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DESIGN AND INSTRUMENTATION OF AN ULTRASONIC FATIGUE TESTING MACHINE

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ABSTRACT

Ultrasonic fatigue testing machine are being used to perform materials testing in the range of 10^7 to 10^{10} fatigue cycles. The so-called very high cycle fatigue regime is now an established technology in which concerns the lay-out of ultrasonic fatigue machines, but the accurate measurement of the parameters that influence fatigue life (load, strain, displacement,) at ultrasonic frequencies still is a matter of concern and continuous development. The objective of this paper is to describe the design and construction of a fully instrumented ultrasonic fatigue testing machine at 20 kHz working frequency. In order to achieve fully automated tests, a closed loop control system was developed to use monitored temperature and displacement to set the power and the cooling periods of the machine. The monitoring of the displacement, considered here in the bottom face of the specimen, is carried out using a high resolution laser. The specimen´s temperature is monitored online through a pyrometer. The cooling of the specimen is achieved with cooled dry air. To manage and process the data a data acquisition device working at 400 kHz from National Instruments is used. The software was developed in house using the LabView package.

KEYWORDS

Ultrasonic fatigue testing machine, Instrumentation, Displacement and temperature control

INTRODUCTION

The necessity to increase performances in terms of lifetime and security in mechanical components or structures is motivation of intense research. Have a proper knowledge of the damage and rupture mechanisms in materials fatigue at VHCF domain is extremely important nowadays. However, using conventional fatigue testing machine to carry out VHCF tests can be very time-consuming; for instance, making a fatigue test with hydraulic machine at 30 Hz as working frequency would take about one year to reach 10^9 cycles. The ultrasonic approach in fatigue testing procedures turns these tests practicable in a feasible way. It is possible to achieve in few hours the fatigue strength at 10^9 cycles or even 10^{11}, which is the utmost value of the range currently used in mechanical design. The advantages of the ultrasonic tests associated to the improvements in piezoelectric devices became the ultrasonic fatigue testing an attractive technique used around the world to establish S-N curves in VHCF. The piezoelectric techniques applied to fatigue tests started with Hopkinson in the beginning of the 20th century. He created the first piezoelectric fatigue testing machine working in longitudinal resonance with 33Hz. Fifty years later, in 1950, an ultrasonic fatigue testing machine with 20 KHz as working frequency was presented in scientific community by Mason. 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 doesn't guarantee a convincing correlation between results and experiments. Nowadays, some issues were overcome but some scepticism still remains about some aspects. Therefore, the research in this field still is a subject of concern.

The objective of this work is the design and instrumentation of an ultrasonic fatigue testing machine at 20 kHz working frequency; this machine must eliminate the unwanted effects of using high frequencies providing results compatible with the data obtained by lower frequency. The method of investigation was implemented in the lab and workshop. Some components were acquired and adapted others machined. The observation of the fatigue testing needs and the necessity of eliminating some issues unresolved in the instrumentation of this kind of testing machines are the main reasons of the targets created in this work.

MACHINE ELEMENTS AND PROCEDURES

The ultrasonic fatigue testing machine is an integrated system with several elements, each one of them with a specific task. In Fig. 1 it is presented the system implemented for the present research work. All resonant elements are mechanically connected by a screw connection; the piezoelectric actuator is connected to the booster who in turn is connected to the horn. The specimen is connected to the end of the horn. These four elements form the resonant system of the testing machine. The actuator is headed through the signal generator who in turn is controlled through one control box. This box is commanded through a software developed in house using the LabView package from National Instruments (NI). The lasers and pyrometer are connected to the data acquisition device (DAQ) and the vortex is actuated through one servo-valve with the feedback obtained from the pyrometer.

