Development of a Very High Cycle Fatigue (VHCF) multiaxial testing device

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ABSTRACT. The very high cycle region of the S-N fatigue curve has been the subject of intensive research on the last years, with special focus on axial, bending, torsional and fretting fatigue tests. Very high cycle fatigue can be achieved using ultrasonic exciters which allow for frequency testing of up to 30 kHz. Still, the multiaxial fatigue analysis is not yet developed for this type of fatigue analyses, mainly due to conceptual limitations of these testing devices. In this paper, a device designed to produce biaxial fatigue testing using a single piezoelectric axial exciter is presented, as well as the preliminary testing of this device. The device is comprised of a horn and a specimen, which are both attached to the piezoelectric exciter. The steps taken towards the final geometry of the device are presented. Preliminary experimental testing of the developed device is made using thermographic imaging, strain measurements and vibration speeds and indicates good behaviour of the tested specimen.

KEYWORDS. Multiaxial fatigue; Very high cycle fatigue; Fatigue testing machines; Strain measurements.

INTRODUCTION

Fatigue damage has special relevance on the life span of mechanical components and structures, as it takes responsibility for the majority of the registered structural failures. Although its mechanisms have been the subject of continuous research, the growing need for greater lifespans forced the understanding of the behavior of materials under very high cycle loadings [1], also known as the Very High Cycle Fatigue (VHCF) regime. This field of research, which studies the mechanical behavior of materials for fatigue lives over 10E7 cycles, has recently gained notoriety [2], largely due to the appearance of ultrasonic fatigue testing machines, working at 20-30 kHz and due to the acquisition and control equipment capable of handling signals at such high frequencies.
In this context, the results found in the bibliography [1, 2], which usually focus on either axial or torsional fatigue tests, allow us to understand the behavior of materials on the very high cycle region of the S-N curves, remarking the absence,

for some materials, of the fatigue limit that used to be considered on mechanical design. However, these results only refer to uniaxial loadings when, in real conditions, mechanical components are usually loaded under multiaxial loadings. Because of the axial character of the excitation created by the piezoelectric exciter, only axial, bending or fretting specimen testing were able to be performed up to now. The appearance of torsional piezoelectric exciters allowed for VHCF testing on torsional conditions, as well. But, for multiaxial conditions, no VHCF results have been described on the literature due to conceptual limitations of these devices.

Multiaxial loading fatigue has been the subject of intense research for low and high cycle regimes, but not on the VHCF region, due to the inexistence of machines capable of operating on ultrasonic frequencies and submit specimens to multiaxial loadings. For the high cycle regime, the von Mises criterion on biaxial loading has been questioned since experimental data does not correlate well, either for in-phase or out-of-phase loadings [3].

In this paper, the development of a fatigue testing machine for biaxial conditions working at VHCF is presented. The device is comprised of a horn and a specimen, which are both attached to an ultrasonic piezoelectric axial exciter.

BIAXIAL FATIGUE TESTING MACHINE FOR VHCF

The present work describes the processes of creation and development of a VHCF testing device for biaxial conditions, using a single axial piezoelectric exciter. The device is comprised of a horn and a specimen, being the latter the component to be tested on biaxial conditions, with a loading that was predefined to have in-phase sinusoidal components of axial and shear stress in R=-1.

The horn

Since the horn receives a sinusoidal axial displacement from the piezoelectric exciter, and it is intended to induce also torsional loadings on the specimen, the horn has to be responsible for the generation of the rotational movement which will be imposed on the specimen and will promote shear stresses in it. This implies that the horn takes special importance on the behavior of the device, specifically on the relationship between axial and torsional loadings imposed on the specimen.

The computational modal analysis made to this geometry proved that a certain dynamic vibrational mode could be achieved in which the horn would vibrate in a hybrid mode composed by the first axial mode and the first torsional mode, where axial and rotational displacements were amplified on the smaller free end. Still, there was a need for a horn that would possess this specific mode on the frequency at which the exciter operates (20 kHz).

