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# Harmonic Acceleration Estimation for Shaking Table with Artificial Hummingbird Algorithm

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## Abstract

The Artificial Hummingbird Algorithm is a meta-heuristic algorithm presented to the literature by Liying Wang in 2021 and is a nature-inspired optimization algorithm that mimics the foraging behaviours of hummingbirds. The algorithm implements guided feeding and migration mechanisms using axial, diagonal and omnidirectional flight capabilities. In this study, harmonic estimation is performed using the Artificial Hummingbird Algorithm to solve the acceleration harmonic problem at the output of an electro-mechanical shaking table system. The Artificial Hummingbird Algorithm is run many times on a harmonic signal containing six harmonic components proposed in the literature and the estimation results obtained are analysed. In this process, precise amplitude and phase values are obtained and these values are compared with other optimization algorithms in the literature. As a result of the comparison, the performance of the proposed algorithm is evaluated and its effectiveness in terms of accuracy is analysed. As a result, the Artificial Hummingbird Algorithm, with its high accuracy and efficient estimation capability, provides a successful and reliable solution method for the harmonic estimation problem whose solution is sought in the literature.

**Key words:** Shake Table, Acceleration harmonics, Artificial Hummingbird Algorithm, Amplitude and Phase

## 1. Introduction

Earthquakes are natural disasters that occur unexpectedly and severely affect the lives of millions of people, the infrastructure of cities and the economy of countries. Depending on their severity, earthquakes can have devastating consequences on a large scale [1,2]. Analysing these earthquakes is of great importance for assessing future risks and developing preventive measures. In this context, the shake table is used as a critical analysis tool in the fields of civil, earthquake and structural engineering [3-5].

A shake table is a platform that uses artificial vibration generation up to three dimensions to simulate dynamic motions and vibrations. The test structure, which includes a servo motor, servo drive, top table and linear actuator, is installed on the shake table and its behaviours is monitored by subjecting it to dynamic motions. [6,7]. However, the harmonics caused by the nonlinearities of the mechanical materials in the electro-mechanical shake table system make the analysis difficult. One of the commonly used methods for estimating harmonics is the Fast Fourier Transform (FFT) [8]. However, this method cannot identify time-varying harmonics and transients accurately

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enough. Moreover, errors may occur in the frequency and amplitude estimation of harmonics due to the spectral escape effect. These drawbacks have led researchers to search for alternative methods. Accordingly, heuristic and meta-heuristic optimization methods have been widely used in many harmonic estimation studies.

The studies in the literature on the acceleration harmonic problem on the shake table are reviewed and the prominent findings of these studies are compiled in Table 1. In Table 1, the article title of each study, the authors, the algorithm developed in the study and a brief description summarizing the main findings of the related study are given. Thus, the methodological diversity and scientific contributions of the research on the acceleration harmonic problem are clearly shown.

**Table 1.** Studies on the harmonic problem in the literature

| Ref. | Improved Algorithm | Results |
|---|---|---|
| [9] | Particle Swarm Optimization (PSO) | A PSO-based algorithm is developed to estimate and cancel parasitic harmonics in the acceleration response of a hydraulic shaking table. The proposed method accurately estimates the amplitude and phase of the harmonics and achieves better results than conventional FFT methods. The algorithm is experimentally validated on a shake table and effectively identifies harmonic distortions caused by system nonlinearity. |
| [10] | Extended Kalman Filter (EKF) | This paper proposes an extended Kalman filter-based method to estimate harmonics in the sinusoidal acceleration response of an electro-hydraulic servo shaking table. We build a nonlinear state-space model of the acceleration response and estimate the phase information and harmonic amplitude directly from the states. The accuracy and real-time applicability of the algorithm are verified through both simulations and experiments. |
| [11] | Modified Artificial Bee Colony (MABC) + Recursive Least Squares (RLS) | In order to estimate and remove acceleration harmonics in a shake table system, this research suggests a novel method that combines the MABC and RLS algorithms. The RLS method removes the harmonics from the acceleration signal, while the MABC algorithm estimates the amplitude and phase of the harmonics. According to simulation and experimental data, the suggested method performs more accurately and robustly than PSO, BA, and traditional ABC algorithms. |
| [12] | Simulated Annealing (SA) | This work proposes a harmonic estimation approach for a hydraulic servo shaker table based on simulated annealing. Each harmonic's amplitude and phase are estimated by minimizing the objective function, which is defined as the sum of squared errors. Results from experiments and simulations demonstrate that the suggested approach is appropriate for real-time applications and reaches quick convergence and high estimation accuracy. |
| [13] | Water Cycle Algorithm (WCA) | This paper proposes the Water Cycle Algorithm (WCA) for estimating the harmonic content in the acceleration response of a hydraulic shaking table affected by system nonlinearities. The algorithm minimizes an objective function to estimate the amplitude and phase of fundamental and higher order harmonics. Both simulation and experimental results confirm that WCA offers fast convergence, high accuracy, and is well suited for real-time harmonic estimation applications. |
| [14] | Cheetah Optimization Algorithm (COA) | This paper introduces the Cheetah Optimization Algorithm (COA) for harmonic analysis of accelerometer signals obtained from a shake table system. The algorithm estimates the amplitude and phase of harmonics and is compared with other well-known methods such as PSO, BA and MABC. The results show that COA outperforms previous approaches in terms of error performance and provides an effective solution for harmonic estimation in nonlinear systems. |

The main objective and methodology of the study are;

- To facilitate the analysis of earthquake shaking signals by estimating the amplitudes and phases of the harmonics at the output of the shaking table.
- To demonstrate the effectiveness of the suggested Artificial Hummingbird Algorithm (AHA) in solving the harmonic analysis problem.
- As far as we are aware, this is the first time that an acceleration harmonic estimating method based on the Artificial Hummingbird Algorithm (AHA) has been reported. The suggested algorithm is contrasted with earlier research on the same signal in the literature to demonstrate the analysis's accuracy.

