < L \\ y(x) &= R_1\cosh(\alpha x), \quad |x| \le L_2 \end{aligned} \tag{4}$$

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where: $L = L_1 + L_2$ and $\alpha = \dfrac{1}{L_2} arc \cosh\left(\dfrac{R_2}{R_1}\right)$
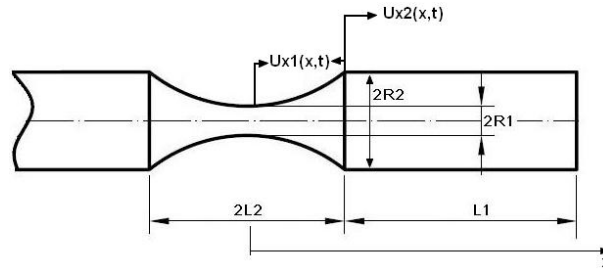

Fig.1 Standard specimen test geometry

Considering the appropriated boundary conditions in the specimen and resonant boundary conditions, the solution Eq. (5) and Eq. (6) represent the displacement behavior at longitudinal mode.

$$u_1(x,t) = A_0 \frac{\cos(kL_1)\cosh(\alpha L_2)}{\sinh(\beta L_2)} \frac{\sinh(\beta x)}{\cosh(\alpha x)} \sin(\omega t), x < L_2 \tag{5}$$

$$u_2(x,t) = A_0 \cos\left(k\left(L-x\right)\right)\sin(\omega t), L_2 < x \le L \tag{6}$$

with:

$$k = \sqrt{\frac{\omega^2}{C^2}} \tag{7}$$

$$\beta = \sqrt{\alpha^2 - k^2} \tag{8}$$

where A_0 is the displacement amplitude at the end of the specimen.
With Eq. 5 and 6 is easy to obtain the strain and stress for specimen.
Strain:

$$\varepsilon(x,t) = \frac{\partial u(x,t)}{\partial x} \tag{9}$$

Stress:

$$\sigma(x,t) = E_d\, \varepsilon(x,t) \tag{10}$$

Fig. 2 represents the displacement and stress along a specimen with same geometry used in ultrasonic tests.
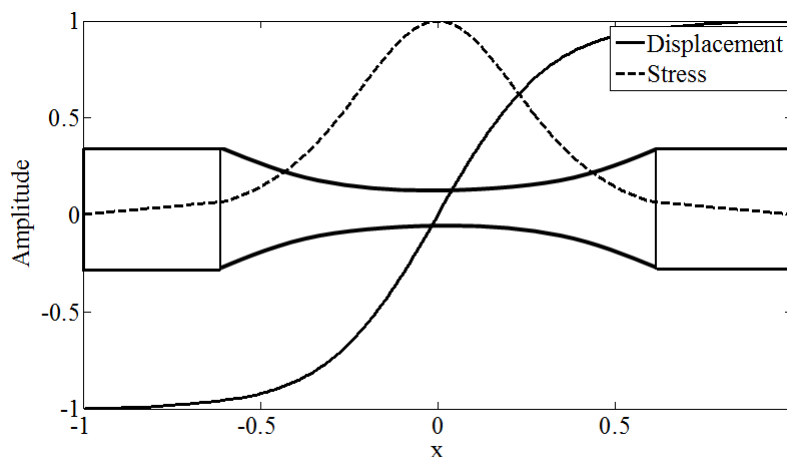

Fig.2 Distributions of displacement and stress on specimen

3. FATIGUE TEST MACHINE AND THEIR PERFORMANCE

In ultrasonic fatigue testing machine, the ultrasonic energy must be transmitted between resonant elements in an efficient way. Due to specific geometric properties of the elements at the longitudinal mode, the amplitude of vibration change, starting in the actuator and ending at the specimen bottom, which means different levels of axial stress along all elements [1-5]. In Fig. 3 is represented the booster, horn and specimen with the typical evolution of displacement and stress along the amplification line [6].
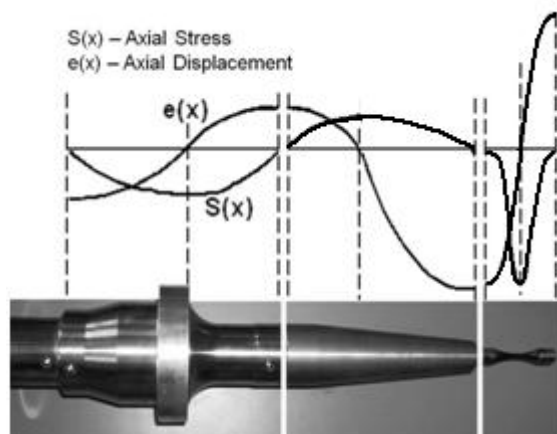