The iterative process to obtain the final geometry was produced using finite element software, and a schematic representation is shown on Fig. 1:

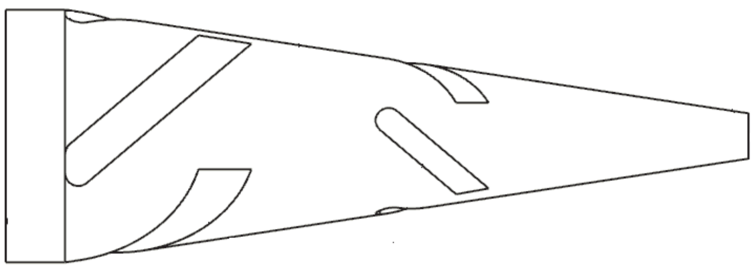


Figure 1: 2D representation of the developed biaxial horn.

The final horn geometry consists of a conical shaped piece possessing two groups of oblique slits responsible for the generation of the rotational character of the horn, which in turn will promote sinusoidal rotations on the specimen that will add to the already existent sinusoidal axial excitation.

The specimen

Before introducing the final geometry of the used specimen, it might be interesting to analyze the dynamic equation for a generic bar, Eq. 1, [1]:

$$\frac{\partial^2 u}{\partial t^2} = \frac{E}{\rho}\frac{\partial^2 u}{\partial x^2} \quad (1)$$

where u is the displacement, t is time, E is the Young Modulus, x is the associated coordinate system and ρ is the specific mass of the material. The mathematical solution of Eq. 1 is:

$$u(x) = A_0 \cos\left(\frac{n\pi x}{l}\right) sen\left(\frac{\pi ct}{l}\right) \quad (2)$$

where A_0 is the generic amplitude of vibration, l is the bar length and c is the wave propagation speed. Eq. 2 represents the axial displacement along the generic bar, respective to a certain n^{th} mode, while Eq. 3 represents the natural non-damped frequency, ω_n for the n^{th} mode.

$$\omega_n = \frac{n\pi}{l}\sqrt{\frac{E}{\rho}} \quad (3)$$

The solution found at Eqs. 2 and 3 are equally valid for torsional modes, replacing the Young Modulus by the Shear Modulus of a certain material. Solving the equation for a cylindrical bar with a length of 250 mm (and noting that for this solution, the diameter of the bar does not affect the final results), the following results are obtained for the first five modal non-damped frequencies for the axial and torsional directions for common construction steel (E=200 GPa, ρ=7800 kg/m3):

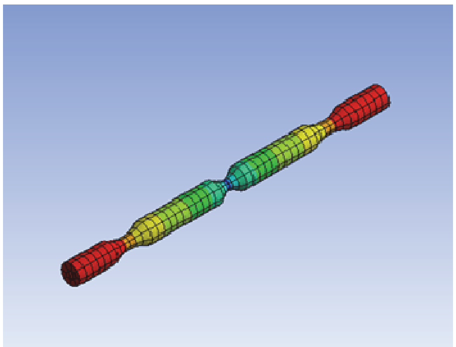
	Axial frequencies			Torsional frequencies	
n	(rad/s)	Hz	n	(rad/s)	Hz
0	0.0	0.0	0	0.0	0.0
1	63632.3	10127.4	1	40244.6	6405.1
2	127264.6	20254.8	2	80489.2	12810.3
3	190896.9	30382.2	3	120733.8	19215.4
4	254529.2	40509.6	4	160978.4	25620.5

Table 1: First five modal frequencies for axial and torsional directions.

Obviously, and due to the differences found between the Young and Shear Modulus, the results are lagged by a certain ratio. This implies that, for a cylindrical shape, the first axial mode will have a significative different frequency value from the respective first torsional mode. If a cylindrical shaped specimen is pretended, this raises a relevant problem to the creation design. One could think, from the analysis of Tab. 1, that the second longitudinal mode (n=2) and the third torsional mode (n=3) could be used to design a specimen to produce biaxial testing, since frequencies are very close together. Still, this solution is of little application since, because of the shapes of these two modes, axial and shear stresses on specimen would be higher on different locations. Other combinations of modes were considered, but the final design consisted of a specimen that possesses its first axial mode (n=1) and its third torsional mode (n=3) at the same frequency. This is achieved by designing a cylindrical specimen with three throats, as seen in Fig. 2:

Figure 2: 2D representation of the developed specimen.

