

INTERNATIONAL SOCIETY FOR SOIL MECHANICS AND GEOTECHNICAL ENGINEERING



This paper was downloaded from the Online Library of the International Society for Soil Mechanics and Geotechnical Engineering (ISSMGE). The library is available here:

<https://www.issmge.org/publications/online-library>

This is an open-access database that archives thousands of papers published under the Auspices of the ISSMGE and maintained by the Innovation and Development Committee of ISSMGE.

The paper was published in the proceedings of the 20th International Conference on Soil Mechanics and Geotechnical Engineering and was edited by Mizanur Rahman and Mark Jaksa. The conference was held from May 1st to May 5th 2022 in Sydney, Australia.

Novel vibration based integrity testing for deep foundation piles

Nouveaux tests d'intégrité basés sur les vibrations pour les pieux de fondations profondes

Ahmet Serhan Kirlangic

Department of Civil Engineering, Bahcesehir University, Besiktas, Istanbul, Turkey

Len Gelman

School of Computing and Engineering, The University of Huddersfield, Huddersfield, United Kingdom

ABSTRACT: Damage in the driven concrete piles due to the impact exerted on them during installation is generally assessed by the wave propagation-based testing, commonly known as the pile integrity test (PIT). Although the PIT is beneficial to estimate the location of any anomaly along a foundation pile, the reliability of diagnosis by the PIT depends on the operator skill. Therefore, there exists a need to develop an automated condition assessment technique with the capability of objective diagnosis for the precast concrete foundation piles. The vibration-based tests can be adapted for this purpose. This paper introduces a nonlinear vibration based structural integrity testing method, which bases on the detection of the higher harmonics of the piles excited by a shaker. The developed technique proposes a new diagnostic feature, named the frequency response function of chirp-Fourier bicoherence (FRF-CFB), which measures the nonlinearity in the recorded pile vibration signals by utilizing non-stationary higher order spectral analysis. The developed method is demonstrated on nine real-size concrete piles driven into the ground. It is found that the FRF-CFB improves probability of correct damage detection up to 57% compared to the conventional PIT method.

KEYWORDS: Driven concrete piles; pile integrity testing; vibration-based diagnosis; higher order spectral analysis.

1 INTRODUCTION.

The main concern after driving a precast concrete pile into the ground is whether any damage is occurred or not during installation. In the piling industry, the high strain dynamic and the low strain sonic echo techniques are two suitable inspection techniques for the driven precast piles. The former can be used for the purpose of integrity diagnosis of piles by interpreting any unexpected wave reflection recorded during pile installation (ASTM D4945-17). Implementation of high-strain dynamic test costs more compared to the low-strain sonic echo test, also known as the pile integrity testing (PIT). The PIT technique estimates a driven pile's effective length by determining the arrival time of the wave-front reflected due to any imperfection along the pile (ASTM D5882-16). However, the quality of PIT results relies on the skill of the operator as well as on the experience of the experts interpreting the test signals. To overcome such shortcomings, some recent research efforts focus on automation of PIT utilizing machine learning tools (Protopapadakis et al. 2016; Cui et al. 2017; Garcia et al. 2017). The vibration-based tests can be also adapted to achieve objective diagnosis for the driven precast foundation piles. With this regard, the motivation of this paper is to develop such an inspection technique for the structural integrity of the driven foundation piles based on vibration testing. For this purpose, hereby, first a portable shaker is deployed to provide fully controlled pile excitation unlike the one generated by the drop-hammers. Secondly, an innovative nonlinear signal processing technique, which bases on the frequency response function (FRF) of the higher order spectra (HOS), is utilized in order to extract diagnostic features from pile vibrations and eliminate influence of phase coupled interferences caused by the excitation. Lastly, a time-frequency short-time chirp-Fourier transform (ST-CFT) is adapted in order to detect pile resonances and to develop higher order FRF by processing non-stationary pile vibration responses.

The higher-order spectra (HOS) technique has been widely used for detection of nonlinearities in the vibration signals obtained from machinery systems (Fackrell et al. 1995; Collis et al. 1998; Hickey et al. 2009; Dong et al. 2015). Whereas there exist very limited research studies of the HOS regarding the concrete structures, of which few investigated the crack detection in concrete members (Hamad et al. 2015; Kirlangic 2020).