Fig.3 Amplification line along the elements

All resonant elements are mechanically connected by a screw connection; the piezoelectric actuator, booster, horn and specimen elements form the resonant system of the testing machine.

3.1 Machine Elements and setup

The piezoelectric actuator converts electrical signals into mechanical vibrations and needs to be headed by one signal generator. The piezoelectric actuator used is a 2.2 kW Branson DC222 transducer with [19.5 – 20.5] KHz as working frequency range and 20μm peak to peak of maximum displacement.

The objectives of using one horn, is amplifying the displacements delivered by the booster and allow the connectivity between the specimen test and the resonant system.

To estimate the stress applied in the middle section of the specimen we perform tests measuring the displacement at the free end of the specimen and the strain in middle section. The monitoring of the displacement, considered here in the free face of the specimen, is carried out using a high resolution laser, the strain using a strain gage at the middle of the specimen and the field temperature using a pyrometer and thermographic camera. This pyrometer have a [- 40ºC to 600ºC] as measure range, the accuracy is about 1% or ±1ºC and have a 150 ms as response time. A LabVIEW® routine is used to control the initial parameters of the transducer, such as the frequency reset, the frequency seek and the load amplitude and to record data from all sensors during the tests. Data acquisition devices are from National Instruments®, NI USB-6216, is a bus-powered USB M Series multifunction data acquisition (DAQ) device optimized for fast sampling rates: 16 analogue inputs, 400 kS/s sampling rate, two analogue outputs, 32 digital I/O lines, four programmable input ranges (±0.2 to ±10 V) per channel, digital triggering and two counter/timers [6].
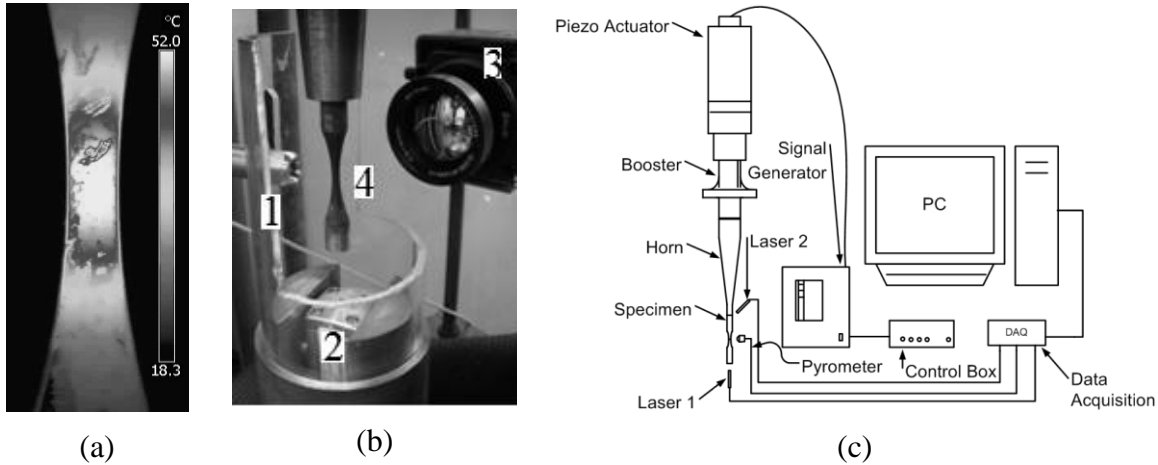
Fig.4 a) Specimen termographic image. b) Experimental setup (1 - Pyrometer; 2 - Laser displacement; 3 - Termographic camera; 4 - Specimen test). c) System and connection layout