Generally speaking, while the presence of the middle throat lowers the first axial and torsional modes, the presence of the two outside throats is used to considerably lower the third torsional mode. The correspondent first axial mode shape and third torsional mode shape of the developed specimen are presented on Fig. 3, both having the same inherent natural frequency:



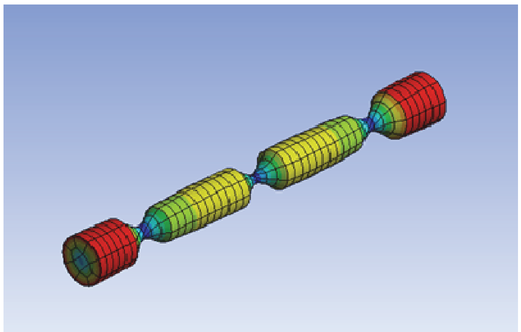


Figure 3: Representation of the specimen first axial mode (at left) and third torsional mode (at right), both with the same natural frequency.

Coupling of the horn, specimen and exciter

After the specimen and horn have been designed, it became mandatory to produce computational analyses to understand the dynamic behavior of the coupled system, formed by the booster, horn and specimen.

A computational model of the developed system was built, shown in Fig. 4.

Then, finite element analyses were run in order to obtain the mode shape at the pretended frequency, as shown in Fig. 5.

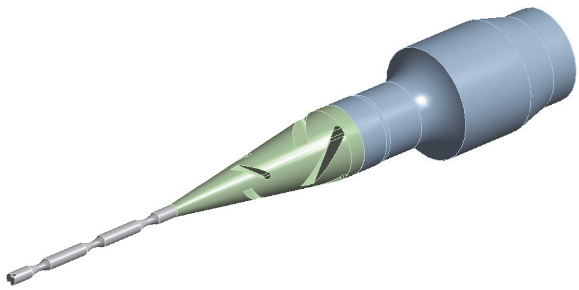


Figure 4: 3-dimensional model of the developed device.

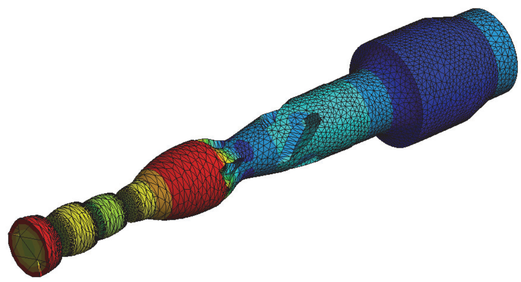


Figure 5: Modal shape of the operational mode for the developed device.

The developed device is patent pending under INPI 20161000008542 Ref. number.

EXPERIMENTAL TESTING OF THE DEVICE

After the theoretical definition of the equipment, a prototype of the design was built in order to produce several experimental testing to evaluate its correct behaviour.

Laser vibrometer results

In order to correctly evaluate rotation on the specimen, two notches were created at the bottom of the specimen. These notches are used to measure surface speeds. Speeds are measured using a vibrometer from POLYTEC with two laser channels, with high frequency measuring capabilities. Results obtained from these experimental testing have already been published [4]. Axial speeds measured at the free-end of the specimen are presented below, Fig. 6:

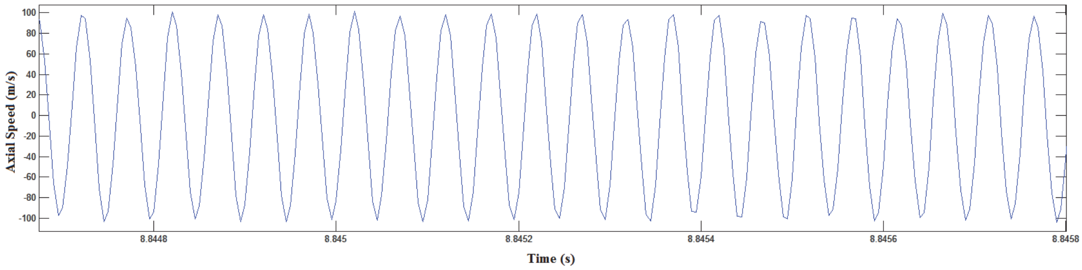


Figure 6: Axial speeds measured at the free-end of the tested specimen [4].