Hereby, for the first time, the HOS technique is utilized for the inspection of the driven concrete piles. For this purpose, 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 type excitations (Gelman & Petrunin 2010). The normalized bispectrum (i.e. the bicoherence), is then determined to measure the non-linearity in transient sweep-sine responses recorded on the piles. The determined bicoherence is valid based on the assumption that the non-linear behavior of vibration signal is solely due to the damage in the structure (Gelman & Petrunin 2007). However, in practices, the non-linearity in the signal may be caused also due to an excitation source (e.g. a shaker) employed during the test (Gelman 2010). To eliminate such non-linearity source from the real response of a structure, hereby the novel technique, which is called the frequency response function based on the chirp-Fourier bicoherence (FRF-CFB) is investigated (Gelman & Kirlangic 2020). This technique is based on normalization of the bicoherence of the output signal of pile with respect to the bicoherence of excitation signal.

In this paper, first, the frequency response function based on the chirp-Fourier bicoherence (FRF-CFB) technique is explained, and then, the diagnosis of pile integrity with the FRF-CFB technique is demonstrated by the vibration tests conducted on nine real-scale concrete precast piles. Finally, a comparison of the proposed technique with the traditional PIT is performed.

2 THEORETICAL BACKGROUND

The classical bispectrum is defined 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, $*$ 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 set as the frequencies of the resonance harmonics. To determine the bispectrum B the bispectrum analysis is performed for each

time segment, and then the bispectrum is obtained by averaging all bispectra of time segments. By normalizing the bispectrum B , the bicoherence b is obtained as (Gelman & Petrunin 2007):

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

The classical bicoherence technique given above may provide misleading results of diagnosis in the case of the phase coupled interferences imposed by an excitation source. This effect on the diagnosis can be eliminated, if the bicoherence of the output signal (i.e. structural vibration) is normalized with respect to the bicoherence of the input signal (i.e. excitation). Therefore, hereby the higher order frequency response function technique is proposed:

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

The significance of the higher order frequency response function (Eq. 3) is that it essentially reduces influence of the phase coupled interferences originated from an excitation. Since, hereby, it is proposed to excite piles by the swept-sine excitation with the linear change of the excitation frequency, instead of the Fourier transform, an adaptive transformation, namely the short-time chirp-Fourier transform (ST-CFT), is preferred, which is defined as (Gelman & Petrunin 2007):

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

where $x(t)$, the time signal, w_m , the time window, T_m , the time center of the window, and c is the chirp rate. 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. The swept sine excitation in combination with the short time CFT is an effective technique for resonance detection. In order to maintain the adaptive properties of the short time CFT, the chirp rate c should be equal to the chirp rate of pile structural vibration response (Gelman & Petrunin 2007). For realizing this adaptation rule, the chirp rate of the short time CFT is set in accordance with the selected chirp rate of the shaker excitation.

3 EXPERIMENTAL WORK

3.1 Pile Descriptions

The experimental work is conducted on nine precast concrete piles having the dimensions of 35cm x 35cm x 10m (Figure 1). The piles are manufactured of grade C50 concrete and contain four T12 reinforcement bars. 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 kept intact, whereas damages were created on the remaining seven piles before the installation. On these seven piles, the damages were created at a different depth from the pile top: 1 m, 2 m, 3 m, and 8 m. Damage is generated by applying a point load 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. The damage severity of the piles is classified based on the largest and widest crack observed in each pile as summarized in Table 1.

3.2 Numerical Model

A numerical model for a typical pile is created with the surrounding soil in the simulation software ANSYS to estimate its natural frequencies prior to the field tests (Figure 2). The pile

is modelled having a length of 30 cm above the ground surface to represent the real practice. A higher order hexahedron element is used for modelling the pile and soil, which are constrained together by fixed connections without any interface element for simplicity. The elasticity modulus of the concrete pile is set to 37 GPa, provided by the pile manufacturer, and for the soil it is 65.8 MPa, which is derived from a cone penetration test carried out in the proximity to the site. The density for concrete is 2400 kg/m³ whereas the soil's density is neglected in order to reduce computational time. And finally, the Poisson's ratio is chosen 0.3 for both concrete and soil. Following the modal analysis of the numerical model, the first three natural frequencies for bending are found to be 47.5, 83.1 and 95.2 Hz. These frequencies are used for guidance to set the frequency band-width of the swept-sine excitation during the vibration tests conducted on the real piles.



Figure 1. Pile driving.

