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Stress based non-destructive evaluation using thermographic approaches: From laboratory trials to on-site assessment

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ABSTRACT

Vibration based loading has been successfully used to facilitate out of laboratory inspections using thermoelastic stress analysis enabling stress based non-destructive assessment of structures. An initial plate study verified the technique. A laboratory demonstrator of the on-site implementation was created to facilitate the development and assessment of a suitable loading device. The developed system was then taken on-site at a coal fired power station during a scheduled outage period. Vibration loaded thermoelastic stress analysis was successfully applied to welds in high pressure steam drain lines in-situ.

1. Introduction

The most common techniques currently applied in non-destructive evaluation (NDE) in industry are generally ultrasound (UT) based approaches. Essentially, UT is a 'point-by-point' measurement technique so inspections of large areas can prove extremely time consuming [1]. In the power industry, as with many others, the most common procedure used for the identification of defects in welds is phased array UT [2]. The process for weld inspection and reporting is laborious involving comparison to a reference case and manual plotting of results. As such the time consuming nature of UT leads to the inspection of selected sites only. The results of thermoelastic stress analysis (TSA) form images hence there is no need to make drawings to estimate damage size rather the data may be directly assessed and stored. While UT may successfully locate and size defects it cannot provide directly any prognostic information on how the defect is affecting the structural performance. There is a clear case for an alternative on-site inspection technique to be used in a complementary manner with UT that can provide rapid inspections and prognostic information. TSA is a full-field thermographic technique which relates the thermal response of a component subjected to cyclic loading, within the elastic limits of the material, to the sum of the principal stresses [3]. TSA data can be captured in as little as 10 s. Perhaps more importantly, TSA provides visual information as a stress map which shows directly the redistribution of the stresses resulting from any defect enabling it to be used as both a diagnostic and, with some addition material property information, prognostic tool. Although TSA is a surface technique, sub surface damage will cause a redistribution of the stresses which, depending on the defect depth, will modify the thermoelastic response from the surface. The present paper focuses on the development of TSA as a new stress based NDE approach which could be used for standalone inspections or in conjunction with traditional NDE approaches.

The aim is to use TSA for the inspection and analysis of in situ in service components. Therefore an alternative means of loading has been devised based on exciting the component at its resonant frequency during data collection to generate sufficient stress to provide a measurable thermoelastic response. Some early work [4] used the Stress Pattern Analysis by Thermal Emissions (SPATE) system to identify delaminations in a fibre reinforced polymer composite cantilever beam. It was shown at 13.5 kHz the delamination caused a change in the thermoelastic response, but there were significant limitations imposed by SPATE system data capture rate. By the late 1990's detector capabilities had significantly improved enabling much higher thermal, spatial and temporal resolution. A study [5] using a more modern array based detector showed that a measureable thermoelastic response could be obtained from aluminium alloy, steel and polycarbonate beams up to the fourth mode of vibration. More recently, vibration-based

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excitation has been used on aircraft composite sandwich panel components to explore the possibility of using TSA as an NDE technique [6].

In the present paper a new approach is proposed for NDE of ferritic steel pipes using TSA, although it should be noted that the procedure is applicable to all metals. Firstly the underlying idea is demonstrated in the laboratory environment on clamped thin aluminium plates. The challenge of generating sufficient load for much stiffer components than previously studied is addressed through the design of a laboratory demonstrator that incorporates a thick walled pipe representative of that used in steam plant for electricity generation. A new means of excitation is devised to provide the necessary cyclic loading that does not require electrical power so it can be deployed on-site. Finally, a detailed account of the preparations for and the installation of the new system during a scheduled outage at EDF Energy's coal fired power station at West Burton, UK is provided. The system is used to inspect a number of steam lines welds and its viability is demonstrated for use in on site applications. It is shown that TSA can be used to obtain the stresses in the pipework and that TSA can be used as NDE system in the challenging environment of a coal-fired power station. The work represents an important advance in NDE assessment as the stresses in the component are evaluated directly without recourse to models. The work described in the paper provides the basis for developing a generic stress based NDE system that can be used in a wide range of service applications.

