Novel Vibration Non-Destructive Testing of Deep Foundation Piles by Non-Stationary Higher Order Frequency Response Function

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Abstract

Fatigue damage in the precast concrete piles occurs mostly while being driven into the ground. The wave propagation based non-destructive testing (NDT) is commonly used to estimate the effective length of the pile after pile installation and to detect pile damage. However, information regarding damage detection extracted from this type of NDT is limited and subjective (i.e. non-automatic damage detection). On the other hand, the proposed vibration based NDT could provide a comprehensive automatic NDT tool. In this paper, a new class of higher order vibration NDT technology, which utilizes a shaker to generate sweep-sine excitation and an adaptive nonlinear non-stationary higher order spectral analysis, is introduced

for deep foundation piles. The research described in this paper is promising and leading in the research area related to NDT in construction industry. It is replaced the traditional higher order spectral analysis with “new thinking” novel higher order frequency response analysis. Two different technologies, namely the advanced nonlinear non-stationary chirp-Fourier bicoherence (CFB) technology and the novel nonlinear non-stationary frequency response function of the chirp-Fourier bicoherence (FRF-CFB) technology are investigated. The CFB is a technology which is capable of quantifying the amplitude and phase coupling between harmonics of pile resonance oscillations. These couplings are caused by a fatigue damage. However, in practices, the amplitude and phase coupling between harmonics of pile resonance oscillations may be caused also due to the phase coupled harmonics of an interference imposed by an excitation source (e.g. shaker). Therefore, the novel NDT technology, FRF-CFB, which detects non-linearity caused solely by a structural damage, is proposed and implemented for real-scale industrial precast concrete damaged and undamaged piles. It is found that the FRF-CFB technology provides full separation of diagnostic features which indicates successful NDT of the damaged and undamaged piles. Finally, the NDT based on the conventional pile integrity testing (PIT), experimentally conducted on the same piles, is presented for comparisons with the FRF-CFB technology and with the CFB technology. Novel comparison of the proposed FRF-CFB technology and the advanced CFB technology is also performed.

Keywords: Damage diagnosis, foundation piles; vibration testing; chirp-Fourier bicoherence; higher order frequency response analysis

1 Introduction

Damage in the precast concrete piles occurs during pile installation in the form of spalling or fatigue cracking [1, 2]. The main concern after driving a precast concrete pile into the ground is whether a damage is occurred during installation. Some of the commercially available non-

destructive testing (NDT) technologies are cross-hole sonic logging, gamma-gamma logging, thermal integrity profiling, high strain dynamic testing, and low strain sonic echo testing. The first NDT method, the cross-hole sonic logging [3], requires casting two PVC pipes into the cast-in-situ piles (drilled shafts) to allow dipping a sonic source and a receiver into one of the pipes. The source and the receiver are lowered together along the shaft and the wave emitted by the source is captured via the receiver. The variation in the wave velocity is then inspected in order to detect any defect in between the pipes. The improved version of the cross-hole sonic logging is called the cross-hole tomography where four pipes are placed in the drilled shaft and multi-path measurements are taken at different depths in order to generate a three-dimensional tomography of the pile [3]. The second NDT method is the gamma-gamma logging which has similar arrangement of the pipe tubes as the cross-hole sonic logging has; however, instead of sonic waves, gamma radiation is used to detect the anomalies. The quality of the concrete between the tubes is estimated by the intensity of the gamma radiation [4]. Another NDT method for piles is the thermal integrity profiling. It is performed during the casting of the pile by deploying thermal sensors which may be either embedded in the pile or placed in the tubes casted into the pile. The test aims to monitor the heat radiation of the concrete during its curing since any defect within the fresh concrete will alter the thermal profile of the shaft [5].

These three mentioned above NDT technologies require embedded tubes in the shaft; therefore, they are only applicable for the cast-in-situ concrete piles. Whereas, regarding the driven piles, the high strain dynamic NDT technology and the low strain sonic echo NDT technology are the suitable NDT technologies. The former one is based on recording the propagating stress waves in pile which are generated during the installation into the ground. Although it was developed to estimate the ultimate axial load capacity, yet it can be also used for the purpose of NDT of piles by interpreting any unexpected wave reflection recorded during pile installation [6]. High-strain dynamic test are preferred for the driven piles rather than the cast-

in ones since the driving rig's drop hammer can be used as the excitation source at the same time during pile installation. However, implementation of high-strain dynamic test costs more compared to the low-strain sonic echo test, which is another NDT technology that is conducted following pile installation, also applicable for the cast-in piles. This technology is the most preferred over the previous ones due to its fast execution and low cost. Although each of the technologies mentioned above are NDT technologies, the low strain sonic echo technology is referred as pile integrity testing (PIT) technology within the pile industry. Thus, to be in agreement with the scientific terminology, the low strain sonic echo technology will be called after PIT within this paper.