Table 1: The damage description for piles

Pile	Damaged	Crack Length (cm)	Crack Width (mm)	Damage Severity	Damage Depth (m)
P1	No	N/A	N/A	N/A	N/A
P2	No	N/A	N/A	N/A	N/A
P3	Yes	35	3	Severe	2
P4	Yes	26.3	0.5	Moderate	2
P5	Yes	28.2	1.5	Moderate	3
P6	Yes	29.5	2	Severe	8
P7	Yes	28.5	1	Moderate	8
P8	Yes	31.5	2	Severe	1
P9	Yes	29.9	1	Moderate	1

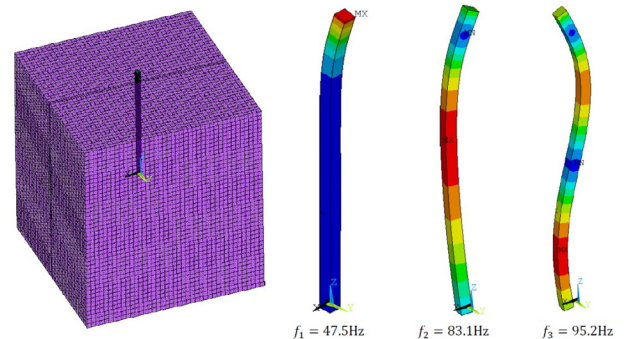


Figure 2. The numerical model of pile and the first three bending modes.

3.3 Vibration Test Set-up

The vibration based diagnostic technique is conducted with the compact electro-magnetic shaker shown in Figure 3 (I-Beam VT200 by Sonic Immersion Technologies), which is run by the

DataPyysics Signalstar Vector shaker controller. 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. It weighs only 1.6 kg and does not require any air-cooler. The shaker is fixed by screws on the piles and located 10 cm below the top of the pile. Two tri-axial accelerometers (PCB 356B18) are placed at 10 cm and 25 cm below the top of the pile on the pile face opposite to the shaker. 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 pile excitation. The rest of the test set-up comprises two 4-channel data acquisition cards (National Instrument 9234) along with an USB Chassis (NI cDAQ9174), and computer (Figure 4). The sweep-sine tests are repeated twice for each pile which results in two transient vibration signals for each pile.

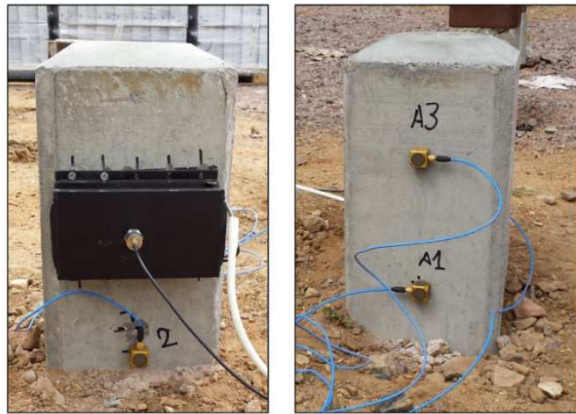


Figure 3. (left) The electro-magnetic shaker, (right) the sensors.

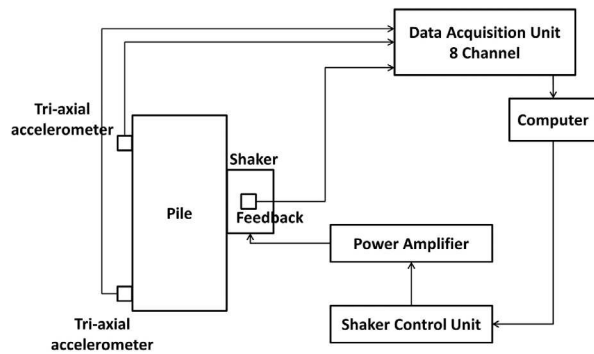


Figure 4. Test instrumentation.

4 VIBRATION BASED DIAGNOSIS OF PILES

Piles are excited under sweep-sine in a frequency band-width from 60 Hz to 130 Hz, which is chosen in accordance with the numerical results, and at a chirp-rate of 0.1 Hz/s. 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, 45 Hz. The signals captured via the channels in the perpendicular direction with respect to the pile face are considered for further analyses since the highest amplitude of pile vibration response are attained in these directions.

The Higher Order Frequency Response Function technique based on the Chirp-Fourier Bicoherence (FRF-CFB) is applied as described in Section 2. First, the pile resonance frequency and its arrival time in the time history are determined by performing the short-time chirp-Fourier transform (ST-CFT). Then, the FRF-CFB is performed on a time block of 30 seconds, of which time

center is at the determined resonance in the time domain of pile vibration signal. The time block is then further divided into time segments of 0.5 seconds long. 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 repeated for four cases (i.e. the second and the third modes; and top and bottom accelerometers).

