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Modal and strain experimental analysis to an improved axial-axial cruciform specimen for ultrasonic fatigue testing

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Abstract

Fatigue behavior for any material or composite is an ever-evolving complex subject of big engineering importance. Within the very high 10^6 to 10^9 cycle regime the use of ultrasonic fatigue has been a big research topic in recent years, ranging from all metals and composite studies, new experimental methods and induced stress states, to the frequency effect and associated fracture mechanics. Following the associated cruciform ultrasonic fatigue testing research in development, new and improved cruciform specimens were acquired and subjected to experimental analysis. The conducted fatigue cruciform testing method induces an axial-axial in phase stress state through the use of a piezoelectric ultrasonic testing machine built at Instituto Superior Técnico laboratories. A modal response analysis was performed within the frequency working range of the used piezoelectric transducer using a Polytec laser vibrometer. A modal calculation method termed Frequency Domain Decomposition (FDD) was adapted to the measured cruciform vibration displacements. The points of measure were in correlation to a previous published numerical research. The results were then compared to previous cruciform specimens' behavior and numerical results. Strain gauges were also used for the strain and stress study at the specimen's center. With both conducted experiments showing promising results, the new and improved specimens were led to fatigue failure and a preliminary fracture analysis made.

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Nomenclature

C-T	Compression-Tension
FDD	Frequency domain Decomposition
FE	Finite element
PSD	Power Spectral Density
T-T	Tension-Tension
UFT	Ultrasonic Fatigue Testing

1. Introduction

Fatigue behaviour and knowledge has changed throughout the years since it was first introduced, as well as the test methods. The conventional and standard tests performed to any material under fatigue study use forced cyclic damage, most commonly through electromechanical or hydraulic machines. Such studies apply low cycle and high cycle fatigue tests to an ever-increasing range of materials and composites. In metals, it was initially considered that no failure beyond $10^6/10^7$ cycle range would ever occur. It was later proven that such concept was untrue in certain cases but due to the low cycling frequency that common machines could apply fatigue damage the study of the very high cycle fatigue (VHCF) regime was highly unreliable in time and energy wise (Bathias (1999)). To solve such issue Mason built a high frequency machine capable of reaching high frequencies in the 20 kHz range (Bathias and Paris (2005)). Such fatigue testing method was denoted as ultrasonic fatigue testing (UFT). In recent years such type of fatigue test became a specific area of fatigue research, having a high range of experimental variances and studies, mainly to metal samples.

UFT applies resonance concepts to reach high stresses at high frequencies. The first designed machine induces a material sample tension-compression fatigue with stress ratio R = -1. With the growth of the research investment in this area, there has been an array of different tests and machines built and tested (Bathias (2006)): from different stress ratios, corrosion (Pérez-Mora et al. (2015)) and high temperature (Wagner et al. (2012)) environments in tension-compression to the creation of ultrasonic pure torsion (Marines-Garcia, Doucet, and Bathias (2007); Nikitin, Bathias, and Palin-Luc (2015)), bending (Xue et al. (2007)), multiaxial bending (Brugger et al. (2016)), multiaxial tension-compression/torsion (Costa et al. (2017)) and the testing method used in this study, ultrasonic cruciform fatigue testing (Montalvão and Wren (2017)).

1.1. Ultrasonic cruciform fatigue testing

To reach a functioning testing method for ultrasonic fatigue machines, modal analysis of all components is required. Taking the tension-compression ultrasonic machine as an example, all components including booster, horn and specimen, are modally designed to have specific resonant modes at the vibrator transducer frequency of work. The horn and booster amplify the axial displacements induced by the transducer and the specimen is designed so to have one region of higher stress for the fatigue study.

The same concept was followed for the designing of cruciform fatigue testing at ultrasonic frequencies (Montalvão and Wren (2017)). Cruciform geometries were modally studied to reach designs capable of achieving resonance at the piezoelectric transducer with the displacement and consequent strain of interest at one region.