PIT bases on low strain wave propagation and estimates the effective length of the pile by determining the arrival time of the wave-front reflected due to any variation in the pile cross-section [7]. PIT also provides NDT capability and non-destructive evaluation (NDE) capability: i.e. evaluation of damage severity. However, the quality of PIT results depends on the operator skill and, therefore, NDT and NDE of damage severity by PIT cannot be performed automatically. Vibration based NDT technologies for piles potentially could provide effective automatic NDT and effective automatic NDE of pile damage size. A big number of literature sources related to vibration investigation of dynamic behavior of deep foundation piles exist with a particular focus on soil-pile interaction. However, vibration of piles is mostly a subject for researchers in order to investigate pile performance either during installation procedure or under a seismic loading rather than the purpose of assessment of pile integrity [8-18]. Thus, the motivation of this paper is to develop a novel automatic vibration based NDT technology for the foundation piles at early stage of damage development.

In order to overcome the inherent inaccuracies in the conventional low strain NDT, four main contributions are proposed in this study: (i) replacement of impact hammer with a portable shaker that could provide controlled non-stationary pile excitation (ii) implementation of the novel frequency response functions (FRF) based on the higher order spectra (HOS) for the pile vibrations (iii) implementation of adaptive non-stationary transform for the novel higher order FRF (iv) a novel proposition for a qualitative NDE of pile damage severity based on the higher order FRF. The first improvement in NDT of piles, employing a shaker instead of a drop-hammer, provides a controlled pile excitation. Particularly, the sweep-sine type of excitation, rather than an impulse triggered by a hammer, provides a well-controlled excitation of the resonances of pile under NDT. Additionally, since the shaker allows the full control of the excitation, customized excitations with a high repeatability are ensured, which leads to the improved accuracy in NDT of pile damage. The second improvement is the utilization of an innovative nonlinear signal processing technique: the FRF based on the higher order spectra (HOS) in order to extract diagnostic features from pile vibrations and eliminate influence of phase coupled interferences from pile excitation. The third improvement is implementation of adaptive non-stationary time-frequency short time chirp Fourier transform in order to detect a priori unknown pile resonances and to develop nonstationary higher order FRF for detecting damage by processing non-stationary pile vibration responses. The fourth improvement allows qualitative NDE of pile damage severity by the proposed FRF technology.

The higher-order spectra (HOS) have been widely employed for stationary and non-stationary signals for early detection of nonlinearities in structures and machinery [19-28]. Hereby, the third order spectra (i.e. the bispectrum) is modified by incorporating the chirp-Fourier transform, instead of the conventional Fourier transform, which suits the instantaneous frequency change of the swept sine excitation generated by the shaker [29-31]. The normalized

bispectrum (i.e. the bicoherence), is then determined to detect non-linearity in the transient sweep-sine responses recorded from the piles, which is caused by fatigue damage in piles.

The bispectrum technique is effective to test any structure based on the assumption that the non-linear behavior of vibration signal is solely due to the damage [29]. However, in practices, the non-linearity in the signal may be caused also due to an excitation source (e.g. a shaker) employed for a non-destructive test, which will lead to misleading conclusion for any NDT of objects [32]. To eliminate non-linearity caused by an excitation source from a response of a structure under NDT, hereby the novel technology, which is called the frequency response function based on the chirp-Fourier bicoherence (FRF-CFB), proposed by L. Gelman [32], is developed and investigated. This technology is based on the bicoherence of the output signal of pile normalized with respect to the bicoherence of pile excitation signal.