3.2 Monitoring

The machine calibration is implemented with the relation between the power applied and the displacement at specimen test extremities. Due to the several amplification levels in the resonant system the lasers are a useful tool which permits to achieve accurate results in the axial stress prediction and monitoring the specimen mechanical behaviour during the fatigue test, as example, the hysteretic damping can be analysed with these two lasers and dynamic elastic modulus can be determined. The fatigue test monitoring is performed with a LabVIEW routine, Fig. 5, 6 and 7, which receive signals from the monitoring system through the DAQ device. This routine determines the testing frequency, establishes the power delivered to the piezoelectric actuator to achieve the desired axial stress, indicate the specimen temperature history and the number of cycles at rupture time. When the fatigue test is finished a summary with the monitoring history is shown. The LabVIEW routine interface is composed by three menus:

(1) Primary Setup, Fig. 5;
(2) Trigger Setup, Fig. 6;
(3) Acquisition, Fig. 7.

The "Primary setup" is to set channels, the analog waveform sampling, the exciter parameters (with or without amplitude displacement control) and the initial value to power excitation.
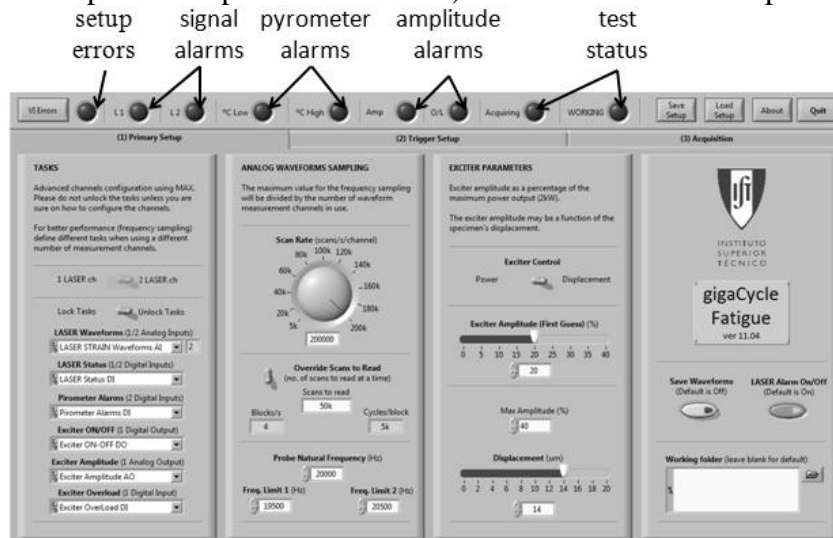

Fig.5 Primary Setup

In the second menu interface is possible to test the previous configuration and assure the performance of the required test. It is also possible to monitor the shapes of measured signals, calculate the respective frequencies and amplitudes. This interface is also used to configure the beginning and the end of data used to calculus of FFT in each period of heating. For more details see [7] where is explained the concept of temperature control and how are composed the period of heating and cooling.
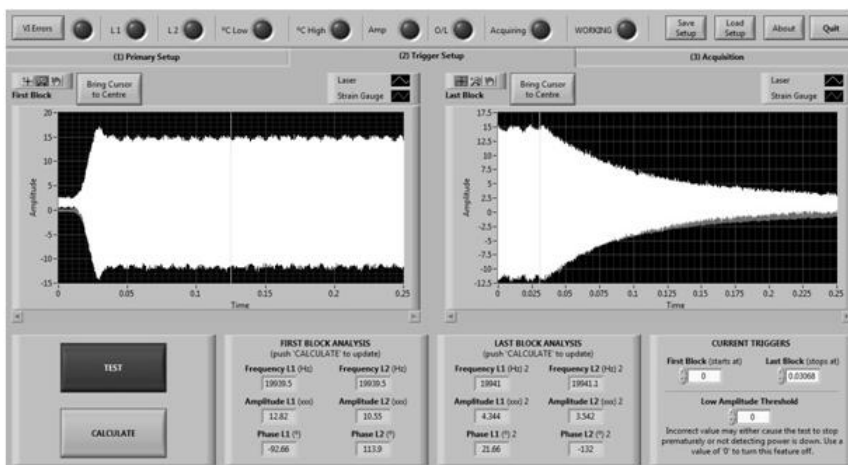