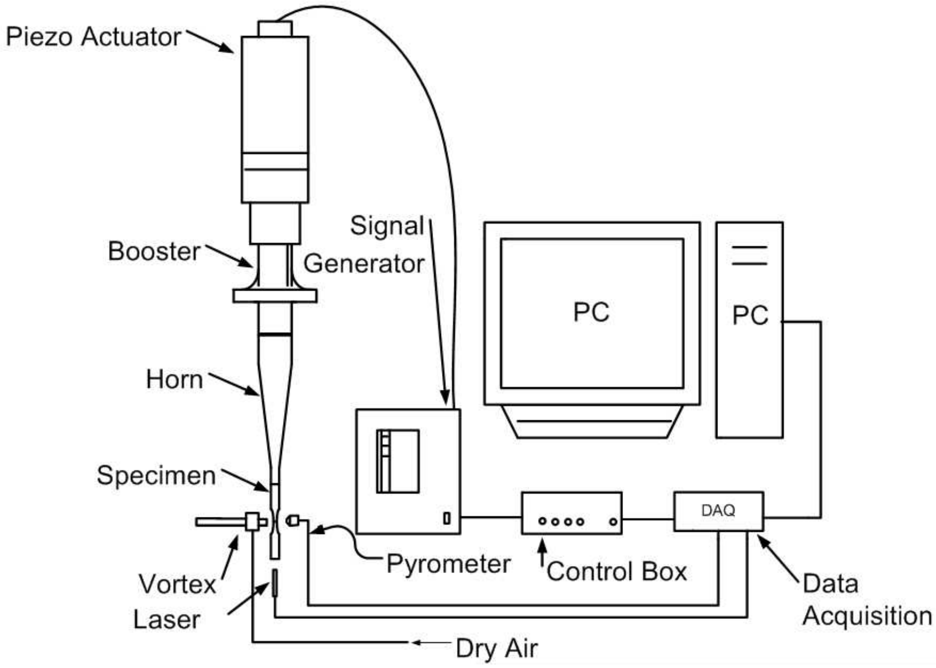

Fig. 1 System and connection layout

Machine Elements

The generator delivers an electric signal with a sinusoidal shape and predetermined resonant frequency to the piezoelectric actuator, converting it into mechanical vibrations. The signal generator is a Branson DC222 with a [19.5 – 20.5] kHz working frequency range. The piezo actuator is a 2.2 kW Branson transducer with a 20µm peak-to-peak maximum amplitude. This equipment was originally designed to be used in polymers welding. Therefore, it was adapted to the machine's purpose, and one control box was specifically designed and built. Besides working as a hub and a power supply, the control box has two main operational functions: 'reset' of the signal generator and 'seek' of the system's resonant frequency.

The excitation displacements delivered by the actuator are amplified by means of a booster and a horn. The booster is made of titanium with a 1:2 amplification ratio and has a resonant frequency around 20 kHz. It also has an outer ring, positioned at its vibration node, to work as clamping fixture of the whole system. The goal of the horn is to further amplify the displacements and to provide connectivity between the test specimen (much smaller) and the actuator. The horn was designed using a finite element routine and machined in a workshop in house; the material used is the 42CrMo4 steel. The amplification ratio is around 1:3.

The test specimen is monitored with one laser displacement transducer which allows measuring the displacement at the polished bottom of the specimen (free end) during the whole fatigue test. This laser works under an autofocus measurement principle with a 0.13 [mm] measurement range and has a frequency response up to 30 kHz.

A pyrometer is used to monitor the temperature of the specimen on-line. This pyrometer works in the [-40 to +600]°C temperature range (±1 °C) and has a 150 ms sampling time. Extended periods of fatigue testing are possible through the introduction of continuous cooling. Cooled air is obtained using a vortex tube. The vortex selected can remove 2650 BTUH. The inlet nominal pressure is ≈7 bar and delivers cooled air with 1 m^3/s at 1 bar. This solution does not need electricity or refrigerants and is reliable, compact and lightweight.

The information is gathered by a DAQ and processed with the LabView routine installed in a PC computer. The NI USB-6216 is a bus-powered USB DAQ optimized for fast sampling rates (400 kHz), with 16 analogue inputs, 2 analogue outputs and 32 digital I/O lines.

Monitoring and working procedures

Due to the several amplification levels in the resonant system the laser is a useful tool which permits to achieve accurate results in the axial stress prediction and monitoring the specimen mechanical behaviour during the fatigue test. The fatigue test instrumentation and monitoring is shown in Fig. 2. The LabView routine, shown in Fig. 2b) receives signals from the monitoring system represented in Fig. 2a), through the DAQ device. This routine determines the testing frequency, establishes the power delivered to the piezoelectric actuator to achieve the desired axial stress (expressed as a displacement) and indicates the number of cycles performed until final failure. A set of alarms is used to control the machine's operation. The temperature is continuously monitored with the pyrometer's software running background.

Fig. 2a) indicates the arrangement of the monitoring elements. The pyrometer (1) and the laser (2) are connected to the computer and DAQ. The vortex (3) is controlled by the LabView routine through the feedback from the pyrometer and deliver cooled air to the specimen's surface (4).