These results confirm the sinusoidal axial behaviour of the specimen. Rotational speeds measured at the notches are presented on Fig. 7:

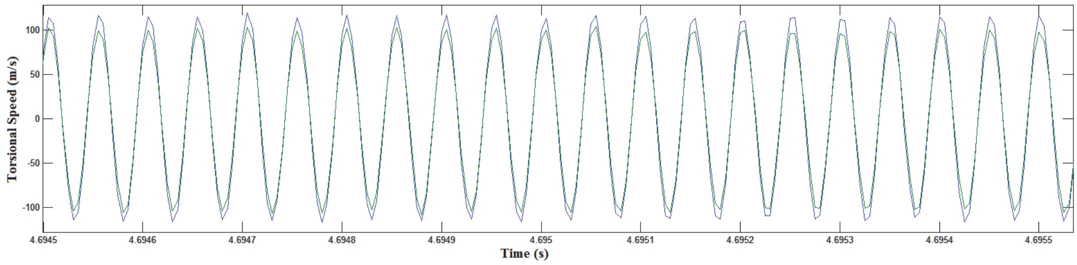


Figure 7: Rotational speeds measured at the specimen notches [4].

These results confirm the presence of a rotational behaviour of the specimen at its free-end, since both signals are in-phase and with very similar amplitudes. The difference in the amplitudes comes from the difficulty to guarantee that both lasers are measuring at the same distance from the center of the specimen.

Thermographic imaging

Because of the high frequencies used on this type of specimen testing, material temperature control represents a challenge on the completion of such tests [1, 5]. Still, because of the fact that the specimen heats up faster on regions where stresses are higher, thermographic imaging may be used to evaluate an approximation of the stress profile on the specimen. For this evaluation, the specimen was painted with high emissivity paint. First, the specimen was tested using an axial horn, which means that no rotation was being imposed to it. The results of this test are represented on Fig. 8, and axial testing of the specimen confirmed that it is correctly synchronized at the exciter excitation frequency and higher temperature are only observed in the middle throat.

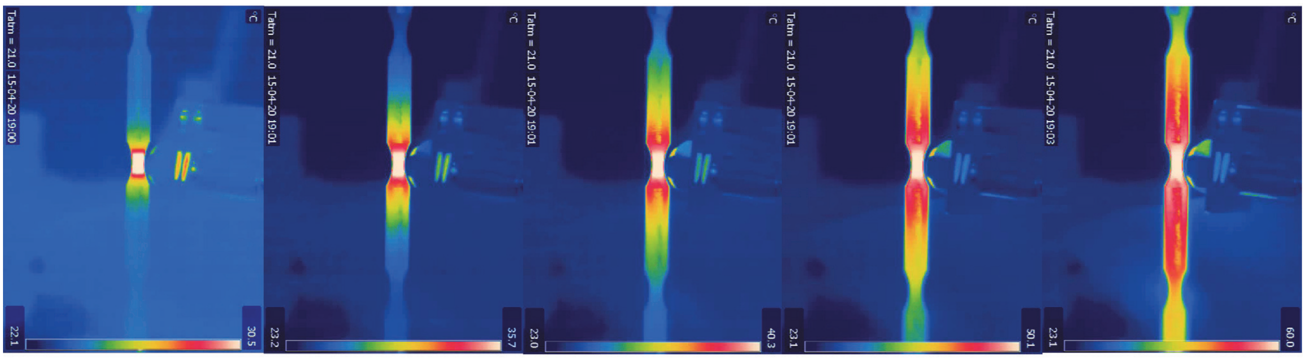


Figure 8: Thermographic image sequence of the axial tests performed on the specimen.

Second testing was produced with the developed horn, showing also higher temperatures occurring at the three throats with the highest one at middle throat, Fig. 9.

