EXPERIMENTAL STUDY OF THE INFLUENCE OF CORROSION ON THE NONLINEAR ELASTIC PROPERTIES OF METALS

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ABSTRACT

In the frame-work of damage detection by means of nonlinear ultrasonic spectroscopy (NEWS), a comparative study of corroded and intact samples is presented. A thin metallic plate of 2024-T3 aluminium alloy was subjected to corrosion damage in salt fog chamber. Nonlinear elastic characterization is carried out by means of a resonance analysis. In particular, the nonlinear amplitude dependence of frequency and harmonic distortion is used.

INTRODUCTION

In contrast with classical material nonlinearity, attributed to anharmonicity of the microscopical lattice, the so called non-classical nonlinearity has been studied in connection with damaged materials. Defects such as fatigue or corrosion cracks may be interpreted as mesoscopic contact units with two possible states (open or closed), depending on loading conditions. Macroscopically, this is reflected as an hysteretic contribution to the material elastic properties, leading to end-point memory [1]. In stationary vibrations, linear shift of the resonance frequency, quadratic third harmonic generation and frequency mixing are signatures of these effects, and have been studied in materials such as plexyglass [2], slate [3], concrete [4], and more recently, in fatigued metal alloys [5]. In [6], a model for flexural vibrations which includes the main features of hysteretical nonlinearity was proposed and analyzed in connection with glass plates with thermal shock damage. In this paper, the same model is applied to nonlinear behaviour of low frequency resonant flexural vibrations of thin Aluminium plates, both intact and with corrosion damage. Finally results, problems and future trends are discussed.

EXPERIMENTAL

Samples preparation

The samples prepared for this study consist of bare 2024-T3 aluminum alloy panels of 250 x 75 x 1 mm approximated dimensions. This alloy is commonly used in aerospace for structural purposes and has been chosen for this study due to its facility to corrode because of its high Fe and Cu content.

To induce pitting corrosion on the samples surfaces, the coupons were introduced in a Salt Fog Chamber meeting the requirements of the MIL-PRF-85582 standard. Salt-fog testing is an environmental accelerated test that exposes the alloy panels to a humid, salt-containing atmosphere for at least 168-336 hours. Salt spray corrosion fog testing provides a controlled means of assessing the performance of materials in a corrosive atmosphere. This test is the standard aviation test to determine the effectiveness of material finishes and protective anticorrosion coatings, or to determine the effects of the salt deposits on the alloy performance.

For this study the specimen was kept inside the chamber for 336 hours. A second panel without any exposure to the corrosive environment was used as reference during the nonlinear tests.
The salt fog atmosphere creates pitting corrosion on the aluminum alloys surface. This type of corrosion is characterized by the removal of metal at localized sites on the surface and results in small holes or cavities. The pits are first noted because of the white or gray powdery deposits, similar to dust, which blotsches the alloy surface. If the deposit is cleaned away, tiny pits or holes can be seen in the surface. In figure 1, both intact and corroded samples can be observed.

**Fig. 1: Samples**

### Characterization procedure

Two PZT patches are bonded to the surface of the studied sample in a unimorph configuration. The system is driven by a Yokogawa FG300 signal generator, and the velocity response is obtained by a Polytec vibrometer through a Tektronix TDS3034B oscilloscope, to be further processed (Figure 2). The vibratory response at the fundamental frequency, second and third harmonic are recorded.

**Fig. 2: Experimental setup**

For small voltage driving, the PZT patches induce a flexion torque which depends linearly in the electric field. However, the strain levels needed to observe nonlinear effects forces us to drive the actuator over this range. As reported in [7], piezoelectric materials present nonlinear hysteretical behaviour, due to a mesoscopic polarization domain switching dynamics, and will have the characteristic effects of end point memory as well. The analysis presented here must then be comparative.
RESULTS:

Two characteristic effects of hysteretic nonlinearity have been considered. First, the system is excited at frequencies near a resonance, but where no internal resonances occur. A linear shift of the resonance is measured and quantized. Next, harmonic distortion is studied. Flexural vibrations are dispersive, meaning that harmonics are not, in general, resonant. The excitation frequency range is chosen in such a way that the fundamental response is not resonant, while response at the second, or third harmonic are. This allows the quantification of harmonic generation. Finally, we comment the situation where the fundamental is resonant and there exists an internal resonance.

