Structural Damage Detection Using Non-Classical Vibro-Acoustic Approaches

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Abstract

The paper demonstrates how non-classical approaches can be used for structural health monitoring. Wavelet-based modal analysis, various non-classical nonlinear acoustic techniques and cointegration are used for damage detection. These approaches are illustrated using various examples of damage detection in metallic and composites structures.

Keywords: structural damage detection, fatigue cracks, delamination, time-variant modal analysis, nonlinear acoustics, cointegration

1. Introduction

Modern engineering structures utilise new stiffer and stronger materials (e.g. composites) and integrate various hybrid and complex elements (e.g. controllers, electronics, sensors). Such structures often operate under undesirable and harsh conditions. Therefore inspection and maintenance of such structures is a major challenge to designers and end-users. Although many reliable damage detect methods in Structural Health Monitoring have been developed over the last few decades challenges still remain due to ageing (e.g. aircraft structures), limited access (e.g. offshore wind turbines), environmental/operational conditions, intermittent nature of damage and data ambiguity. For example, the main difficulty with the application of ultrasonic guided waves for damage detection in composite materials is that signal changes - produced by defects - tend to be small when compared with those obtained from other effects (e.g. structural features, environmental conditions, variable load) and so are difficult to detect reliably.

Finding a non-classical or unconventional solution could help to overcome many problems and challenges in Structural Health Monitoring. Taking advantage of undesired phenomena (e.g. nonstationarity or nonlinearity) is one of the possible approaches. Looking outside boundaries is the second possible approach used to overcome difficult research problems. The ability to see the problem from a new research perspective is often fundamental to creating breakthroughs in engineering. The paper illustrates how these two non-classical approaches can be used for structural damage detection.

The paper consists of three major parts. Section 2 demonstrates how the time-variant Frequency Response Function can be used to detect abrupt stiffness change in building structures. Examples of damage detection - based on non-classical nonlinear acoustics - are demonstrated in Section 3. The application of cointegration – originally developed in econometrics – for the removal of undesired operational trends from damage detection data is presented in Section 4. Finally, the paper is concluded in Section 5.

2. Detection of Abrupt Changes to Natural Frequencies of Structures

Analysis of vibration and dynamic testing are two critical components of structural design. Traditional vibration analysis relies either on time-domain or frequency-domain approaches. Various methods have been developed for vibration analysis, e.g. [1-3]. Classical vibration analysis assumes that systems/structures are time-invariant, i.e. the output for such systems does not change with a delay in the input. However, this assumption is not valid for many engineering systems with time-variant (global or local) coefficients in the corresponding governing equations. Traditional concepts, analytic methods and experimental techniques of linear time-variant analysis cannot be applied to such systems since modal analysis has been developed for linear time-invariant systems and is not appropriate for time-variant systems. Conventional definitions of modal parameters are not valid for time-variant systems. Varying mass and/or stiffness leads inevitably to varying natural frequencies and mode shapes whereas system responses to harmonic excitations are non-stationary. Such systems do not have even impulse response functions in the classical sense.

A new, non-adaptive concept of the Frequency Response Function (FRF) - based on wavelet analysis - for time variant systems was proposed in [4]. The classical input-output relation was transformed to the wavelet domain to obtained the wavelet-based FRF as

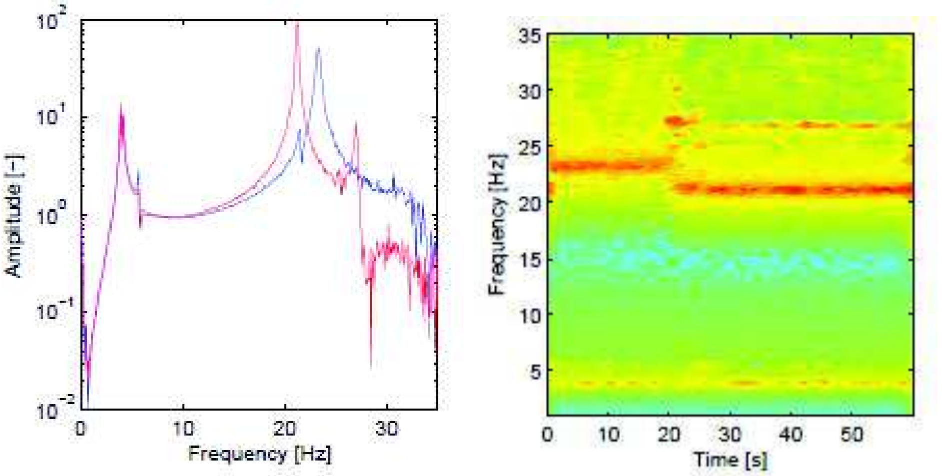
$$H_{\psi}(a,b) = \frac{W_{\psi}[y(t)]}{W_{\psi}[x(t)]} \tag{1}$$