Fig.6 Trigger Setup

Finally, the third menu is used to start up of the test and save all data into the desired folder.
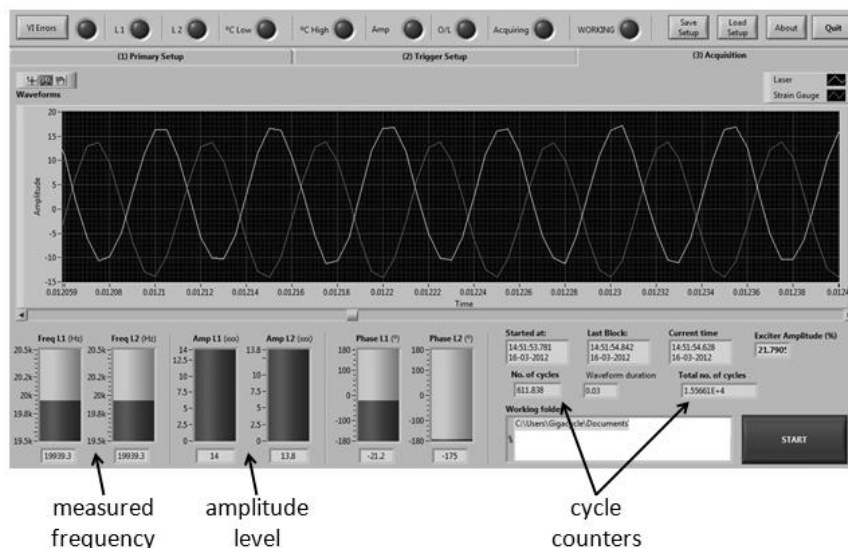

Fig.7 Acquisition

3.3. Stress measurement technique

The monitoring of the applied stress in middle section of the specimen will be made in two ways, first from the measurement of micro strains placing a strain gauge in middle section and second calculating the stress from the displacement measured by the laser on the extremity of the specimen through analytical solution Eq. 5 to 10, as exemplified in Fig. 8.
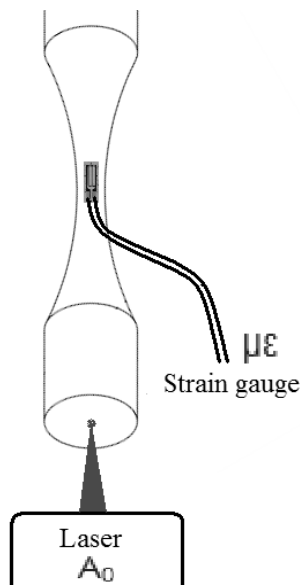

Stress estimated by:

Strain gauge - measuring micro strain in middle section:

$$\sigma_{strain\ gauge} = E_d \mu\varepsilon \times 10^{-6} \qquad (12)$$

Nano laser - measuring displacement amplitude on specimen extremity:

$$\sigma_{laser} = E_d \left|\frac{\partial u}{\partial x}\right|_{x=0} \qquad (13)$$

Fig.8 Strain gauge and laser positioning

4. RESULTS

Fatigue tests were carried out on the piezoelectric fatigue testing machine, on specimens of the geometry shown in Fig.2 [7] made of 42CrMo4 steel, presenting a natural frequency close to 20 kHz. The objective of these preliminary tests on very high cycle fatigue (VHCF) is to compare the data acquired from the strain gage and the laser transducer. Therefore a low power was applied in order to obtain a significant number of cycles without failure of the specimen due to the fatigue of material or to the failure of the strain gauge due to heating.

The first results concerning fatigue were obtained from test carried out with the actuator power set to 17% and operating without temperature control. The data was acquired from the strain gage and the laser transducer.

The results show the data acquired for the resonant frequency, Fig 9 (a), the temperature evolution at the centre of the specimen, Fig 9 (b), the displacement amplitude at the bottom of the specimen, measured by the laser and calculated from the strain gage data, Fig 9 (c) and the correspondent stress amplitude at the center section of the specimen calculated from both the strain gage, Eq. 12 and the laser transducer data, Eq. 13, Fig 9 (d). The test had a duration of approximately 7 000 s and performed about 14×10^7 cycles, during which we can observe the effect of the increase in temperature and its stabilization close to 60ºC. With the increase of temperature, there is a decrease of the resonant frequency of the system and consequently an increase in amplitude of displacement, as expected, since the power supplied to the system remains constant.