In this paper, first, both the advanced bicoherence technology (i.e. the CFB) and the novel frequency response function based on the bicoherence (FRF-CFB) technology are introduced, and then, the improvement achieved for the NDT of piles with the FRF-CFB technology over the CFB technology is demonstrated by presenting the results obtained from the experimental study conducted on a group of real-scale industrial concrete precast piles. The novel non-destructive evaluation of pile damage severity based on the FRF-CFB is also proposed and experimentally verified. Finally, a novel experimental comparison of the proposed NDT technology with the traditional PIT technology is performed. So, the objectives of this paper are as follows:

- to develop, investigate and experimentally validate a novel nonlinear non-stationary technology for NDT of deep foundation concrete piles based on the higher order frequency response function technique
- to perform a novel experimental comparison of the proposed technology with the advanced nonlinear non-stationary technology based on the higher order spectra

- to develop and experimentally validate the novel method of pile damage severity non-destructive evaluation (NDE) based on the higher order frequency response function technology
- to perform a novel experimental comparison of the proposed novel NDT technology and advanced bicoherence technology with the traditional PIT technology

2 Theoretical Analysis: NDT Technology Based on the Higher Order Frequency Response Function

The generic formulation of the nonlinear classical bispectrum is given as:

$$B(f_1, f_2) = \frac{1}{M} \sum_{m=1}^M X_m(f_1)X_m(f_2)X_m^*(f_1 + f_2) \quad (1)$$

where X_m , denotes the Fourier transformation of pile vibration data, $*$ is the symbol of the complex conjugate, m refers the time segment number, M is the total number of time segments, and f is the frequency. In Eq. 1, frequencies f_1 and f_2 are chosen as frequencies of the resonance harmonics of a pile vibration mode. To determine the bispectrum, B , the bispectrum analysis is performed for each time segment, and then the bispectrum is obtained by averaging all bispectrums of time segments. By normalizing the bispectrum, B , the bicoherence, b , is obtained as follows [29]:

$$b(f_1, f_2) = \frac{\sum_{m=1}^M X_m(f_1)X_m(f_2)X_m^*(f_1 + f_2)}{\sum_{m=1}^M \sqrt{|X_m(f_1)X_m(f_2)|^2 |X_m^*(f_1 + f_2)|^2}} \quad (2)$$

It is well-known that bicoherence is an effective tool for early damage detection in structures and machinery. However, the classical bicoherence technology may provide misleading results of NDT of pile damage in the case of the phase coupled interferences imposed by an excitation source. The effectiveness of NDT of pile damage can be improved, if the bicoherence of the pile output signal (i.e. pile structural vibration) is normalized with respect to the bicoherence

of the input signal (i.e. pile excitation). Therefore, hereby the higher order frequency response function technology is proposed to use:

$$FRF_b(f_1, f_2) = \frac{b_o(f_1, f_2)}{b_i(f_1, f_2)} \quad (3)$$

The physical significance of the novel higher order frequency response function technology (Eq. 3) is that it essentially reduces influence of the phase coupled interferences from an excitation. The higher order frequency response function technology is also providing early damage detection for structures and machinery. Since we propose here to excite piles by the non-stationary swept-sine excitation with the linear change of the excitation frequency, hereby, instead of the Fourier transform, an adaptive transformation, the short-time chirp-Fourier transform (CFT), is preferred to use in the technology this transformation is defined by [29]:

$$X_m(f, c, T) = \int_{-\infty}^{\infty} w_m(t - T_m) x(t) e^{-i2\pi(f t + \frac{c}{2} t^2)} dt \quad (4)$$

where $x(t)$, the time signal, w_m , the time window, T_m , the time centre of the window, and, c is the chirp rate (i.e., frequency speed) of the CFT. The reason of exciting piles by the swept sine excitation is that, normally, pile resonances are unknown a priori and need to be detected before performing NDT of piles. The swept sine excitation in combination with the short time CFT is an effective technology for structure resonance detection. In order to maintain the adaptive properties of the short time CFT, the chirp rate, c , of the short time CFT should be equal to the chirp rate of pile structural vibration response [29]. For realizing this adaptation rule, the chirp rate of the short time CFT is set in accordance with the selected (i.e. known) chirp rate of the shaker excitation.