where $W_{\psi}[y(t)]$ and $W_{\psi}[x(t)]$ are the wavelet transforms of the output y(t) and input x(t), respectively. The interpretation of the method - based on the generalised wavelet convolution [5] - was proposed in [4]. Although the wavelet-based extension of the FRF is quite natural and relatively simple, the computation procedure is not as straightforward as Equation (1) implies. Additional data post-processing (i.e. time-frequency domain averaging, ridge extraction, crazy climbers optimisation algorithm) needs to be used in practice in order to obtain the smooth estimate of *H(a,b),* as shown in [6]. The amplitude and phase of the new FRF can be analysed to identify time-variant systems [6] and/or detect abrupt changes to modal parameters [7]. The latter problem is relevant to damage detection since damage often results in local stiffness reduction, leading to the abrupt change of natural frequency. Detection of abrupt changes in natural frequencies from vibration responses of time-variant systems is a challenging task due to the complex nature of physics involved.

The application of the wavelet-based FRF for structural damage detection can be illustrated using a simple example that involves vibration analysis of a three-floor building model. The building model – shown in Figure 1 - consists of three plates connected with four continuous vertical rods. The top plate is additionally connected to the middle plate by a taut string (without any slack) that has been cut in the experiment to simulate an abrupt change of stiffness resulting from structural damage due to earthquake or landslide.

Figure 1. Time-variant three-floor building model

Firstly, the classical experimental analysis was used to analyse vibration of the structure. The random excitation and vibration response were Fourier-transformed to obtain the classical FRF for the undamaged and damaged structure. The results -presented in Figure 2a- clearly show that the FRF changes once the structure is damaged. The snapped string leads to local stiffness reduction that results in the shift of one natural frequency. An additional mode can be also observed when the structure is damaged. Despite all these changes to the classical FRF, structural damage can be identified reliably only when the actual moment of abrupt change of stiffness can be detected. This is illustrated in Figure 2b, where the magnitude of the wavelet-based FRF is presented. The application of the wavelet transform leads to the exact detection of time of the abrupt change of stiffness. The string is snapped after approximately 20 seconds when the experimental modal test is performed. This moment can be clearly identified in the magnitude and phase of the wavelet-based FRF. The magnitude of the wavelet-based FRF also exhibit the change of natural frequency and the extra vibration mode.



(a) (b)

Figure 2. Modal analysis for the three-floor building: (a) classical FRF magnitude for the undamaged (blue line) and damaged (red line) three-floor building; (b) wavelet-based FRF magnitude.

3. Structural Damage Detection Using Non-Classical Nonlinear Acoustics

Ultrasonic testing used for damage detection relies on linear phenomena of wave propagation (e.g. reflection, scattering). Recent years have shown a considerable growth of interest in nonlinear damage detection ultrasonic approaches. Damage-related nonlinear ultrasonic phenomena are quite sensitive but not easy when used for damage detection. This mainly due to the fact that nonlinearities may result not only from cracks but also from other non-damage related effects such as: friction between elements at structural joints or boundaries, overloads, material connections between transducers and monitored surfaces, electronics and instrumentation measurement chain.

Nonlinear acoustics is particularly attractive to detect contact-type damage. This includes fatigue cracks in metals or delamination/debonding in composites. Nonlinear acoustics methods used for damage detection include classical and non-classical approaches. The former methods utilise higher harmonics generation or frequency shifting. These methods are well established and used for many years for material testing. The latter approaches are based on various recently developed non-classical nonlinear phenomena observed in materials. These methods use for example frequency mixing and various approaches based on wave modulation. Non-classical nonlinear phenomena are relatively weak in undamaged and remarkably strong in damage material. Physical mechanisms behind these phenomena are often complex and not easy to explain, as reviewed in [8].