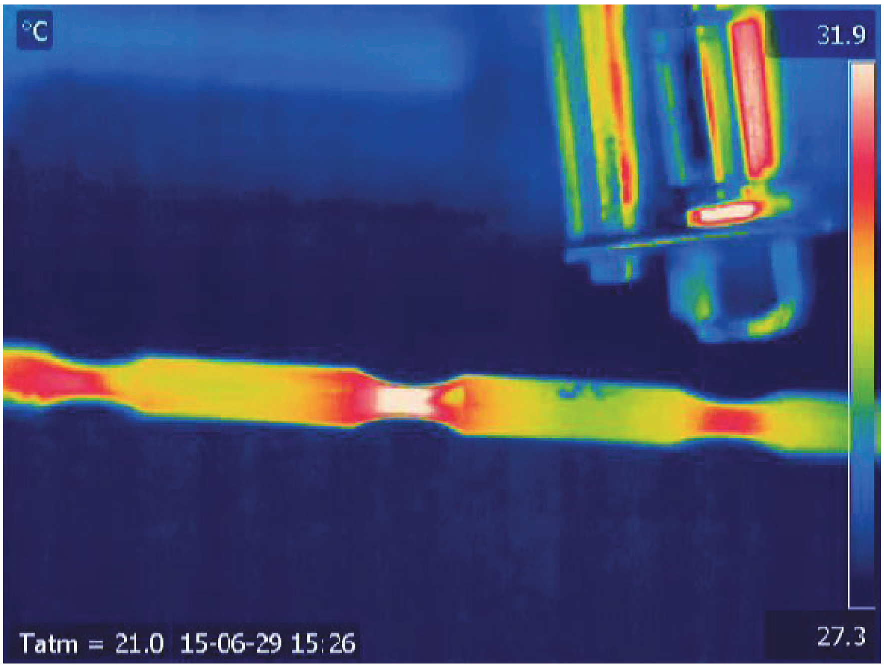


Figure 9: Thermographic image of specimen testing in tension/torsion.

Thermographic imaging of the developed specimen indicates that the specimen heats up on the three throats, but more on the middle one, due to the higher stresses on this region, as it was designed to behave.

Strain Results

To evaluate strains and stresses on the specimen middle throat, a rosette-type strain gage with three gages from TML, reference FRA-1-11, was used.

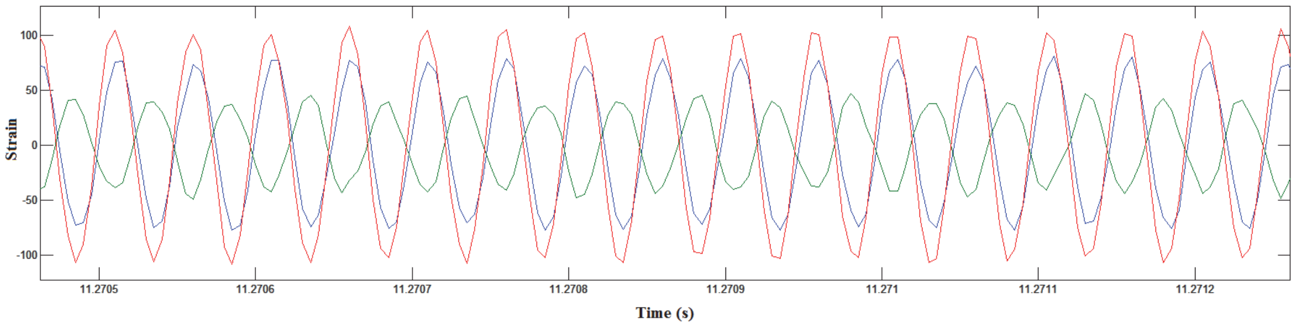


Figure 10: Signals from the rosette strain gage at the specimen middle throat.

Data from the strain gages during test was measured with a NI 6216 DAQ with the capability of acquiring two signals with a 200 kHz sampling frequency. Testing was produced at 20 kHz, using the biaxial horn and specimen and the results obtained from the three-way strain gage installed at the middle throat of the specimen are presented on Fig. 10. Data confirms the existence of a tension/torsion stress field in the specimen middle throat [4].

CONCLUSIONS

A device to produce biaxial testing at the VHCF regime, using a single axial ultrasonic exciter, has been developed and presented on this paper. This device (patent pending) consists of a horn and a specimen featured together in order to allow the biaxial testing.

Extensive experimental analyses were produced in order to qualitatively evaluate the dynamic behaviour of the device, specifically on the specimen. Laser vibrometer measurements have confirmed the correct axial and rotational behaviour of the free-end of the specimen. Thermographic imaging comproved that maximum stresses are registered at the middle throat. A three-way rosette type strain gage was installed on the middle throat in order to acquire strains and evaluate the stresses present on this region, confirming the existence of a biaxial stress state.
Further research is strongly suggested on this field, specifically on specimen control and behaviour, horn geometry influence on the τ_{xy}/σ_y stress ratio and final specimen dimension.

ACKNOWLEDGMENTS

This research was financed by Fundação para a Ciência e Tecnologia (FCT) under Portuguese National Project PTDC/EMS-PRO/5760/2014.

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