3 Experimental Work

3.1 Pile Descriptions

The experimental work is conducted on nine precast concrete standard industrial piles installed by company Aarsleff (Poland) and having the dimensions of 35cm x 35cm x 10m. The piles are manufactured of grade C50 concrete and contain four T12 reinforcement bars. The piles are placed as to ensure at least 2 meters distance between their cross-sectional centers in order to avoid pile cross-influence. As to comply with the standard practice in the most construction sites, the piles are driven into the ground as to leave a height of 30 cm above the ground surface. Two of the piles are installed with no damage, whereas each of the remaining seven piles is fatigue damaged at a different depth from the pile top: 1m, 2m, 3m and 8m. The damage location and damage condition of the piles are summarized in Table 1. Damage is generated by applying a bending force (Figure 1, left) using the piling rig on the piles resting on two supports located as to ensure that damage occur in the desired part of the pile before driving the piles into the ground (Figure 1, right).

Table 1: The description for piles

Pile notation	Cross-section (cm x cm)	Length (m)	Damaged	Damage severity	Damage depth (m)
P1	35 x 35	10	No	N/A	N/A
P2	35 x 35	10	No	N/A	N/A
P3	35 x 35	10	Yes	Severe	2
P4	35 x 35	10	Yes	Moderate	2
P5	35 x 35	10	Yes	Moderate	3
P6	35 x 35	10	Yes	Severe	8
P7	35 x 35	10	Yes	Moderate	8
P8	35 x 35	10	Yes	Severe	1
P9	35 x 35	10	Yes	Moderate	1

Figure 1: (left) Damage generation, (right) Pile driving

3.2 Vibration Test Set-up and Configuration

The vibration NDT technology is conducted with the compact electro-magnetic shaker shown in Figure 2 (shaker type is I-Beam VT200 by Sonic Immersion Technologies), which is run by the DataPyhsics Signalstar Vector shaker controller and powered by an amplifier (300W RMS, 20Hz/20KHz) manufactured by the American Audio Professional company. The maximum force that the shaker generates is 1000 N at its resonance 45 Hz, whereas its output force is 300 N between 60 Hz and 200 Hz. Its rectangular prism case has the dimensions of 15x9x6 cm³, and it weighs only 1.6 kg. The shaker does not require any air-cooler and is able to operate within a wide frequency range from 20 Hz to 800 Hz.

The shaker is fixed by screws on the piles and located 10 cm down with respect to the pile top. Two tri-axial accelerometers (type is PCB 356B18, sensitivity is 1000mV/g) are placed at 10 cm and 25 cm down with respect to the top of the pile on the pile face opposite to the shaker as depicted in Figure 2. The sensors are screwed into the piles through threaded insert to ensure stiff coupling. A separate accelerometer is also deployed on the shaker to provide a feedback signal to the controller and for estimation of a pile excitation. The rest of the test set-up (Fig.

3) comprises two 4-channel data acquisition cards (National Instrument (NI) 9234) along with an USB Chassis (NI cDAQ9174), and laptops. During the data acquisition, along with the pile vibration, the shaker vibration feedback signal and the speed signal (that characterizes the instantaneous frequency variation of the sweep-sine excitation targeted by the shaker controller) are also recorded.

Figure 2: (left) The electro-magnetic shaker mounted on a pile, (middle) the sensors mounted on a pile, (right) schematic of the shaker and sensor locations

Figure 3: Test set up and instrumentation

3.3 NDT of Piles

Each pile is subjected to a sweep-sine excitation in a specific frequency band-width and at a specific chirp-rate as to excite pile resonances. The second and the third bending modes of piles are examined since the frequency of the first bending mode of piles overlaps with the shaker's resonance frequency and, therefore, it is very hard to use the first bending mode of piles for NDT using this shaker. The signals captured via the channels in the perpendicular direction with respect to the pile face are considered for NDT as the second and the third bending modes in this direction have the highest amplitude of pile vibration response. To demonstrate an improvement in NDT of piles by the FRF-CFB technology compared to the CFB technology, the piles are first examined with the CFB technology and then the results of NDT based on the FRF-CFB technology are presented.