The method based on vibro-acoustic wave modulation [9-11] is one of the most widely used non-classical techniques. When a monitored structure is excited modally (f_L - low-frequency excitation), an ultrasonic wave (f_H - high-frequency excitation) is introduced, as illustrated in Figure 3. Then ultrasonic responses are used for damage detection. Intact (or undamaged) structures exhibit mainly two frequency components associated with the high- and low-frequency excitations. In contrast damage (e.g. fatigue crack in metals or delamination in composites) leads to additional vibro-acoustic wave modulations that can be observed as a pattern of sidebands in ultrasonic response spectra. The frequencies of these additional sideband components are equal to

$$f_{s_n} = f_H \pm n f_L \tag{2}$$

where $n = 1,2,3, \ldots$. The presence of sidebands and their amplitude indicate possible damage and its severity, respectively. It is important to note that often modulation sidebands can be observed in undamaged specimen due to intrinsic (e.g. material) nonlinearities. However the amplitude of these sidebands increases significantly when damage is present in the structure.

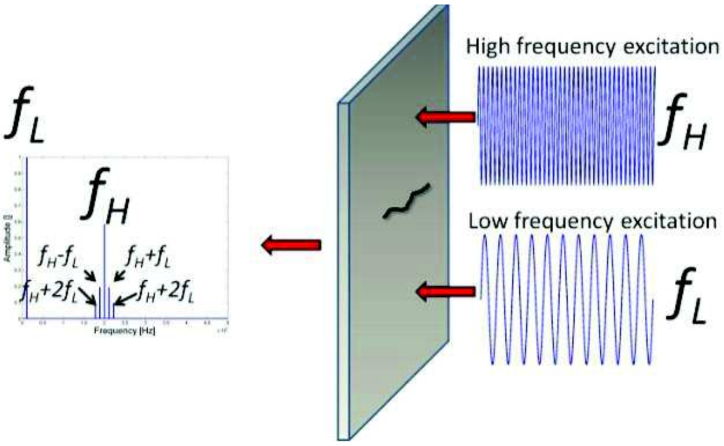


Figure 3. Nonlinear vibro-acoustic wave modulations used for damage detection

The intensity of modulation R = (A1 + A2)/A0, where A1, A2 are the amplitudes of the first pair of sidebands and A0 is the amplitude of the carrier ultrasonic spectral component, can be used as a damage indicator.

Figure 4 demonstrates the application example. An a rectangular (400×150×2 mm) aluminium plate was in the presented application, as shown in Figure 4a. Low-profile *PI Ceramics* PIC-155 piezoceramic transducers of diameter 10 mm and thickness 1 mm were surface-bonded to the plate and used for ultrasonic excitation and response measurement. A *PI Ceramics* PL-055.31 piezoceramic stack actuator (5 × 5 × 2 mm) was additionally bonded on the plate for low-frequency modal excitation. Once the plate was modally excited with the frequency equal to 625 Hz (corresponding to one of the strongest 10th vibration mode), an ultrasonic wave of 60 kHz frequency was introduced to the plate. Figure 4b shows the ultrasonic response spectra for the intact (upper part) and cracked (lower part) plate. A clear pattern of modulation sidebands can be observed when the plate is damaged (11 mm fatigue crack). The intensity of modulation R, defined above, can be used to investigate the severity of damage, as illustrated in [9-11].