The FRF-CFB maps generated for pile P2 (undamaged) and pile P3 (damaged) are presented in Figure 5. The red dotted peaks visible on Figure 5b (damaged pile) represent the coupling between the three harmonics of the pile vibration, in other words, the maximum values for the FRF-CFB feature. This feature is clearly visible for the damaged pile (Figure 5b), whereas no clear peak is observed on the map given for the undamaged pile as expected (Figure 5a).

In Figure 6 and 7, the histograms of the FRF-CFB features obtained from the maps for the cases Mode 2 and 3, respectively, display full separation between the features from the undamaged and damaged piles. Although, it is evident from the histograms that NDT of piles for all test cases is successful, the effectivities of the proposed technique are also 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 FRF-CFB diagnostic features of both undamaged and damaged piles are split 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 FRF-CFB diagnostic features of the first group are used for training purpose, and the FRF-CFB diagnostic features of the second group are used as the testing group to perform diagnosis of piles. The decision-making is performed based on the k-nearest ($k = 5$) neighbors technique (Gelman & Petrunin 2012). Estimates of P_{AvgCor} are obtained as 100% for all four cases, which confirms successful diagnosis for all four cases.

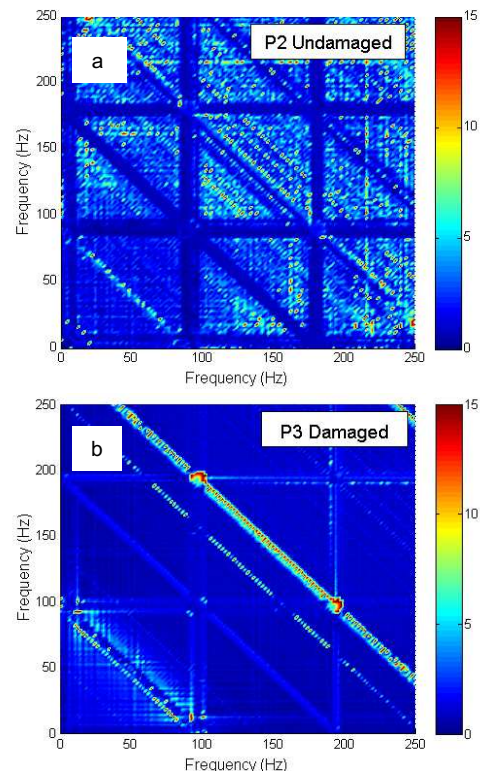


Figure 5. The FRF-CFB maps for: (a) pile P2 and (b) pile P3.

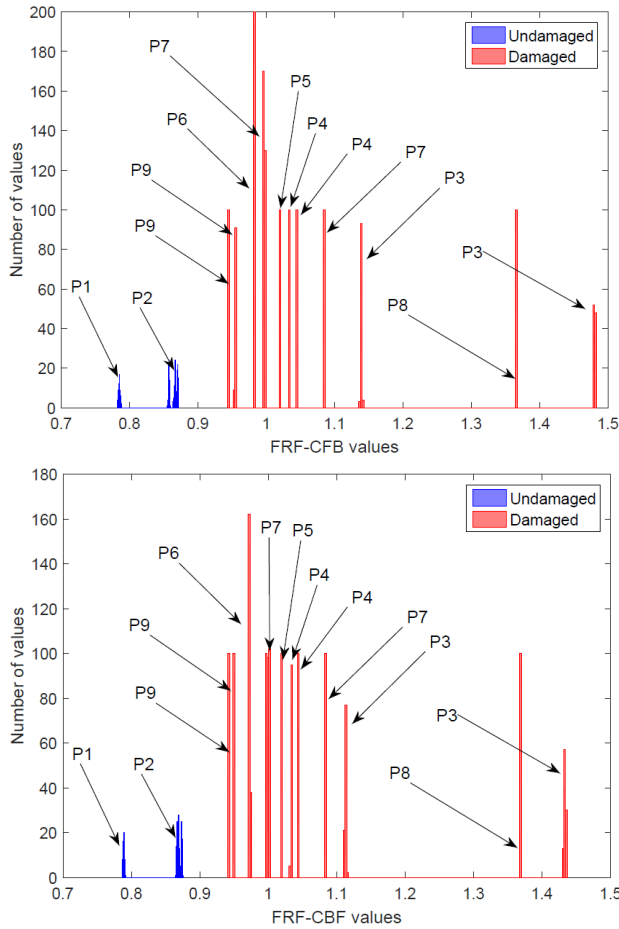


Figure 6. Histograms of the FRF-CFB diagnostic features obtained for Mode 2 from (top) Top Sensor and (bottom) Bottom Sensor.