An already conducted initial study tested two different cruciform geometries (R. da Costa et al. (2019)). The two created geometries were made to induce transverse biaxial stress tension-compression state: in-phase tension-tension (T-T) and out-of-phase Tension-Compression (T-C). Both specimen's geometry rules and design followed an optimized geometry made by Baptista et al. (2015). New ultrasonic cruciform specimens with non-unitary biaxiality ratios are also being developed and under study Montalvão et al. (2019).

The first experiments showed a functioning C-T cruciform specimen. Conducted laser experiments displayed the predicted deformed resonant shape. Thermal analysis reinforced such measurements and proved a higher induced stress in the specimen's center. With such results the specimen was led to fatigue failure successfully, showing a similar fatigue fracture shape to out-of-phase numerical results from the studies of Baptista, R. A. Cláudio, et al. (2016); Baptista, R.A. Cláudio, et al. (2016). The T-T cruciform specimens showed a non-predicted resonant deformed shape and the heat generated at the specimen's center was not as high as would be expected. A deep modal analysis was made with laser measurements as reference. The related issue was determined to be a neighbour resonant mode with displacement compliance to the axial displacement transmitted by the horn to the specimen.

In this work new aluminum specimens were manufactured from the same material but with a different geometry dimension combination. These specimens were made so to have higher frequency difference between the mode of interest and the parasite mode. To understand if the parasite mode impact was still considerable, a modal experimental analysis was conducted to the new specimens as well as strain gauge measurements. All tests were repeated with two different horns, a tapered and hyperbolic horn. The hyperbolic horn has a higher area reduction leading to a higher displacement amplification.

All test experiments took the resonant mode of interest and the parasite mode modal shape into consideration. Figure 1 shows both modes modal shape under consideration of one T-T cruciform.

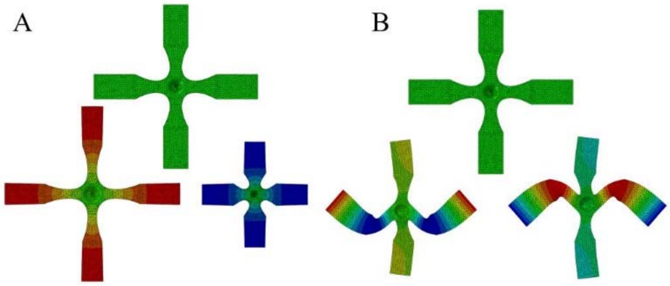

Fig. 1. Cruciform T-T resonant modal shapes (a) Mode of interest; (b) parasite mode (R. da Costa et al. (2019)).

2. Experimental modal analysis

For any common modal analysis experiment there are key important measurement and excitation requirements. In a standard frequency modal analysis of a given component or structure a shaker is used for the excitation of the resonant modes, force sensors are connected between the exciter and the structure, and sensors for measuring the resulting displacement behavior are carefully placed. The type of vibration measurement can be displacement, velocity or acceleration. The shaker induces a range of frequencies and with the results a complete modal analysis can be calculated. Therefore, a displacement, a force and an excitation are required to obtain the complete modal behavior of a given structure or component.

Due to the way the components set is connected (booster, horn, specimen) and other operational constraints, it was not possible to attach force transducers in such a way that the dynamic response would not be changed. Therefore, force transducers could not be used as in Experimental Modal Analysis. Instead, to calculate and obtain the modal behaviour of the ultrasonic component's set a method applied in large structures (buildings, bridges) was conducted, the Frequency Domain Decomposition method (Brincker and Zhang (2009); Zhang, Wang, and Tamura (2010)).

FDD is majorly applied to buildings due to the unknown natural forces values present, as the wind. Its theory bases itself on the relationship between the unknown inputs and measured responses through the power spectral density (PSD) that is decomposed by taking into a set of single degree of freedom systems using the singular value decomposition. By not requiring the determination of present forces to calculate a simpler modal behavior characterisation, an understanding of the existing modal frequencies and modal shapes of the ultrasonic fatigue set was obtained.