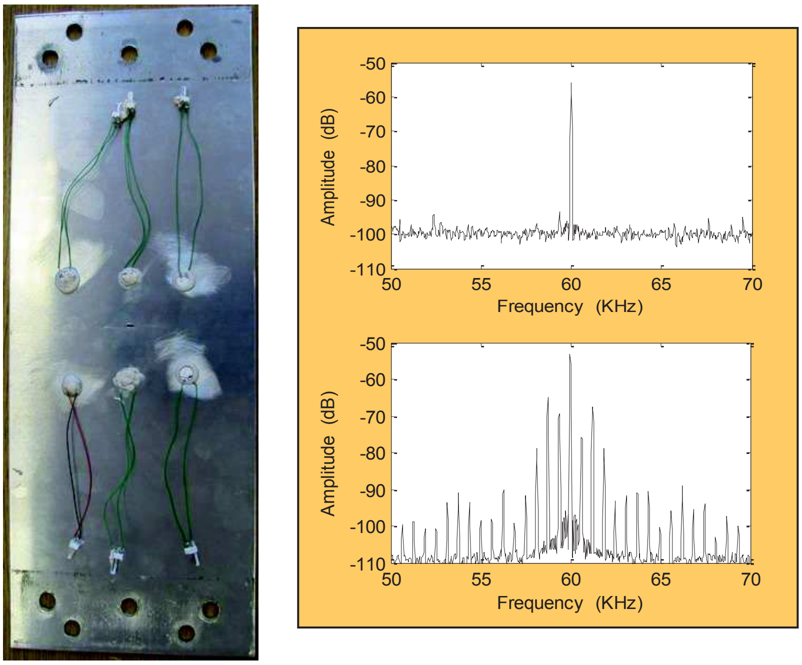

(a) (b)

Figure 4. Nonlinear acoustics used for fatigue crack detection: (a) aluminium specimen instrumented with low-profile, surface-bonded piezoceramic transducers; (b) damage detection results for the intact (upper part) and cracked (lower part) plate.

Damage location is one of the major problems when non-classical nonlinear acoustics is used to monitor structures. However, recent studies in [12] demonstrated that modulation sidebands can be used not only to reveal damage or assess its intensity but also to locate damage. An example of damage location based on nonlinear acoustics is illustrated in Figure 5. A rectangular (300×150×2 mm) composite plate (carbon/epoxy prepreg) was impacted in the centre. The impact energy was equal to 3.9 J. The *Monit SHM* vibrothermographic system with the 35 kHz ultrasonic excitation column – was used to reveal butterfly-like delamination in the plate, after impact (Figure 5a). Following these investigations, a non-classical nonlinear acoustic test was performed. Low-profile, surface bonded transducers were used again for low- and high-frequency excitations. Once the plate was excited, ultrasonic responses were gathered The plate was scanned using a 3-D laser vibrometer to analyse sideband amplitudes at various positions. The intensity of modulation R was calculated to reveal the same delamination in Figure 5b.

A new damage detection method was proposed recently in [13] to combine damage location capability offered by Lamb waves and damage sensitivity offered by nonlinear acoustics. Lamb waves are guided plate waves that are widely used for inspecting large areas of structure to reveal damage.

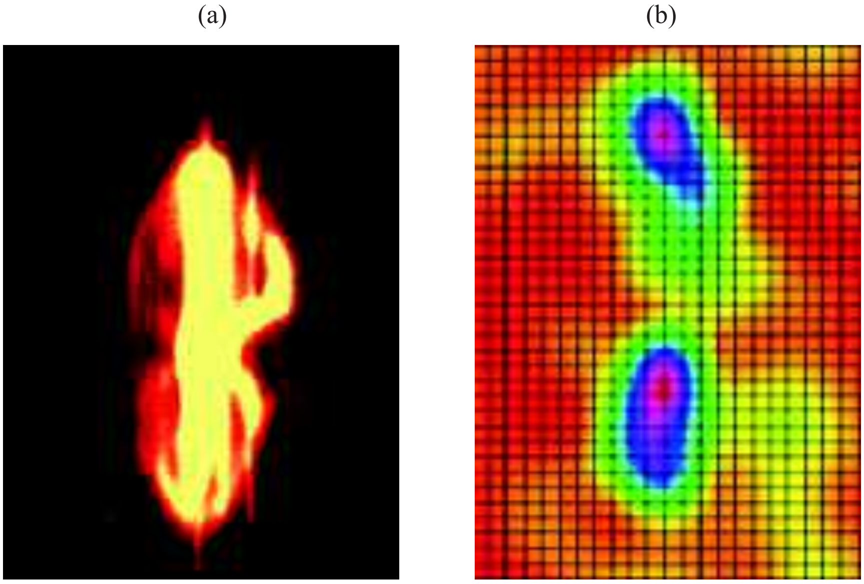


Figure 5. Impact damage detection in composites using. Delamination after 3.9 J impact revealed by: (a) vibrothermography; (b) nonlinear acoustics.