Before testing and after the specimen has been screwed to the horn, the signal generator must perform a frequency scan in order to calibrate the system's resonant frequency. At this point the fatigue test may be started. During the fatigue test, the signals that come from the laser and pyrometer are acquired for monitoring the specimen's behaviour. With the laser's waveform time signal and through the use of a filter based on the FFT (Fast Fourier

Transform), it is possible to determine the working frequency (which is continuously updated online by the piezo actuator and signal generator), the displacement at the free end of the specimen and the total number of cycles. The LabView routine also has the ability for online adjusting the power delivered to the actuator in order to achieve the needed displacement level (correlated to the stress level the specimen is subjected to).

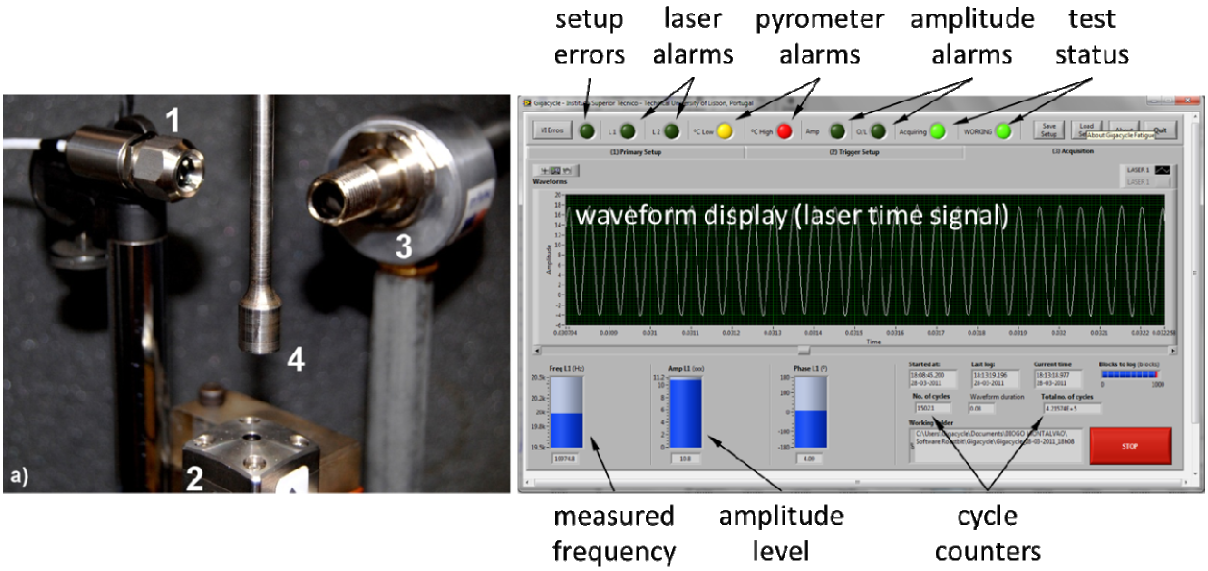

Fig. 2 a) Left: Monitoring arrangement (1 - Pyrometer; 2 - Laser displacement transducer; 3 - Vortex cooling system; 4 - Secimen test). b) Right: LabView routine

If the temperature achieves a pre-defined maximum value (e.g., 27 ℃) the pyrometer alarm is activated and the measurement is interrupted. The exciter will not start working until the specimen is cooled down until the temperature reaches a minimum value (e.g., 23 ℃). The amplitude and temperature monitoring is made simultaneously after a certain amount of time has elapsed. This period between each feedback may be adjusted on the LabView routine. First, it is necessary to define the sampling frequency for the laser analogue input, which, in this case, may be as much as 400 kHz (equivalent to 20 points per cycle at 20 kHz). For continuous acquisition, circular buffers are used, where portions of data are read from the buffer while the buffer is filled. Thus, the application must retrieve data in blocks with a size that depends both on the system’s performance and the user’s choice.

The test is stopped when the bottom laser loses focus (detected by the laser alarms, for instance, when rupture occurs) or when the amplitude level decreases below a pre-defined minimum level. At this point, the monitoring history up to date is registered and saved to a file. For each block, the frequency, amplitude and number of cycles is registered. During the measurement, some sample blocks of time signals are saved to a file as well, for later check.