The average values of the diagnostic feature FRF-CFB are also obtained from two pile vibration modes (i.e. Mode 2 and Mode 3), two accelerometer channels (i.e. top and bottom channels) and two vibration tests for each pile and used to classify the damage severity. 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 2, 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. In result, estimate of the total probability of correct evaluation of the damage severity is found as 89%.

Table 2: Evaluation 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

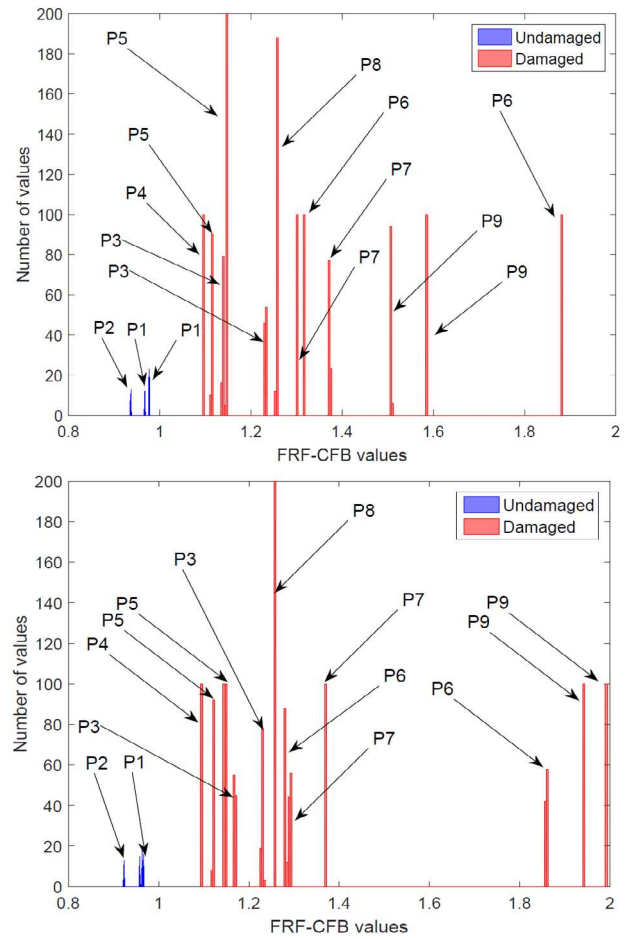


Figure 7. Histograms of the FRF-CFB diagnostic features obtained for Mode 3 from (top) Top Sensor and (bottom) Bottom Sensor.

5 COMPARISON OF THE FRF-CFB WITH THE PIT

The conventional pile integrity testing (PIT) is also performed on the same piles in order to make a comparison of the proposed technique and the PIT. The PIT is conducted using the hardware and software provided by Pile Dynamics Inc. (USA). The wave velocity is measured within the range of 4200 to 4450 m/s for all piles. Typical signals recorded on a damaged pile and one without any damage are displayed in Figure 8. The PIT 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 43%. The complete PIT results are summarized in Table 3. So, the effectiveness gain in estimates of the total averaged probability of correct damage detection that is provided by the proposed diagnosis technique in comparison with the classical PIT is 57%.

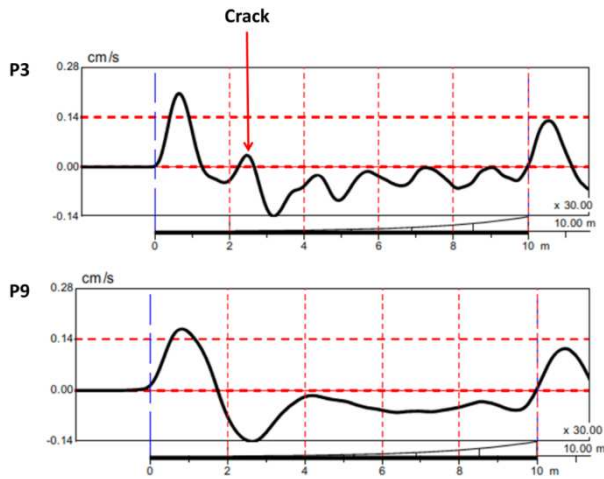


Figure 8. Wave signals recorded on P3 and P9.