Fatigue testing was used to introduce a crack in the mid span of an 300×20×10 mm aluminium beam (Figure 6). A guided ultrasonic wave (150 kHz) was introduced to the beam when the structure was modally excited (harmonic sinusoidal 10 Hz excitation). Then ultrasonic responses were gathered for two different scenarios of low-frequency excitation, i.e. when the beam was not excited modally and when the beam was excited with the maximum modal amplitude. This measurements were gathered for various positions on the surface of the beam using a 3-D scanning laser vibrometer. Then Ultrasonic responses were band-pass filtered, and their difference was calculated. The RMS values for different measurements are shown in Figure 7, were B-scan (measurements for various positions vs. time) are presented for the intact and cracked beam. The crack is clearly revealed by the increased amplitude of the analysed image (150 mm from the edge of the beam) in Figure 7b.

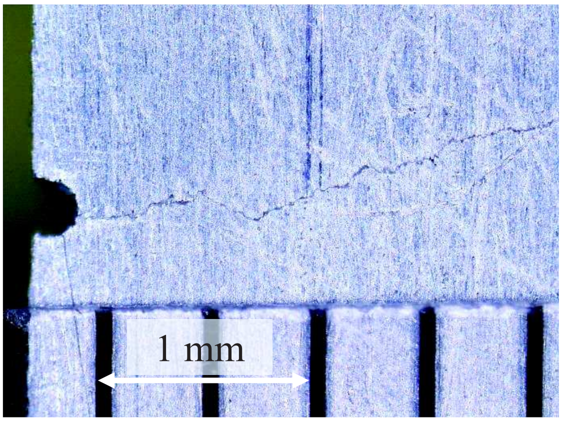


Figure 6. Fatigue crack in an aluminium beam

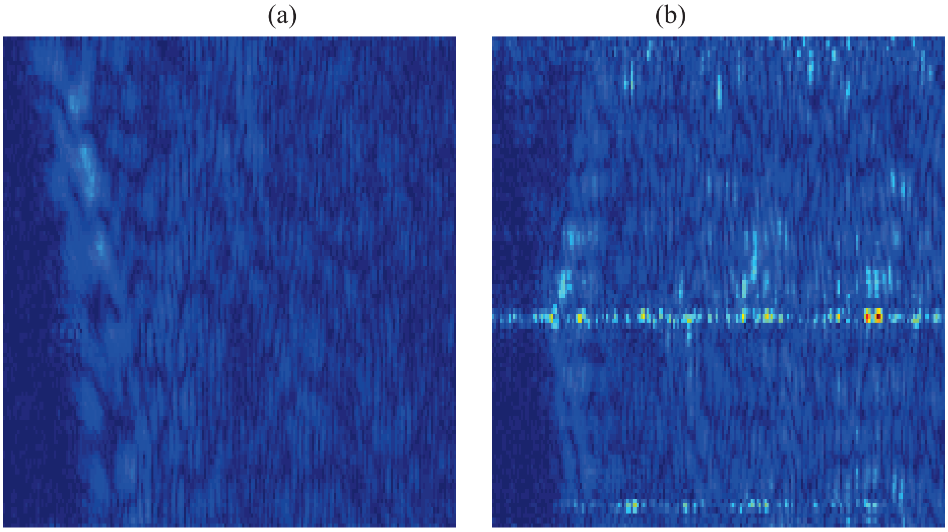


Figure 7. B-scans for the difference signals gathered in the non-linear acoustic test: (a) intact beam; (b) cracked beam

4. Structural Damage Detection Using Non-Classical Nonlinear Acoustics

It is well known that sensor data often needs to be processed and refined before any analysis that can reveal structural damage. Various undesired features – such as noise - are removed from the data. Data drifts, outliers and trends are common undesired nonstationarities. Low-frequency drifts can be removed relatively easy using statistical regression. Unknown trends - caused for example by environmental and operational conditions - are very difficult to remove. These trends often mask damage-related features in analysed signals. For example., it is well known Lamb wave responses - used monitored structures - can be severely affected by temperature changes. Since the majority of Lamb wave based damage detection procedures rely on baseline measurements it is very difficult to find whether signal changes are caused by damage or by temperature. Therefore, compensation for trends - caused for example by temperature or load variation is important to develop methods that are sensitive only to damage but insensitive to other effects.