RESULTS AND DISCUSSION

By taking advantage of the natural frequencies, ultrasonic tests provide a powerful way for introducing a large number of heavy cyclic loading on a short time span, with lower costs when compared to traditional fatigue testing that commonly uses low frequency hydraulic machines. However, the booster, horn and test specimen have to be carefully designed taking into account the vibration mode shapes. For complex shapes or threaded connections, the geometric plan of the element must be determined by using a finite element approach. In short, the principle behind is that the test specimen must be vibrating at his first longitudinal mode shape, where the displacement achieves maximum values at both its ends, having a node at the middle where the stress (and strain) reaches the maximum value. This is expressed by:

$$u(x,t) = U_0 \cos(2\pi f t) \cos\left(\frac{\pi}{L}x\right) \Longrightarrow \varepsilon_{xmax} = \left(\frac{du}{dx}\right)_{max} = \frac{\pi}{L}U_0$$

where $u(x,t)$ is the displacement of the specimen at x, U_0 is the displacement amplitude, f is the frequency, t is the time variable, L is the specimen's length and ε_{xmax} is the maximum strain (at $x = L/2$).

A test was conducted with a cylindrical steel specimen with L≈130mm length and 10mm diameter, presenting a natural frequency a bit under 20 kHz (≈19.9 kHz). The actuator power was set to 10% (220 W) and the operating temperature range from 23 ℃ to 27 ℃. With a 400 kHz sampling frequency and a 100k samples buffer, each acquisition block lasted 0.25s. Hence, the feedback loop was updated every ≈5k cycles or ¼ of a second. After approximately 23 minutes, 6 sets of data were acquired and the test was stopped. The results are presented on Fig. 3.

Note: The curly brackets signal the actuator working regions. Outside, the system is cooling down.

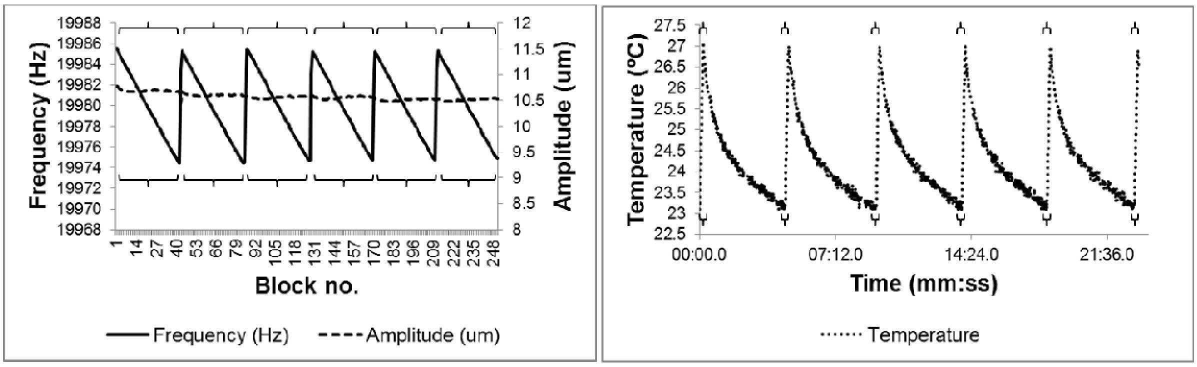

Fig. 3 a) Left: Specimen's frequency and amplitude variation over each 5k cycle block. b) Right: Specimen's temperature variation over time.

During each measurement, the temperature raised from 23 ℃ to 27 ℃ in 11 s , mostly as a result from the internal friction (damping). At the same time, the resonant frequency decreased 0.55%, which, incidentally, corresponds to about 1Hz/℃. Each cooling cycle took barely 4 minutes and a half to complete (the Vortex was off during this test). While the temperature and natural frequency showed remarkable shifts during each run (practically linear and very consistent), the displacement at the specimen's free end seemed to present slight oscillations (although it did not show considerable changes). Calibration work with strain gauges is still needed. On the whole, the specimen was subjected to a total of 1.23E6 load cycles in 23 minutes (without forced cooling).

CONCLUSIONS

An ultrasonic fatigue testing machine was designed and assembled. Optimized geometries for the horn and specimen were designed and manufactured with resonant frequencies within the piezoelectric actuator working frequency range. The instrumentation associated with the ultrasonic testing allows monitoring and controlling the testing frequency, the displacement at the free end of the specimen and its temperature. Fatigue tests in VHCF regime were successfully conducted with controlled temperature at the area of maximum stress of the specimen.

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