3.3.1 NDT of Piles by the Chirp- Fourier Bicoherence technology

First, the pile resonance frequency and its arrival time in the time history are determined in order to perform the NDT. Therefore, initially, the adaptive short-time chirp-Fourier transform (ST-CFT) [30] is performed by employing a 0.5-second-long Hanning window with 50% overlapping. Then, the CFB is performed on time blocks of 30-second long, which centers are at the determined resonances in the time domain of pile vibration signal. These time blocks are then further divided into time segments of 0.5 seconds long which are selected as to provide an appropriate frequency resolution (i.e. 2Hz) for the CFB. The overlapping of the time segments is chosen as 75% to ensure that sufficient number of the bispectrum values is obtained to calculate the averaged bispectrum value. For each pile, the CFB features are calculated for 100 realizations after adding the white Gaussian noise at 50 dB signal to noise ratio to the original signals. This procedure is followed for four cases associated with a specific pile vibration mode

(i.e. the second and the third modes) and a specific sensor (i.e. top or bottom accelerometer) as described in Table 2.

The histograms of the diagnostic features obtained by the CFB technology for all piles and for each case are shown in Figure 4 and 5. It is observed from Fig 4b and Fig 5a, b, that values of most (not all) of diagnostic features are higher for the damaged piles compared to the undamaged ones because the damaged piles have a higher level of non-linearity caused by damage, compared to the undamaged piles. It is observed from Fig 4a that values of all of diagnostic features are higher for the damaged piles compared to the undamaged ones. So, in the three cases out of the four investigated cases, the features obtained from all undamaged piles are not completely separated from the features from all damaged piles. In only one case (i.e. Mode 2, Top sensor) the full separation is achieved, whereas in other three cases the separation is not realized fully.

The effectivity of the NDT is quantified by estimates of the total averaged probability of the correct damage detection of both undamaged and damaged piles, P_{AvgCor} . To calculate estimates of the total averaged probability of the correct damage detection, the CFB diagnostic features of both undamaged and damaged piles are splitted into half to create training and testing sequences. Every odd sample in the feature array is added to the first group, whereas every even sample is added to the second group. The CFB diagnostic features of the first group are used for training purpose, and the CFB diagnostic features of the second group are used as the testing group to perform NDT of piles. The decision-making is performed based on the k-nearest ($k = 5$) neighbors technique as advised by [33]. Estimates of P_{AvgCor} are found as 100%, 95%, 88% and 88% accordingly for Cases 1, 2, 3 and 4.

Not very good NDT results for cases 2-4 are caused by the phase coupled interferences imposed by the shaker. In these cases, the level of non-linearity indicated by the CFB features is associated with both the pile damage and with the phase coupled interferences from a shaker.

To illustrate the existence of the phase coupled shaker interferences, the bicoherence map for pile excitations and for pile vibration responses for one undamaged pile (P2) and one damaged pile (P3) from case 4 (Mode 3, Bottom sensor) are plotted in Figure 6. The existence of the phase coupled harmonics of pile excitation frequency from the shaker is clearly apparent in these maps for both piles. It is, therefore, necessary to utilize the proposed higher order frequency response function using the pile vibration and pile excitation to eliminate the influence of shaker interferences and test accurately the pile non-linearity caused by the pile structural damage.

Figure 4. Histograms of the CFB features obtained for Mode 2 from a) Top Sensor and b) Bottom Sensor.

Figure 5. Histograms of the CFB diagnostic features obtained for Mode 3 from a) Top Sensor and b) Bottom Sensor.

Table 2: Description of the NDT cases

Case	Pile Vibration Mode	Sensor Location
1	2	Top
2	2	Bottom
3	3	Top
4	3	Bottom

Figure 6: Bicoherence maps of pile excitations and output pile signals for P2 and P3.

3.3.2 NDT of piles by the Higher Order Frequency Response Function technology based on the Chirp- Fourier Bicoherence

The Higher Order Frequency Response Function technology based on the Chirp-Fourier Bicoherence is applied as described in Section 2 to eliminate the phased coupled interferences

caused by the shaker, so that the non-linearity in the pile signals due to the pile damage can be solely tested. To demonstrate the NDT improvement, the FRF-CFB maps produced by the technology for pile P2 (undamaged) and pile P3 (damaged) are presented in Figure 7. The red dotted peaks visible on the right plot (damaged pile) are corresponding to the coupling between the three harmonics of the pile vibration. Compared to the CFB maps of the output signals, given in Figure 6, the phase coupled harmonics disappear in the FRF-CFB map of the undamaged pile (Fig. 7: left). However, the FRF-CFB feature related to coupling between the three harmonics of pile resonance oscillations is clearly visible for the damaged pile (Fig. 7: right), which indicates an essential improvement in NDT.