Various approaches can be used to compensate for undesired effects in the data. The method of cointegration – developed originally from the field of econometrics [14] – has been applied recently in structural damage detection for the removal of undesired environmental and operational effects. temperature effect from bridge vibration data and Lamb wave responses [15-16]. The major idea used in these investigations is based on the concept of stationarity. Time series are considered to be co-integrated if they are themselves non-stationary but their linear combinations are stationary. The method assumes that it is possible for a linear combination of a set of (non-stationary) variables to be stationary if these (non-stationary) variables are integrated of the same order and share common trends. In this context, these variables are said to be co-integrated. Monitored variables are cointegrated to create a cointegrating residual whose stationarity represents normal condition. Then any departure from stationarity can indicate that monitored structures no longer operate under normal condition. More details about this mathematical procedure can be found in [16].

Following the work presented in [16] this section shows an example demonstrating how damage detection can be performed using Lamb wave data corrupted by trends due to temperature. Lamb wave responses were gathered from an aluminium plate with a seeded damage. The seeded damage was a 1 mm hole drilled in the middle of the plate. The plate was exposed to various temperatures in the range between 35 and 70^0C. This was sufficient to corrupt the data, so the effects of damage and temperature on Lamb wave responses were undistinguishable. The cointegration procedure was then applied to the corrupted data to obtain the residual vectors. The residual vectors were wavelet-transformed – using the orthogonal wavelet transformed – and the variance of wavelet coefficients were calculated. Figure 8 shows result, where the logarithmic wavelet variance for various wavelet levels is presented for the first three residual vectors of data after cointegration. The results in Figure 8a – for the undamaged plate – exhibit self-similarity through linear variance characteristics. This pattern is broken due to damage in Figure 8b. The temperature trend was removed from the data leaving the nonstationarity related to damage.

(a)

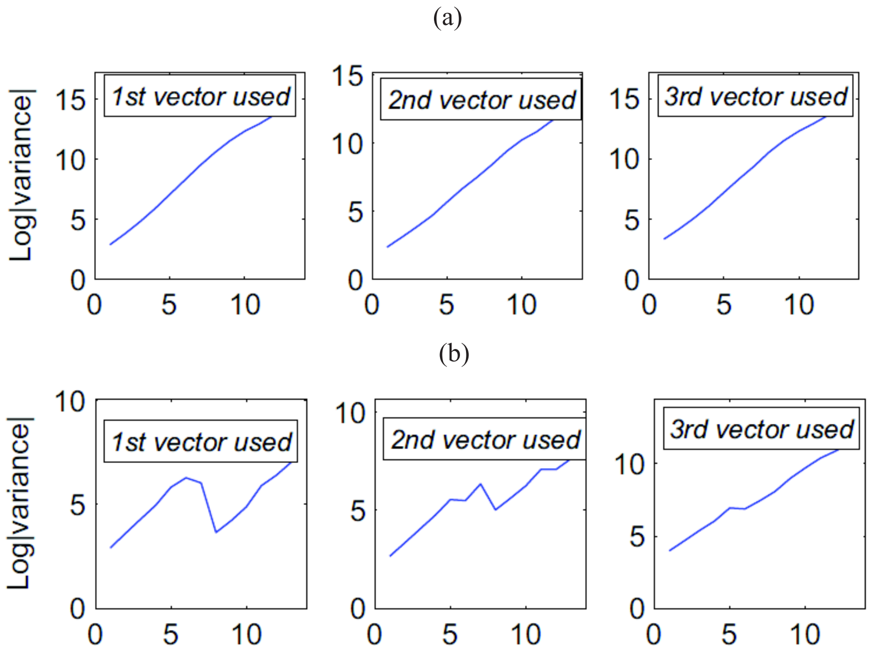


Figure 8. Wavelet variance characteristics calculated from the first three cointegration residuals from Lamb wave data for: (a) intact plate; (b) damaged plate

5. Conclusions

The paper has demonstrated how unconventional modal analysis (wavelet-based FRF), undesired effects (nonlinear phenomena in ultrasonic data) and methods originally developed in other research fields can be applied successfully for structural damage detection. damage detection. Various examples related to structural stiffness reduction, crack detection, impact damage detection have been presented to illustrate that non-classical approaches can often solve damage detection problems for which classical solutions are difficult or impossible. It is anticipated that the work presented will stimulate more research in this area.

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