Table 3: 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

6 CONCLUSIONS

The vibration-based integrity diagnosis for precast concrete foundation piles is proposed, investigated, and performed by the novel nonlinear non-stationary higher order frequency response function based on the chirp-Fourier bicoherence. It is shown by the vibration tests conducted on the industrial piles that 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 evaluation of damage severity is 89%. The proposed inspection technique effectively detects pile damage in the condition of phase coupled interferences caused by the excitation source by normalizing the bicoherence of the pile vibrations with respect to the bicoherence of excitation signal.

Conventional PIT technique is also performed on the same piles. The PIT diagnoses the damaged and the undamaged piles with estimate of the total probability of correct damage detection of 43%. Comparison with the classical PIT, the proposed diagnostic FRF-CFB technique achieves 57% effectiveness gain in the estimates of the total averaged probability of correct damage detection. In conclusion, the proposed higher order diagnostic technique presents a fundamental new concept and has the potential to make a major influence on integrity testing in the construction industry. Since all the piles examined within this project are located in the same site, the effect of the soil type on the diagnosis can be neglected. However, further investigations are needed to fully understand the effect of the soil type in order to achieve objective diagnosis on the piles installed in various types of soils.

7 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].

8 REFERENCES

- ASTM D4945-17: Standard Test Method for High-Strain Dynamic Testing of Deep Foundations. ASTM International, West Conshohocken, PA, 2017.
- ASTM D5882-16: Standard Test Method for Low Strain Impact Integrity Testing of Deep Foundations. ASTM International, West Conshohocken, PA, 2016.
- Collis W.B., White P.R. and Hammond J.K. 1998. High order spectra: the bispectrum and trispectrum. *Mechanical Systems and Signal Processing* 12 (3), 375-94.
- Cui, D., Yan, W., Wang, X. and Lu, L. 2017. Towards intelligent interpretation of low strain pile integrity testing results using machine learning techniques. *Sensors* 17 (11).
- Dong G., Chen J. and Zhao F. 2015. A frequency-shifted bispectrum for rolling element bearing diagnosis. *Journal of Sound and Vibration* 339, 396-418. Doi:10.1016/j.jsv.2014.11.015.
- Fackrell J.W., White P.R., Hammond J.K. and Pinnington R.J. 1995. The interpretation of the bispectra of vibration signals. *Mechanical Systems and Signal Processing* 9 (3), 267-74.
- García, S., Romero, J. and López-Molina, J. 2017. An intelligent pattern recognition model to automate the categorization of pile damage. *ICSMGE 2017 - 19th International Conference on Soil Mechanics and Geotechnical Engineering*, 2017-September 2743-2746.
- Gelman L. 2010. The new frequency response functions for structural health monitoring. *Engineering Structures* 32, 3994-3999.
- Gelman L. and Kirlangic A.S. 2020. Novel vibration structural health monitoring technology for deep foundation piles by non-stationary higher order frequency response function. *Structural Control and Health Monitoring* 27 (6). doi:10.1002/stc.2526.
- Gelman L. and Petrunin I. 2007. The new multidimensional time/multi-frequency transform for higher order spectral analysis. *Multidimensional Systems and Signal Processing* 18 (4), 317-325.
- Gelman L. and Petrunin I. 2012. Novel anomaly detection technique based on the nearest neighbour and sequential methods. *Insight: Non-Destructive Testing & Condition Monitoring* 54 (8), 433.
- Hamad W.I., Owen J.S. and Hussein M.F.M. 2015. Modelling the degradation of vibration characteristics of reinforced concrete beams due to flexural damage. *Structural Control and Health Monitoring* 22 (6), 939-967.
- Hickey D., Worden K., Platten M., Wright J. and Cooper J. 2009. Higher-order spectra for identification of nonlinear modal coupling. *Mech Syst Signal Process* 23 (4), 1037-61.
- Kirlangic A.S. 2020. Nonlinear vibration-based estimation of corrosion-induced deterioration in reinforced concrete. *Journal of Civil Structural Health Monitoring* 10 (4) 639-651. doi:10.1007/s13349-020-00408-1.
- Protopapadakis, E., Schauer, M., Pierri, E., Doulamis, A.D., Stavroulakis, G.E., Böhrnsen, J. and Langer, S. 2016. A genetically optimized neural classifier applied to numerical pile integrity tests considering concrete piles. *Computers and Structures* 162, 68-79.