A Polytec vibrometer measuring velocity was placed in key high displacement locations of the two mentioned modes to better detect and characterise them. An excitation in all frequency range of work of the transducer was conducted as the excitation sequence. The transducer's controller also provided the detected resonant mode frequencies within its working range. The frequencies provided by the transducer were compared to the FDD model and FE results.

Two lasers were active during frequency scanning for all tested cruciform T-T specimens. FDD and frequency scan results of a new and first T-T cruciform designs with the tapered horn are presented in figure 2. The FDD was only calculated in the considered 10 kHz to 30 kHz range of frequencies. Laser 1 relates to a high displacement region of the mode of interest and laser 2 in a high displacement region of the parasite mode.

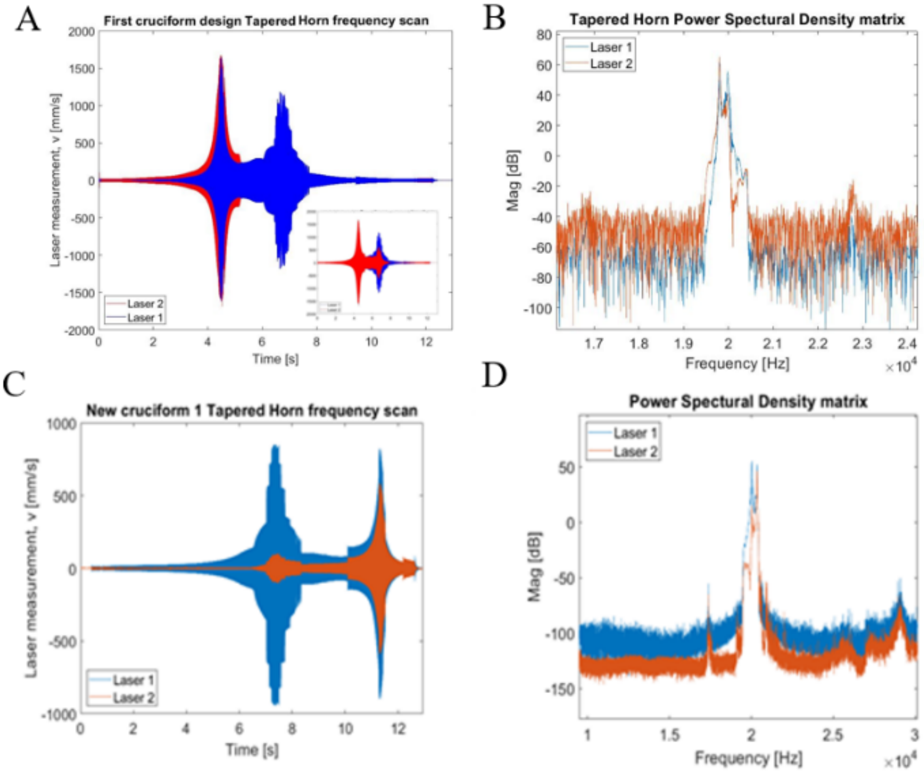

Fig. 2. Modal experimental analysis of the new cruciform specimen (A) frequency scanning; (B) FDD PSD frequency response result; and the first design: (C) frequency scanning; (D) FDD PSD frequency response result.

For each tested specimen, FDD, FE and transducer's determined frequencies of the mentioned resonant modes were compared. The FDD and FE modal shape relations between the measured points were also compared.

Between each T-T cruciform specimen geometry both the obtained frequency scan, modal shape and frequencies were compared to better characterize the improvement made.

3. Strain gauge measurements

Once the laser measurements and FDD modal results validated the designs obtained from FE models, rosette strain gauges were attached to the specimen's center, which is the highest stress region in the specimen. The strain gauges were aligned with the stress tension-tension directions. Several transducer power settings were applied, and the strain values recorded with both mentioned horns. Simultaneously, temperature control was made by a thermal camera. Figure 3 shows a rosette strain gauge applied to a new T-T cruciform specimen.