The FRF-CFB features are calculated 100 times under adding the white Gaussian noise at 50 dB signal to noise ratio after setting the bicoherence parameters (30-seconds long time block is divided into 0.5-seconds-long segments with 75% overlapping) same as the ones in the CFB technique. The histograms of the FRF-CFB features, given in Figure 8 and 9, obtained from the four cases (Mode 2 and 3; top and bottom sensors) display a full separation between the features from the undamaged and damaged piles unlike those of the CFB (Fig. 4b, 5a and 5b). Although, it is evident from the histograms that NDT of piles for all test cases is successful, the effectivities of the NDT are also evaluated by estimates of the total averaged probability of the correct damage detection of both undamaged and damaged piles, P_{AvgCor} . Following the procedure explained in Section 3.3.1, estimates of P_{AvgCor} are obtained as 100% for all four cases, which confirms successful NDT for all four cases. So, the effectiveness gains in estimates of the total averaged probability of correct damage detection, that are provided by the proposed novel NDT technology in comparison with the advanced CFB technology for test cases 2-4 are as follows respectively: 5%, 12% and 12%. For Case 1 there is no gain, as estimates of the total averaged probability of correct damage detection are 100% for the proposed NDT technology and the advanced CFB technology.

Figure 7: The FRF-CFB maps for: left) pile P2 and right) pile P3.

Figure 8. Histograms of the CFB-FRF diagnostic features obtained for Mode 2 from a) Top Sensor and b) Bottom Sensor

Figure 9. Histograms of the CFB-FRF diagnostic features obtained for Mode 3 from a) Top Sensor and b) Bottom Sensor

Qualitative non-destructive evaluation (NDE) of pile damage severity is also investigated in this paper. The novel approach of qualitative NDE of pile damage severity proposed here is based on averaging of the FRF-CFB feature for multiple vibration modes, multiple accelerometers and multiple pile tests. The proposed approach takes into account the following advantage of the FRF-CFB feature: it is invariant to the level of pile excitation and levels of the phase coupled interferences from pile excitation

Based on the proposed approach, the average values of the diagnostic feature FRF-CFB are obtained from two pile vibration modes (i.e. Mode 2 and Mode 3), two accelerometer channels (i.e. top and bottom channels) and two NDT tests for each pile and used for pile severity NDE. Thus, in total, eight FRF-CFB features are used to calculate the averaged FRF-CFB feature. The range of the averaged FRF-CFB features is divided into three equal sub-ranges in order to evaluate qualitatively damage severity. A sub-range length is estimated as 0.15, and, therefore, the damaged pile classes in the following sub-ranges 0.90-1.05, 1.05-1.20 and 1.20-1.35 are defined accordingly as minor, moderate and severe pile damage conditions. As it is summarized in Table 3, 8 piles out of 9 are evaluated correctly in accordance with the known damage conditions. Pile 9 is estimated as severely damaged in contrast to its known stage of damage. Estimate of the total probability of correct NDE of the damage severity is found as 89%.

Table 3: NDE of Damage Severity

Pile	Damage Severity	FRF-CFB (Mode 2)	FRF-CFB (Mode 3)	FRF-CFB (Average)	Estimated Damage Severity
P1	NA	0.83	0.97	0.90	Non
P2	NA	0.87	0.95	0.91	Non
P3	Severe	1.29	1.19	1.24	Severe
P4	Moderate	1.04	1.12	1.08	Moderate
P5	Moderate	1.01	1.13	1.07	Moderate
P6	Severe	0.98	1.58	1.28	Severe
P7	Moderate	1.04	1.33	1.19	Moderate
P8	Severe	1.18	1.26	1.22	Severe
P9	Early	0.95	1.76	1.35	Severe

4 Novel Comparison of the Proposed Technology and the Advanced CFB Technology with the Conventional Pile Integrity Testing (PIT)

The conventional pile integrity testing (PIT) is also performed on the same piles in order to make a novel effectiveness comparison of the proposed technology, the advanced CFB technology and the PIT technology. The PIT was conducted using the hardware and software provided by Pile Dynamics Inc. (USA). A rubber hammer of 400 g weight is used for an excitation in vertical direction. The wave velocity is measured within the range of 4200 to 4450 m/s for all piles. Typical signals indicating pile damage and pile with no-damage are displayed in Figure 10.

