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Dimensional stability of materials subject to random vibration

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ABSTRACT

High precision stable structures are potentially vulnerable to dimensional instability induced by exposure to random vibration. There appears to have been little work in the literature to understand or mitigate structural dimensional instability induced by random vibration. To gain more insight into this issue, a novel test was recently developed to assess the plastic strain response in the 10^{-5} to 10^{-6} range for structural materials subjected to specific random vibration loads. The test was based on a four-point bending configuration with an applied random base excitation. Two types of material were tested – an Al alloy and a CFRP. This paper presents the test setup and results in detail. The Al alloy samples were found to grow slightly in length during testing, due to a small non-symmetry in the applied load. An FEA model of the test setup was solved in the time domain for a sequence of cyclic loads whose amplitude was based on their probability of exceedance in the random environment. This model, using nonlinear kinematic hardening, was able to predict the residual strain response observed during testing with good accuracy. The main implication of this finding is that ultra stable structures subject to random vibration should be assembled in the most strain-free state possible to avoid loss of dimensional stability due to cyclic hardening.

1. Introduction

High-performance optical bench structures must typically exhibit high levels of dimensional stability to meet system performance requirements. Optical components, aligned precisely in laboratory conditions, must maintain their relative translational and rotational positions to a high level of accuracy to avoid problematic aberrations and defocus during operations in the field. Such structures may be required to survive exposure to significant levels of shock and vibration over their operational lifetimes, without recourse to optical re-alignment. For example, optical structures destined for space use must contend with a brief but harsh period of random vibration during launch, caused by aero-acoustic noise, rocket engine noise and stage separation events. Re-alignment in orbit is not always an option, necessitating the need for structures with highly reliable dimensional stability.

A typical optical bench structure might be required to support a pair of mirrors around 1000 mm apart, with a positional accuracy of several 10 s of microns. Thus we are interested in material plastic strain in the 10^{-5} to 10^{-6} region (as opposed to the 0.2% more typical of structures with no dimensional stability requirements).

There is a good body of work in the literature on static microyield strength (defined here as the stress at which 10^{-6} permanent strain is observed) in metallic materials. An established procedure for investigating microyield behaviour is to apply successive load-unload cycles in increasing increments, measuring the residual strain at the zero-load points between each cycle [1]. Microyield information can be found in the literature for a number of materials used in stable structures [2,3]. Repeated stress cycling above this value may result in a residual strain response dominated by material hardening, an effect that is well understood and relatively easy to model [4]. The literature contains an abundance of hardening data for a range of materials, though mostly in the 0.2% permanent strain region and above.

For composite materials of interest in stable structures, some work has been done on the effect of stress cycling on dimensional stability, though mainly due to hygrothermal cycling rather than mechanical vibration (for instance [5–7]). Wolff [8] suggests that transverse microcracks in the matrix material are largely responsible for dimensional changes in such circumstances. Nairn [9] points out that the stress induced by thermal cycling is multi-axial (being due to thermal expansivity differences between the constituent materials), while vibration-induced stresses can be uni-axial.

Material yield behaviour can depend on the rate of the applied strain. To test the effect of strain rate, the Hopkinson Bar method has been used for many decades [10], and again there is an abundance of material data (for example, see [11]). However this test applies a single shock pulse, rather than a series of repeated cycles. The time-dependency aspect of composite yield behaviour can be further complicated by viscoelastic strain recovery [12].

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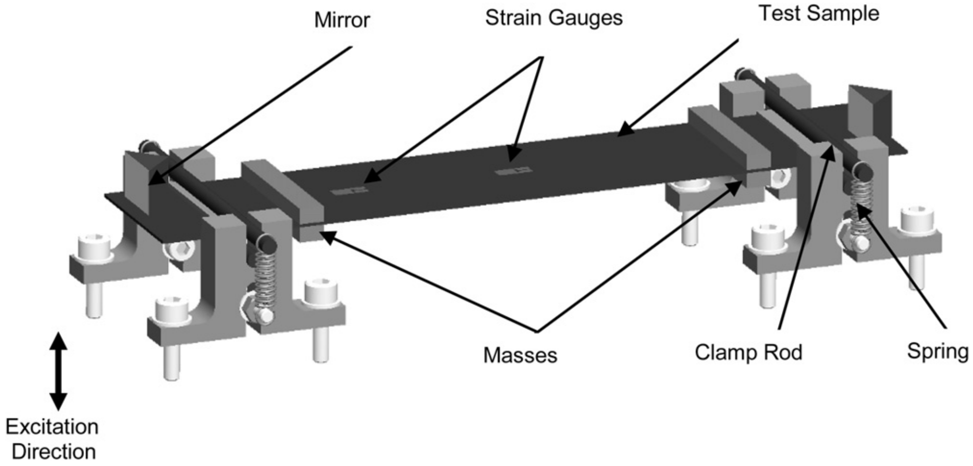

Fig. 1. Test sample support.