2. General considerations for TSA

TSA uses an infra-red (IR) detector to monitor the surface temperature changes of a cyclically loaded component, which are related to the sum of the principal stresses as follows [2]:

$$\frac{\Delta T}{T} = -K(\Delta\sigma_1 + \Delta\sigma_2) \tag{1}$$

where T is the surface temperature, ΔT is the temperature change caused by the thermoelastic effect, $\Delta\sigma_1 + \Delta\sigma_2$ is the sum of the change in the principal stresses (generally referred to as the 'stress sum') and K is the thermoelastic constant of the component material.

$$K = \frac{\alpha}{\rho C_p} \tag{2}$$

where α is the coefficient of thermal expansion, ρ is the density of the material and C_p is the specific heat at constant pressure.

In the present paper a FLIR SC5000 IR system was used. The system incorporates a 256 × 320 InSb photon detector array with a pixel pitch of 30 × 30 μm, capable of recording at 383 Hz at full frame in the spectral range of 3–5 μm. The thermal sensitivity of the detector is 20 mK, which is reduced to approximately 4 mK with application of the lock-in processing used in TSA. Data was collected and processed using the manufacturer's software Altair and Altair LI. As an example typical values of T and ΔT when testing at room temperature are room temperature (i.e. around 293 K) and of the order of 50 mK respectively.

In TSA the lock-in processing uses a 'reference signal' from the loading system to correlate the IR detector response and the applied stress [3]. Hence, both ΔT and T are provided, so the change in the sum of the principal stresses is obtained as per Eq. (1). If isentropic conditions prevail in the specimen the thermoelastic response, ΔT, occurs in-phase (compression) or 180° out-of-phase (tension) with the stress change. Deviation from isentropic conditions results in an out-of-phase response indicating that Eq. (1) is not valid. Therefore the phase data is a very useful and straightforward means of validation, as it is obtained alongside ΔT and T from the lock-in processing.

Typically the cyclic loading necessary to facilitate TSA is imparted using a servo-hydraulic test machine. The reference signal for the lock-in is obtained from the test machine load cell. This tethers TSA to a laboratory environment and hence a different means of imparting the load is required. It is proposed that a vibration based excitation at the component natural frequency could be used to generate the thermoelastic response. Natural frequency excitations have the potential to be much higher frequencies than typically studied with TSA therefore appropriate integration time (IT) [7] and frame rate must be selected. IT is akin to exposure time in photography, i.e. a short IT must be used to collect data from a fast moving scene to avoid blurring. However, a shorter integration time means fewer photons impinge on the detector resulting in a lower detector response. There is a trade-off between noise content and image quality, when selecting an appropriate IT. The frame rate should obey the Nyquist-Shannon criterion relative to the loading frequency. A further consideration is the source of the reference signal to perform the lock-in. There are several possibilities including force transducers, accelerometers as well as self-referencing where the collected IR data is used as the reference source. A range of reference signals were trialled and are discussed alongside each experiment in the following sections of the paper.

In all thermographic assessments there is a requirement to observe a surface of high and uniform emissivity; this is typically achieved through application of a thin layer of matt black spray paint. Substantial previous work has been carried out on selection of paint for the purposes of IR thermography. In most TSA studies RS matt black spray paint from RS Components has been used and a detailed characterisation was carried out in [8]. It has recently emerged that a change in the formula of RS matt black has occurred, reducing the adhesion to the surface of components and providing a significantly lower emissivity, which renders it unsuitable for quantitative TSA studies. To find a suitable replacement, a number of readily available alternative black paints were tested for surface finish and adhesion. From this down select the most suitable paint was identified as Electrolube EMBP400 matt black. To evaluate and compare the response of the Electrolube paint the thermoelastic constant of steel was determined and compared to an identical specimen coated with the original RS matt black paint. The test specimens were 40 × 3 mm in cross sectional area. A cyclic load of 6 ± 5 kN was applied to the specimens with a loading frequency of 10 Hz. Table 1 shows the calculated thermoelastic constant for the steel using both paints. To compare the results from the specimens with the new paint with

Table 1
Alternative paint study results.

Paint	Adhesion	Surface finish	Thermoelastic constant (Pa^{-1})	Normalised thermoelastic constant
Electrolube EMBP400 Matt Black	Very good adhesion to metal substrate. Sprayed in a fine mist	Smooth, even surface finish	3.62×10^{-12}	0.978
New formula RS Matt Black	Good adhesion, sprayed in a fine mist	Reflective and showed surface textures	4.03×10^{-12}	1.087