NDT by PIT tests accurately detects damage in the three damaged piles, P3, P4, and P5, with the right estimate of the crack depth. However, for the remaining four damaged piles, P6, P7, P8, and P9, no indication of damage is observed by the PIT tests. Furthermore, the two undamaged piles, P1 and P2, are diagnosed as damaged. Overall, the PIT identifies all piles with estimate of the total averaged probability of correct damage detection as of 44%. The complete PIT results are summarized in Table 4. So, the effectiveness gain in estimates of the total averaged probability of correct damage detection that is provided by the proposed NDT technology in comparison with the classical PIT technology is 57% for all four test cases. Even the advanced CFB technology performs better than the classical PIT technology. The effectiveness gains in estimates of the total averaged probability of correct damage detection that is provided by the advanced CFB technology in comparison with the classical PIT technology are 57%, 52%, 45% and 45% for test cases 1-4 respectively.

Figure 10. Wave signals recorded on P3 and P9.

Table 4: The PIT results

Pile	Damaged	Damage Location	Wave Speed (m/s)	NDT for piles
P1	No	N/A	4300	Slight damage at 2.5 m
P2	No	N/A	4300	Slight damage at 4.5 m
P3	Yes	2	4300	Slight damage at 2 m
P4	Yes	2	4250	Slight damage at 2 m
P5	Yes	3	4450	Slight damage at 3 m
P6	Yes	8	4450	No damage detection
P7	Yes	8	4450	No damage detection
P8	Yes	1	4250	No damage detection
P9	Yes	1	4200	No damage detection

5 Conclusions

The automatic vibration NDT technology for concrete precast deep foundation piles is proposed, investigated and performed for the first time in worldwide terms by the novel nonlinear non-stationary higher order frequency response function based on the chirp-Fourier bicoherence. It is shown by the comprehensive experiments, conducted on the standard industrial piles, that the proposed novel NDT technology provides more effective pile damage detection comparing with the advanced NDT technology based on the chirp Fourier

bicoherence (CFB) the for the most of the investigated test cases. The proposed novel NDT technology effectively detects pile damage in condition of the phase coupled interferences from pile excitation due to normalizing the bicoherence of the pile vibrations with respect to the bicoherence of pile excitation signal. The higher damage detection effectiveness of the new NDT technology over the advanced chirp Fourier bicoherence technology is demonstrated by the experiments conducted on 9 standard industrial piles install by industrial company Aarsleff (Poland).

The four different test cases, based on the different sensor locations and the different pile vibration modes, are examined. The novel effectiveness comparison of the proposed technique and the advanced technique based on the CFB is performed experimentally. The estimates of the total probability of the correct damage detection is found for the four cases as 100%, 95%, 88% and 88% by the advanced CFB technology. Whereas, by implementing the proposed NDT technology, the full separation between the features obtained from the undamaged and damaged piles are achieved for all four test cases with 100% estimates of the total probability of the correct damage detection, whereas the estimate of the total probability of the correct NDE of damage severity is 89%. So, the effectiveness gains in estimates of the total averaged probability of correct damage detection that are provided by the proposed NDT technology in comparison with the advanced CFB technology for test cases 2-4 are as follows respectively: 5%, 12% and 12%.

Conventional PIT technology is also performed on the same piles. PIT technology diagnoses the damaged and the undamaged piles with estimate of the total probability of correct damage detection of 43%. Thus, the proposed new technology is more effective for pile diagnosis than the classical PIT technology. The effectiveness gain in estimates of the total averaged

probability of correct damage detection that is provided by the proposed NDT technology in comparison with the classical PIT technology is 57%. Even the advanced CFB technology performs better than the classical PIT technology. The effectiveness gains in estimates of the total averaged probability of correct damage detection that is provided by the advanced CFB technology in comparison with the classical PIT technology are 57%, 52%, 45% and 45% for test cases 1-4 respectively. The proposed new class of higher order NDT technology presents a fundamental new concept and will make a major influence on integrity testing in construction industry and also can be effectively employed for other NDT methods: ultrasonic NDT and thermography NDT.

Acknowledgements

The authors would like to thank Dr. I. Petrunin and Dr. L. Zanotti Fragonara (both are from Cranfield University) and company Aarsleff (Poland) for their help during this research. This work was supported by the European Research Council under the Framework Programme FP7 [Project ID: 605676].

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