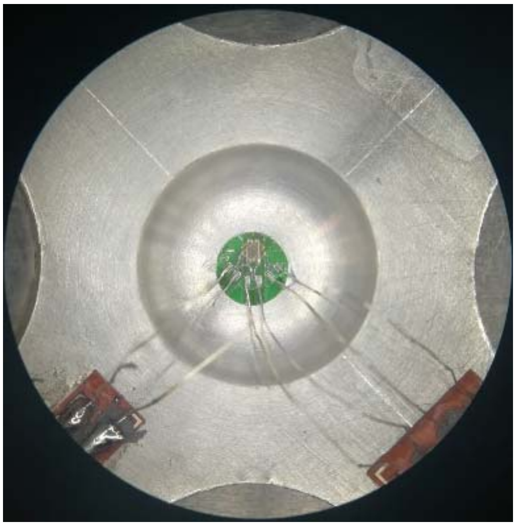

Fig. 3 Attached rosette strain gauge to a new cruciform T-T specimen.

Strain results were subsequently transformed to stress values. Figure 4 shows stress results for the same cruciform tested in figure 2 with both mentioned horns.

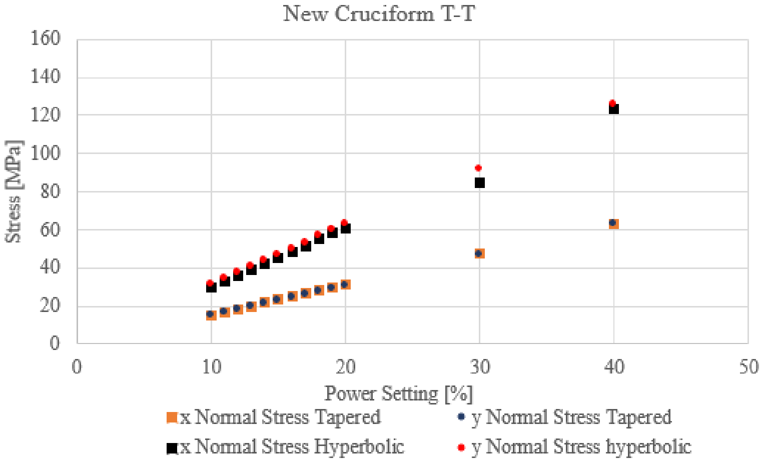

Fig. 4 Stress axial-axial (x-y) amplitude for several transducer power setting for both tapered and hyperbolic horns.

4. Results and Discussion

Just from the frequency scanning the two modes under study were detected in all tested specimens, showing that even in the improved specimen the parasite mode was still present within the frequency range of the transducer but with considerably lower influence in the pretended fatigue resonant mode.

Analytical modal analysis FDD method showed interesting results. The frequencies of the mode of interest and several neighbor parasite modes out of the frequency range of the transducer were possible to be determine. Comparing the old and new T-T cruciform specimens the FDD showed higher frequency difference and lower influence of the parasite mode but it is still within the frequency range of the transducer.

Strain measurements showed under 8% difference between the axial-axial stresses in all tested specimens and in both horns. No considerable shear stress was measured. Comparing strain values, the lower radius of the hyperbolic horn proved, for the same applied power, higher amplification of the transducer displacements leading to higher stresses, but higher difference between axial-axial stresses was found. The higher difference was unpredicted since the parasite mode showed higher frequency difference and lower modal shape influence in the hyperbolic horn. The cause of the higher difference is currently being studied.

5. Conclusions

The employed modal experimental analysis method showed to be a viable tool for determining close parasite resonant modes and modal shapes. With FDD experimental analysis method any new complex geometry created for UFT can be better studied to achieve its correct functioning.

The new and improved specimens show a modal shape considerable closer to the pretended final geometry. Much smaller displacement associated from the parasite was detected and a higher frequency difference between modes.

From strain measurements no considerable shear stress and no higher than 8% difference was obtained between each axial-axial direction.

Thus, a reliable T-T cruciform specimen was achieved using a new and deeper analysis methodology for any complex UFT specimen geometry.

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