The displacement amplitude data obtained from the laser is then compared to and validated by measurements carried out using strain gauge data. As we can see in Fig. 9(c), the error between the two types of measurements is approximately 2%, which can be considered small and can be explained by the longitudinal length of the strain gauge and the analytical approach of the profile of the reduced section of the specimen (hyperbolic versus circular).

Despite this small error, this result confirms the accuracy of the test monitoring carried out by measuring the displacement amplitude on the bottom of the specimen.

Fig. 9(d) shows the evolution of the stress in the middle section calculated from the micro strains measured by the strain gauge and estimated by the displacement amplitude at the bottom of the specimen.
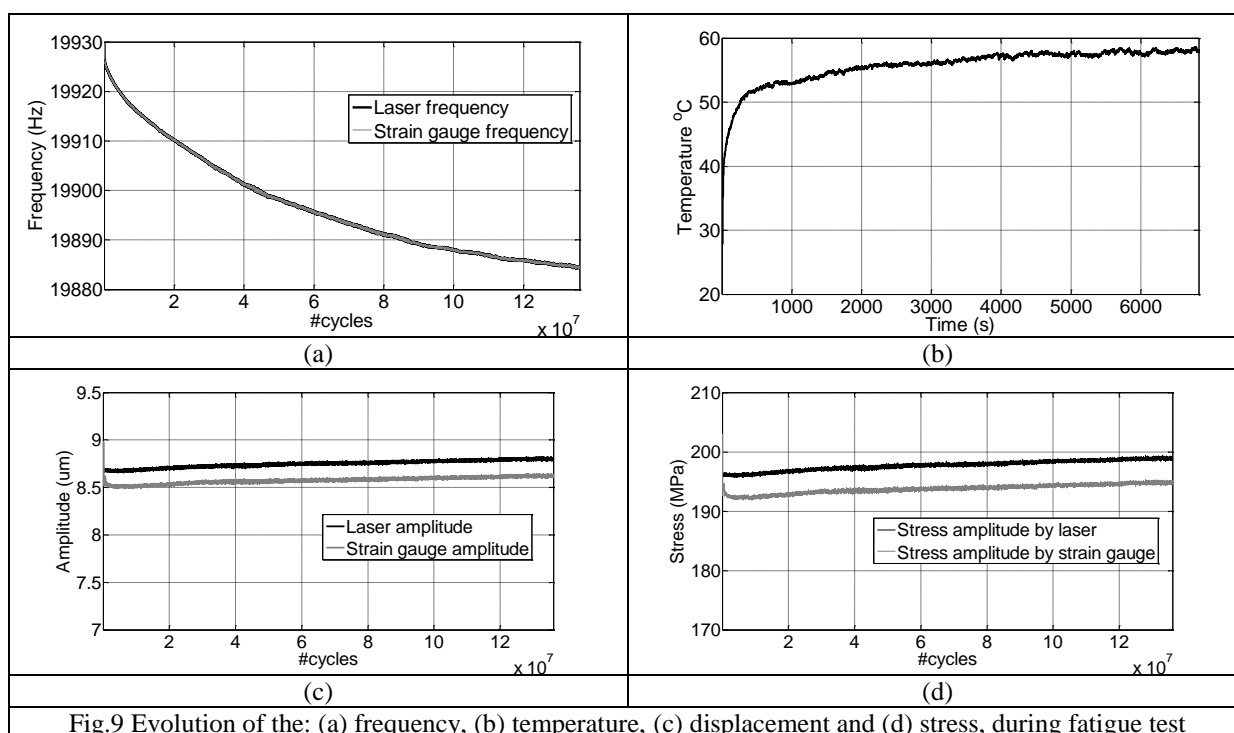

Fig.9 Evolution of the: (a) frequency, (b) temperature, (c) displacement and (d) stress, during fatigue test

Further fatigue tests were carried out similar to the previous ones: same specimen, same power actuator, same displacement amplitudes, but in this case with control of the temperature range, between 35° C and 50° C and only the displacement on the bottom of the specimen was measured. Results are shown on Fig. 10 where the heating and cooling of the specimen can be observed, Fig. 10 (b), its influence on the amplitude of the frequency, Fig 10 (a), on the displacement amplitude at the bottom of the specimen, Fig 10 (c) and on the stress amplitude at the center of the specimen, Fig 10 (d). An accuracy of about 0.5 % of the stress amplitude is achieved, which can be considered an excellent way to monitor the stress applied of the specimen during the fatigue test.