Excitation of a direct resonance:
According [6], a linear variation of resonance frequency with amplitude is assumed, the fundamental response, free of internal resonances, is well described by:

\[
|A| = \frac{2\delta_1 \omega_1 A_{\text{max}}}{\sqrt{\left(\Omega^2 + \omega_1^2 (1 - \hat{\Gamma}_1 |A|)^2 \right)^2 + \left[2\delta_1 \Omega + \omega_1^2 \frac{1}{3\pi} \hat{\Gamma}_1 |A|\right]^2}}
\]

where \(\omega_1\) is the eigenfrequency of the linear system near frequency \(\Omega\), and \(\delta_1\) the anelastic attenuation parameter. \(\hat{\Gamma}_1\) represents the hysteretic contribution to the stationary response. The \(\hat{\Gamma}_1\) contribution to attenuation (second factor in the denominator) has been neglected, and the experimentally obtained resonance curve (normalized by the maximum amplitude) will be fit to:

\[
|\alpha| = \frac{2\delta_1}{\sqrt{\left(\omega^2 + (1 + r - \hat{\beta} |\alpha|)^2 \right)^2 + [2\delta_1 \omega]^2}}
\]

where \(\omega = \Omega / \omega_1\), \(a = A / A_{\text{max}}\), and \(\hat{\beta} \equiv \beta A_{\text{max}}\), where the \(\beta\) parameter is proportional to \(\hat{\Gamma}_1\), and \(r\) is a small correction factor for the estimated linear eigenfrequency.

Comparison of both samples for a direct excited resonance near 2700 is shown in figure 3.

Indirect excitation of an internal resonance:
The system is excited in the range of 2900-2950Hz. For both intact and damaged sample, there exists resonant modes of the structure such that \(f_2 \approx 2f_{\text{exc}}\) and \(f_3 \approx 3f_{\text{exc}}\). Internal resonance is illustrated in Figure 4. For weak nonlinearity, harmonic response can be fit to:
\[ |A_2| = \frac{|A_1|^2}{\sqrt{(2\Omega)^2 - \omega_2^2 + (2\Omega)^2 [2\delta_\omega \omega_2]^2}} \]

\[ |A_3| = \frac{|A_1|^2}{\sqrt{(3\Omega)^2 - \omega_3^2 + (3\Omega)^2 [2\delta_\omega \omega_3]^2}} \]

where \( \omega_2, \omega_3 \) are the angular frequencies of the resonant modes near \( 2\Omega \) and \( 3\Omega \) respectively, \( \Omega \) being the excitation frequency.

As shown in figure 5, quadratic behaviour of second and third harmonic are obtained, in accordance of theory, but no significant difference is obtained.

The effect of an internal resonance:

Due to small differences between the properties of the samples, it is possible for one of them have an internal resonance (intact) while the other one does not (damaged). While the nonlinear properties of both samples have been proved to be similar, the presence of an internal resonance affects the behaviour of the frequency shift. At large amplitudes frequency shifts are comparable and affected only by the direct resonance, but a range where the internal resonance may dominate is observed in the intact case.
CONCLUSIONS

Two samples with slightly different nonlinear properties have been compared. One of samples was corroded in salt fog chamber; the second sample was kept intact and used as reference. Resonance frequency and harmonic generation have been quantified, and the possibility of studying nonlinear interactions of vibration modes for damage assessment has been proposed. Further characterization requires the development of an adequate model.

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References:


