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On-line detection of fatigue cracks using an automatic mode tracking technique

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Abstract

Experimental fatigue tests usually require large testing times. In addition to the resulting increased time-to-market, the large fatigue test time also implies that any structural health monitoring technique that is used should be automatic. When using the modal parameters as damage indicators, an important amount of user interaction is still needed to separate physical poles from computational ones. In this paper, an experimental framework will be developed to automatically track the health of the structure on-line with the performance of fatigue tests. The modal parameters are tracked using a combination of the maximum likelihood estimator and an auto-regressive model. Since confidence levels on the modal parameter are available it is possible to detect if damage is present. In addition, the quasi-static stiffness with computed confidence levels is also used as a damage indicator. The proposed techniques are demonstrated on a steel beam with a propagating fatigue crack.

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1. Introduction

The research presented in this paper is contained in the framework of the SLAT TRACK project, sponsored by the Flemish Institute for the Improvement of Scientific Research in Industry (IWT) [1]. In this project the damage detection, life prediction and redesign of a slat track—which extends the surface of an airplane wing during takeoff and landing—is considered. An important task in this project is the performance of experimental fatigue tests and the structural health monitoring during these fatigue tests. Since the Slat Track has a very high fatigue strength, testing times can typically take several weeks. This testing time increases further when one periodically interrupts the fatigue test to examine the structural health.

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The purpose of this paper is to develop a structural health monitoring technique, which can be used on-line, i.e., without interrupting the fatigue test. The method will be validated by means of experimental fatigue data of a steel beam. Because these measurements are also used to illustrate the theory, a short description on the measurement set-up is given first in Section 2. A first step in the proposed technique is the development of an excitation signal for on-line fatigue experiments (see Section 3). The main issue here is the use of a multi-sine excitation signal which consists of two parts: a low-frequency part (e.g., in-service loads) to obtain fatigue damage and a higher frequency part (typically 50 Hz–1 kHz) to estimate the modal parameters which are used to monitor the structural health. In Section 4, the proposed automatic mode tracking technique is developed. Because the algorithm is based on the maximum likelihood estimator (MLE), it can be shown that the accuracy of the results is optimal. At the same time, confidence bounds of the estimated modal parameters are available. Finally, in Section 5, the use of quasi-static features with confidence intervals to detect damage will be investigated. Conclusions of the research are drawn in Section 6.

2. Experimental set-up

The experimental set-up of the fatigue experiment on a steel beam is shown in Fig. 1. The load is applied using a large B&K® type 4810 shaker. The force is measured with the aid of a PCB® type 208B02 force cell while both displacement and velocity are measured with a Polytec® laser vibrometer. The control and the processing of the measurements are done in Matlab®.

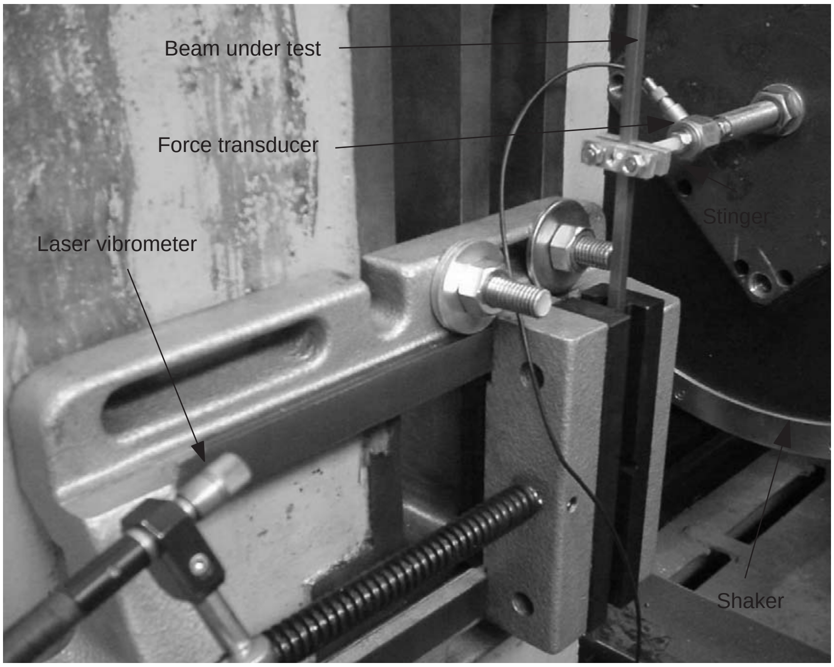

Fig. 1. Experimental set-up of the fatigue experiment.

3. An excitation signal for on-line fatigue experiments

3.1. Introduction

In this section an excitation signal will be developed that:

(1) enables to perform fatigue loading and damage detection at the same time;
(2) gives improved quality dynamic measurements while performing the fatigue tests.

To reach these goals, the designed excitation signal $f(t)$ will be composed of two multi-sine signals, i.e.,

$$f(t) = f_1(t) + f_2(t) = \sum_{i=1}^{N_1} A_i^1 \sin(2\pi i f_0 t + \varphi_i^1) + \sum_{i=N_1+1}^{N_1+N_2} A_i^2 \sin(2\pi i f_0 t + \varphi_i^2). \quad (1)$$

The response of the excitation signal $f(t)$ is the displacement $x(t)$ which can again be decomposed into two signals x_1 and x_2 corresponding to the responses of f_1 and f_2, respectively (assuming that the system is linear).

In all measurements performed with the test set-up, the fundamental frequency f_0 is taken equal to 2 Hz, while $N_1 = 10$ and $N_2 = 1014$. The multi-sines f_1 and f_2 are nothing more than two periodic signals with the same period, however, with 2 different frequency contents. f_1 on the one hand, is a low-frequency signal (the highest component is typically a few Hz) which is used to obtain fatigue damage. On the other hand, f_2 is used to excite the structure and measure the response x_2 in order to be able to estimate the modal parameters (therefore f_2 typically has energy from a few tens to one kHz). The choice of f_1 and f_2 will be discussed in Sections 3.2 and 3.3, respectively.

By making use of composed multi-sine signal f:

(1) no leakage occurs (the signal f is perfectly periodic);
(2) the modal parameters can be estimated after every cycle of the fatigue load signal (because the periods of f_1 and f_2 are the same).

3.2. Low-frequency fatigue signal

Traditionally, fatigue tests were performed using single-frequency sine load tests until rupture of the structure to obtain experimental signal–noise (S–N) curve data. This procedure is very time consuming and the prediction of the fatigue life under operating conditions from the S–N curves can be difficult.

More recently, the trend is to perform fatigue experiments by applying in-service loads on a test rig, and evaluating the number of life cycles that can be performed until breakdown of the structure. This procedure is standard practice in automotive fatigue testing and contains the following steps:

(1) measure the operational load of the structure under operating conditions;
(2) transform the load data into so-called *rainflow cycles* [2];

(3) filter the rainflow cycles (eliminate all cycles that do not contribute significantly to the total damage);
(4) finally, a reduced set of load data samples is reconstructed from the filtered rainflow cycles. This can be done either without [3] or with [4] preservation of the time order of the original signal.

The final result of the latter procedure is a set of n discrete load data points $f_d(1), \ldots, f_d(n)$. Using the following procedure (Eqs. (2) and (3)) it is possible to compute an over-sampled multi-sine signal f_1 (N_{over} times over-sampling) which interpolates at these load data points:

$$[F_d(0)F_d(1), \ldots, F_d(n-1)] = fft([f_d(1), \ldots, f_d(n)]), \tag{2}$$

$$[f_1(1), \ldots, f_1(nN_{over})] = ifft\left(\left[F_d(0), \ldots, F_d\left(\left\lfloor \frac{n-1}{2} \right\rfloor\right) \overbrace{0, \ldots, 0}^{(N_{over}-1)n \ \text{zeros}} F_d\left(\left\lfloor \frac{n-1}{2} \right\rfloor + 1\right), \ldots, F_d(n-1)\right]\right). \tag{3}$$

The analog multi-sine f_1 has the same damage contents as the discrete load data points (and thus is representative for the in-service loads).

3.3. High-frequency dynamic signal

While the low-frequency load signal is usually large (to obtain fatigue), the high-frequency excitation must be kept small in order not to disturb the fatigue loading process (e.g., less than 1% of the fatigue load). Therefore, in order to improve the SNR of the measurements, it is essential that the energy in the signal f_2 is optimized, without enlarging the signals amplitude. If a multi-sine is used for f_2, this can be done by computing phases φ_i^2 of the signal $f_2(t)$ which give rise to an optimal crest-factor, CF.

$$CF(f_2) = \max(|f_2(t)|) \Big/ \frac{1}{T} \int_0^T |f_2(t)|^2 \, \mathrm{d}t. \tag{4}$$

If two signals have the same amplitude, the one with the lowest crest factor will contain more energy and consequently the SNR will be higher. Dedicated algorithms exist to optimize the crest factor of the multi-sine excitation signal [5–7]. Using the algorithm described in Ref. [5] the SNR of the measurements of f_2 could be improved with almost 10 dB compared to a signal with random phases.

4. Damage detection using mode tracking

4.1. Introduction

Damage detection using mode tracking involves two problems:

(1) automatically separate physical from computational modes;
(2) sort out the corresponding modes between two measurements.

In the literature, some contributions have been made in the past regarding the first task (see Ref. [8], and the references therein). The second task is however more difficult to tackle and fewer publications are available on the subject (some time-domain tracking methods are used in the civil engineering community [9]). The main difference of our approach with existing methods is:

(1) the accuracy of the estimated poles is optimal;
(2) confidence levels on the tracked poles are available (this is very helpful to quantify if damage has occurred or not).

In the next sections the algorithm proposed to solve tasks one and two will be described.

4.2. The proposed algorithm

The proposed algorithm uses an on-line least squares AR algorithm in parallel with an off-line ML algorithm. The ML estimator (which is used after every fatigue cycle) gives optimal estimates and confidence levels are available. However, the tracking of the ML estimates is difficult. For this purpose an AR model of the variation of the poles is used. This means that the final damage indicators are the ML estimates (and the confidence levels), while the AR model merely serves to separate the physical from the computational ones and sort the corresponding poles of two different cycles. Algorithm 1 describes the steps in the proposed mode tracking technique. The algorithm is graphically illustrated in Fig. 2.

Algorithm 1. *Mode Tracking*

- Continuously excite the structure with the excitation signal f developed in Section 3.
- Put $i = 0$;
- WHILE (No failure of the structure occurred)

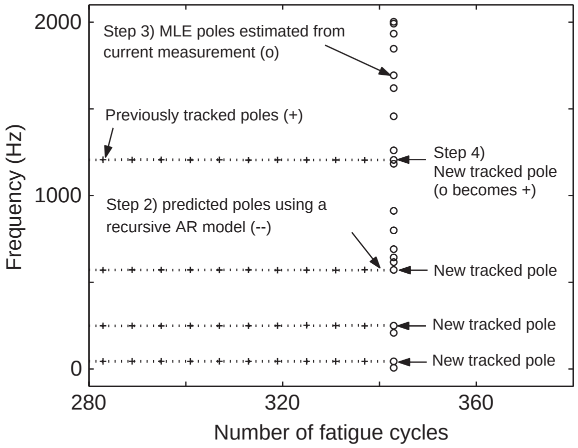

Fig. 2. Illustration of the proposed mode-tracking scheme.

(1) Measure the force f and displacement x (or velocity, or acceleration) signal.
(2) Predict the physical system poles p_i^j from the past tracked poles $p_0^j, \dots, p_{i-1}^j$ using a recursive AR model which is solved in the least-squares sense [10]:

$$p_i^j + a_1^j p_{i-1}^j + \cdots + a_k^j p_{i-k}^j = e_i^j \tag{5}$$

with p_i^j the jth physical pole at iteration step i and k the AR model order. (When $i \leqslant k, p_i^j = p_0^j$, and for $i = 0$ the physical poles p_0^j are given as inputs.) No forgetting factors are used.
(3) Estimate a high-order modal model (with poles q_i^j for $j = 1, \dots, N_p$ with $N_p > N_m$) from the current measurements using the MLE [11].
(4) Select the physical poles $\tilde{q}_i^j$ for $j = 1, \dots, N_m$ by taking the N_m MLE poles closest to the predicted poles $\{p_i^j | j = 1, \dots, N_m\}$.
(5) Put $i = i + 1$;

- END.

Because the MLE is used in the proposed tracking scheme, the resulting poles have a high accuracy and confidence levels are available. Moreover, the procedure is fully automatic.

4.3. Experimental mode tracking results

For the measurements on the steel beam, Step (1) took 2.5 s (five averages of a 2 Hz signal) and Step (2) up to (4) took about 0.5 s. Therefore, a measurement could be done every 3 s (which is equal to six fatigue cycles). The FRFs and uncertainties of both displacement and velocity signals are shown in Fig. 3. Note that as could be expected, the quality of the velocity signal is a lot better at higher frequencies. To test the robustness of the proposed tracking procedure, the poorer quality displacement signal is used, while the velocity signal only serves as a reference.

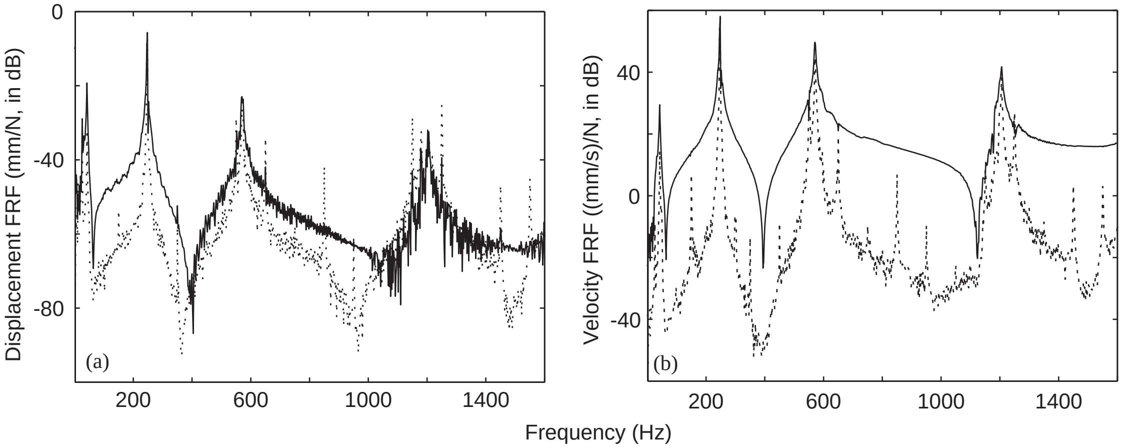

Fig. 3. Measured FRFs and FRF uncertainties for (a) displacement and (b) velocity signal. Key: –, FRF; ···, FRF standard deviation.

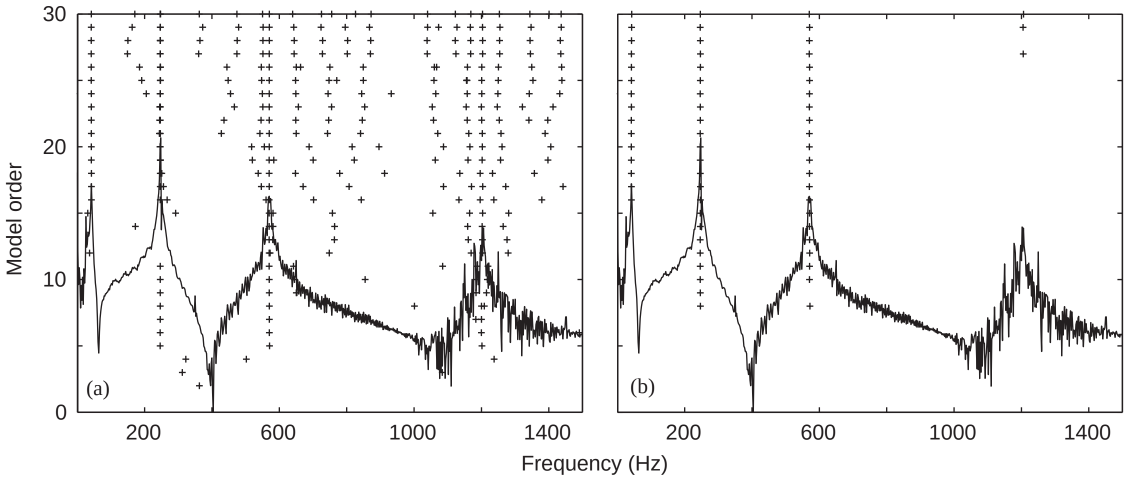

Fig. 4. LSCE Stabilization diagrams (a) LSCE (without using noise information); (b) LSCF (using noise information). Key; +, estimated pole; –, FRF.

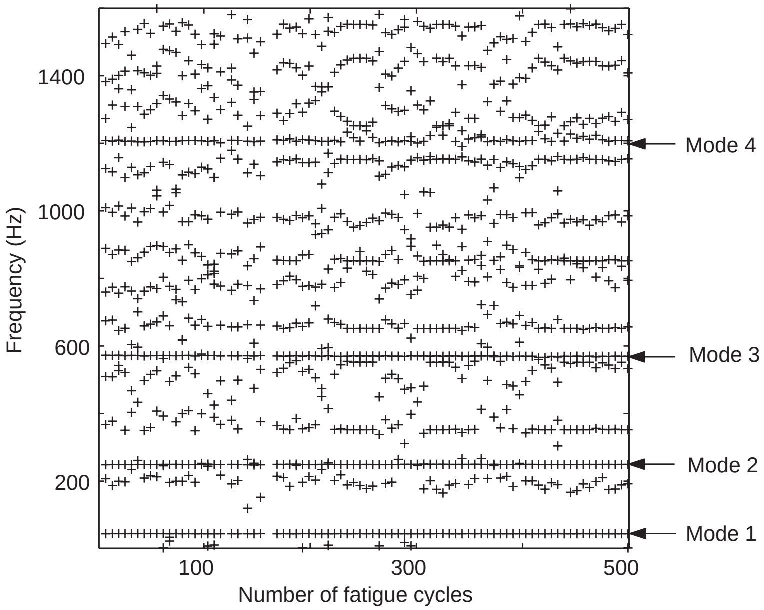

Fig. 5. All estimated poles from which the poles to track have to be extracted.

From Fig. 4, where stabilization diagrams of the LSCE [12] and the MLE are shown, it is clear that the use of noise information significantly improves the quality of the estimated poles. Because of the high noise level near resonances (which occur because the force drops) the LSCE estimator places several poles at locations where only one mode is present.

Because stabilization diagrams require a great deal of user interaction to separate the physical poles from the computational ones, they cannot be used for on-line health monitoring. Using the tracking method presented above, it was possible to accurately monitor the evolution of the

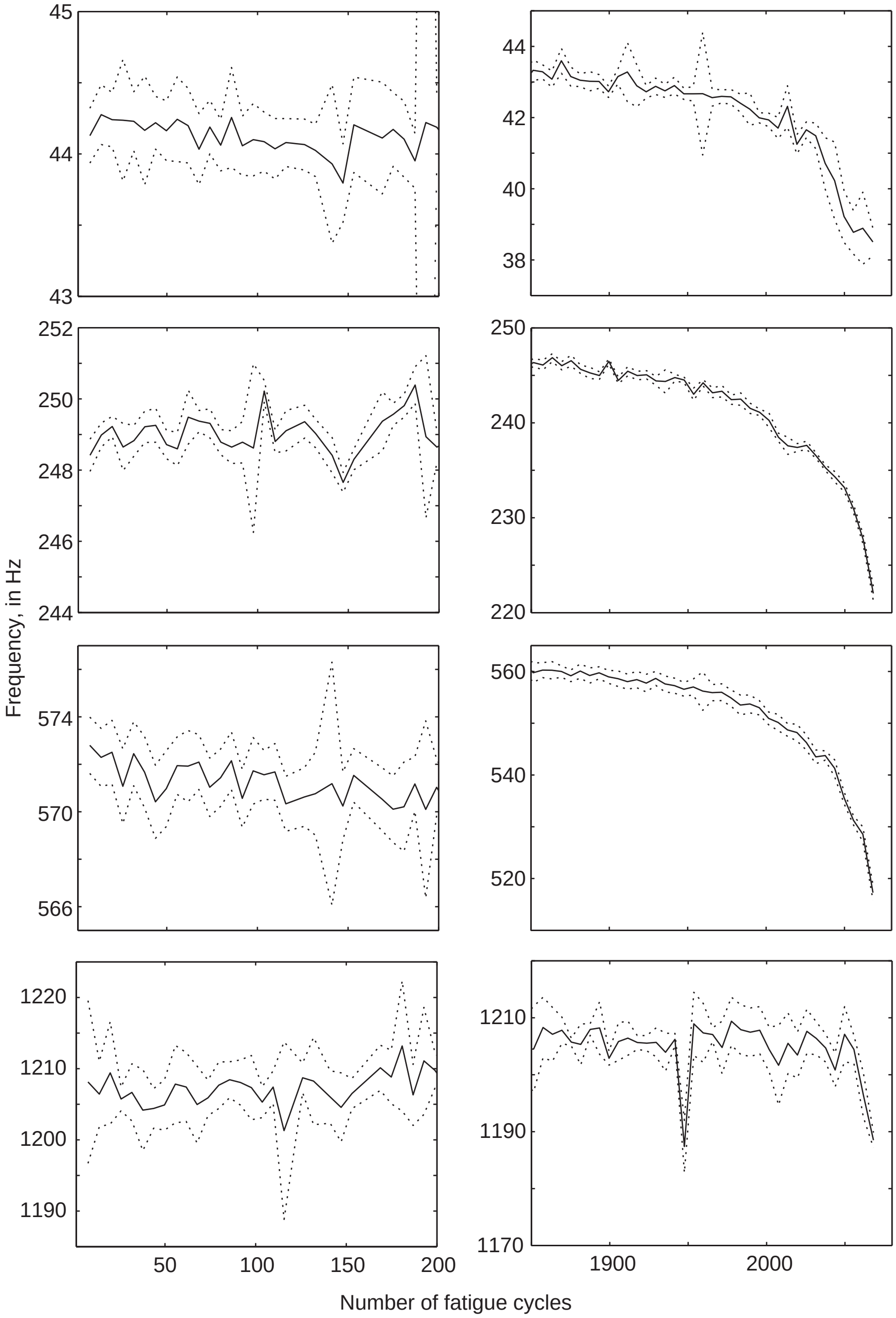

Fig. 6. Frequency of the four tracked poles (using the proposed algorithm) as a function of the number of fatigue cycles: (a) first 200 cycles; (b) last 200 cycles. Key: –, resonance frequency; ···, 95% confidence limits.

fatigue process. The proposed method was used to track four physical poles out of the set of 20 estimated poles (see Fig. 5). In Fig. 6 (b) it can be seen that the first three modes changed about 10% in the last 200 cycles before failure (which occurred at 2075 cycles). During the first 200 fatigue cycles (Fig. 6 (a)) there was almost no change of the resonance frequency outside the confidence interval.

5. Quasi-static damage detection

5.1. Theory

The forces f and the displacements x generated by the low-frequency signal x_1 can be used to estimate the static stiffness k_i (at iteration step i) and its uncertainty due to measurement noise. For a quasi-static condition (this means that the first resonance frequency is significantly higher than f_{N_1}, the upper limit of the low-frequency signal f_1) the computation can be performed: assume $F(f_0), \dots, F(f_{N_1+N_2})$ and $X(f_0), \dots, X(f_{N_1+N_2})$ represent the measured spectra of the forces and displacements. Then low-frequency forces f and displacements x can be reconstructed using: $f(t_n) = \sum_{k=1}^{N_1} F(f_k)\exp(i2\pi k f_0 t_n)$ and $x(t_n) = \sum_{k=1}^{N_1} X(f_k)\exp(i2\pi k f_0 t_n)$. Using a linear regression the static stiffness can be computed from $f(t_n) = kx(t_n) + c$ for $n = 1, \dots, N_t$. Because the standard deviations of $F(f_k)$ and $X(f_k)$ are available (*Note* that five periods are measured), the standard deviations of $f(t_n)$ and $x(t_n)$ can also be computed. From these standard deviations, the uncertainty of k_i is calculated.

5.2. Experimental results

The results of the static monitoring technique are quite surprising. Even for a low number of cycles (see Fig. 7(a)), a decrease in the stiffness is visible. Moreover, for last 200 cycles before failure of the beam, the decrease in stiffness is impressive (a decrease with a factor 15). Note also that the confidence levels are significantly smaller than for the poles from dynamical measurements.

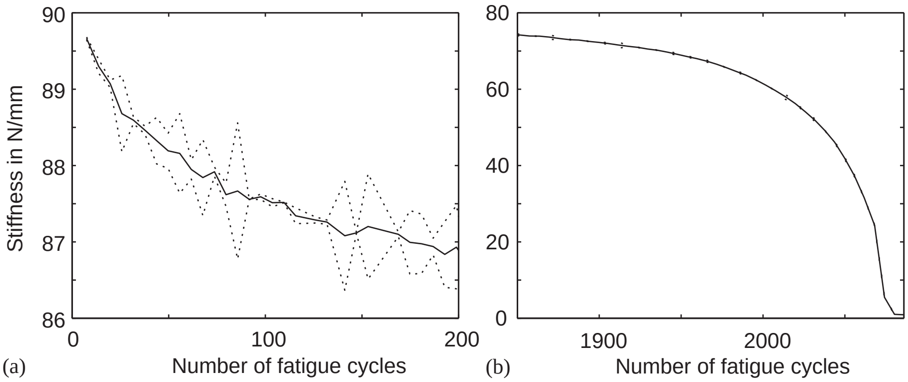

Fig. 7. Static stiffness as a function of the number of fatigue cycles: (a) first 200 cycles; (b) last 200 cycles. Key: –, stiffness; ···, 95% confidence limits.

6. Conclusions

In this paper, an experimental framework was developed to track the health of a structure on-line with the fatigue tests. This gives rise to reduced fatigue experiment times, since the fatigue test do not have to be interrupted to carry out classical non-destructive testing. Because the MLE was used, the technique also works in the presence of high noise levels. In addition, with the proposed technique, confidence levels are available which allow a distinction between changes in resonance frequencies due to noise on the one hand, and changes due to a structural change on the other hand. Finally, it appeared that for the current set-up, quasi-static features where much more sensitive to damage than dynamic system parameters (i.e., resonance frequencies and damping values).

Acknowledgements

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