Fig.12 Evolution of the: (a) frequency, (b) temperature, (c) displacement and (d) stress, during fatigue test
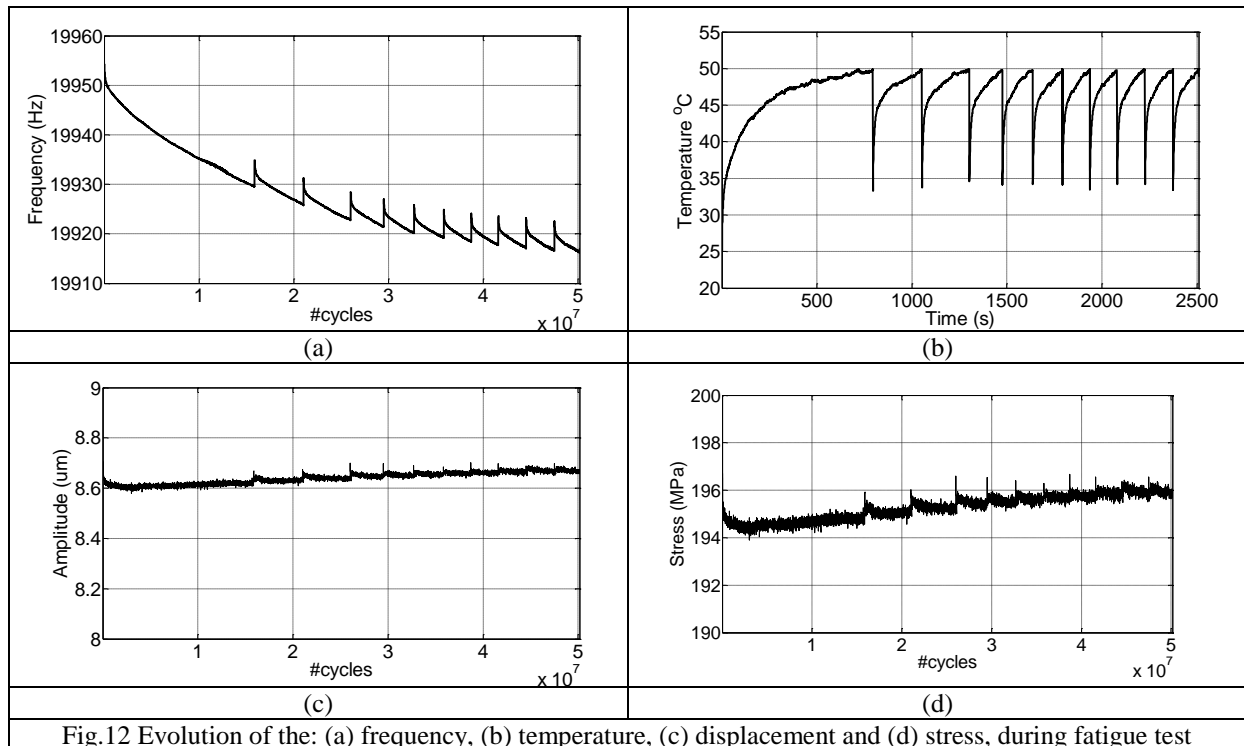
5. CONCLUSIONS

Fatigue tests in VHCF regime were conducted in a ultrasonic fatigue testing machine.

To monitor the applied the stress on the specimen during VHCF test, was performed by measuring the displacement on the bottom of the specimen using a laser transducer.

The results presented here show the accuracy of the method as compared with traditional measurement by the strain gauge.

Combining this method of monitoring the stress with the displacement amplitude and temperature control, proved to be an adequate methodology to perform VHCF test in this machine with quite accurate results.

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