For random vibration effects, the literature is mainly concerned with fatigue damage. There are well-established methods for predicting gross failure in materials under cyclic loading using S–N curve data and Miners Cumulative Damage Ratio [13]. However there appears to be a paucity of material data (or procedural methods) for plastic strain in the 10^{-5} to 10^{-6} region resulting from random cyclic loads.

A structure subject to harmonic excitation is relatively straightforward to analyse. With simple mathematical models (using mass, stiffness and damping parameters), it is possible to deterministically predict stress amplitudes which do not vary from cycle to cycle. Such problems lend themselves to the use of tension-compression cyclic plasticity test data to predict residual strain.

However predicting plastic strain resulting from random vibration can be problematic and there does not yet appear to be an established method for performing these calculations. The difficulties to carry out predictions arise for two reasons. Firstly, it can be difficult to determine a useful stress response to compare with an established yield criterion. The nature of the excitation results in cyclic stresses at a number of different frequencies and amplitudes simultaneously, giving rise to a complex stress state that requires a probabilistic description. It is relatively straightforward to obtain a solution for stress components that are Gaussian with a zero mean. Combining these – to produce a von Mises equivalent resultant for instance – produces a probability distribution that is no longer Gaussian with a zero mean [14], complicating the calculation [15,16].

Secondly, it is not clear how to use such a stress response to predict residual plastic strains. Is the residual strain response dependent on instantaneous high peak stresses that might occur only a few times during the vibration exposure, or is it more likely to depend on lower-amplitude stresses cycles that may occur many thousands of times (or both)? One possible way to tackle this is to use an approach similar to Miner's rule for fatigue analysis, and combine the effects of several stress amplitude levels. The number of cycles of each would be dependent on the probability of exceedance during exposure. This could then be used to approximate a time-history stress response that could be input as sequential load cases in an FEA model that incorporates cyclic hardening. This approach is used later in this paper.

The objectives of this research are to investigate plastic strain behaviour in materials subject to random vibration loading and to asses whether this can be predicted using FEA. The investigation takes a macroscopic view, examining the effects that would typically be of most interest to stable structures practitioners rather than focusing on the microscopic events that cause such effects. A novel test setup has been developed to directly measure the residual strain response in material test samples subject to bursts of random vibration. Two different materials were tested using this setup. This article starts with a detailed description of the test specimens, setup, test procedure and metrology techniques. The results of the test campaign are then discussed in detail. The results for one material are then compared with a finite element model that makes use of nonlinear kinematic hardening with constants based on static test data. The article is concluded with an evaluation of the test and metrology setup, and a summary of the main findings including material behaviour and FEA modelling.

2. Test setup

The main goal for the test setup was to simulate the dynamic stress conditions that might typically be seen in a structural element of an optical payload during launch or environmental testing.

The test setup comprised a material sample in strip form, simply supported with a pair of masses inboard from the support points (see Fig. 1). When subject to a random base excitation at the support points, the first modeshape of the samples approximates the deformed shape of a four-point bend test. Three identical samples of each material were tested simultaneously in order to assess result variability. Equivalent static tests were conducted, also in a four-point configuration.

The material samples were flat panels of size 250 × 50 mm, and 1 mm thick. Two materials were tested – aluminium alloy 2024 T3, and a CFRP that is widely used in space instruments. The Al alloy sample was subject to a stress relief heat treatment (200 °C/1 h). The CFRP used Advanced Composited Group LTM123 cyanate ester resin with M55J fibres. The layup was (0°, 90°, and ±45°), and a low-temperature cure cycle was used with a long postcure.

Simple support was achieved by clamping the samples between a pair of cylindrical rods at either end. To avoid damage to the samples at the contact points, aluminium contact pads were bonded to the samples. The pads at one end were made slightly concave in order to prevent the samples from slipping axially during the test. This is shown in Fig. 2. Extension springs (see Fig. 1) were used to impose a constant clamping force of 40 N at either end. This was determined to be sufficient to prevent gapping at this interface under the highest loads tested.

The masses were bonded-on stainless steel blocks. For the aluminium samples, the masses at either end were 0.050 kg at either end; for the CFRP samples, they were 0.031 kg. For the aluminium