This study consists of four sections. In the first section, the harmonic analysis problem is discussed and a literature review on the subject is presented. In the second section, the proposed method, the Artificial Hummingbird Algorithm, is explained in detail and the mathematical model of the algorithm is presented. In the third section, the results of the analysis are presented and comparisons with other methods are made. Finally, the fourth section presents the overall findings and discussions of the study.

## 2. Artificial Hummingbird Algorithm (AHA)

The Artificial Hummingbird Algorithm (AHA) [15] is a nature-inspired optimization algorithm that mimics the foraging behaviours of hummingbirds. The algorithm implements guided feeding and migration mechanisms using axial, diagonal and omnidirectional flight capabilities [16].

$$X_j = LB + r \times (UB - LB), j = 1,2, \dots, N \tag{1}$$

Initial solutions were determined using r (a number between 0 and 1) randomly chosen between the lower boundary ($LB$) and the upper boundary ($UB$) of the search space.

$$VT_{j,i} = \begin{cases} 0, & if \quad j \neq i \\ null & \quad j = i \end{cases}, j = 1, \dots, N, i = 1, \dots, N \tag{2}$$

Where $VT_{j,i}$ = $null$ indicates that the hummingbird consumed the food at that location.

The hummingbird identifies the food source with the highest nectar regeneration rate and heads towards it. Three different flight types are used in this process:

- Axial Flight;

$$D^i = \begin{cases} 1, & if \quad i = R \\ 0, & \quad else \end{cases}, \ i = 1, \dots, d, \tag{3}$$

- Diagonal Flight;

$$D^i = \begin{cases} 1, & if \ i = P(j) \\ 0, & \quad else \end{cases}, \ j \in [1, k], \ i = 1, \dots, d, \tag{4}$$

$$P = randperm(k), k \in [2, [r1(d-2),] + 1]$$

- Versatile Flight;

$$D^i = 1 \quad i = 1, \ldots, d \tag{5}$$

The updated position is calculated by determining the fitness function $f(X)$;

$$V_i(t+1) = X_{i,t}(t) + a \times D \times (X_i(t) - X_{i,t}(t)), \quad a \in N(0,1) \tag{6}$$

The hummingbird leaves the worst food source and migrates to a random place;

$$X_w(t+1) = LB + r \times (UB - LB) \tag{7}$$

In this context, $X_w$ represents the solution point with the lowest fitness value. To improve search process diversity, $X_w$ is positioned at a new randomly selected point in the search space if this point stays in the same location for longer than the allotted number of iterations.

## 3. Analyses and Results

The mathematical modelling of the acceleration harmonic estimation and the objective function are shown below;

$$\begin{aligned} h(k) = {} & (A_{sub} \sin(\omega_{sub} k T_s) \cos \varphi_{sub} + (A_{sub} \cos(\omega_{sub} k T_s) \sin \varphi_{sub} + \ldots \\ & \sum_{n=1}^{Q} [A_n \sin(\omega_n k T_s) \cos \varphi_n + A_n \cos(\omega_n k T_s) \sin \varphi_n] + \cdots \\ & (A_{int} \sin(\omega_{int} k T_s) \cos \varphi_{int} + (A_{int} \cos(\omega_{int} k T_s) \sin \varphi_{int} + \ldots \\ & A_0 - A_0 \alpha_0 k T_s + n(k) \end{aligned} \tag{8}$$

Where $A_{sub}$ is the amplitude of the lower harmonic, $\omega_{sub}$is the frequency of the lower harmonic and $\varphi_{sub}$ is the phase of the lower harmonic. Similarly, $A_{int}$ is the amplitude of the intermediate harmonic, $\omega_{int}$ is the frequency of the intermediate harmonic and $\varphi_{int}$ is the phase of the intermediate harmonic. The objective function used by the Artificial Hummingbird Algorithm for harmonic estimation is as follows.

$$Objective = min\left(\sum_{k=1}^{K} e^2(k)\right) = MSE(h_k - h_{k_{kestirilen}}) \tag{9}$$

The performance of the AHA algorithm is assessed in this study using a test signal with six harmonics, a frequency of 5 Hz, and a sampling frequency of 500 Hz. The mathematical model of the test signal is given in Equation 10.

$$h(t) = 6\sin(10\pi t + 0.25) + 5\sin(20\pi t + 0.27) + 4\sin(30\pi t + 0.29) + 3\sin(40\pi t + 0.2) + \ldots$$

$$2\sin(50\pi t + 0.3) + 1\sin(60\pi t + 0.4) \quad (10)$$

The graph of the test signal and the signal estimated with the AHA algorithm is shown in Figure 3.1.a. The overlap between the two signals in the estimation result shows the accuracy of the estimation result. The power spectra between the two signals are displayed in Figure 3.1.b to improve the estimation result's dependability.

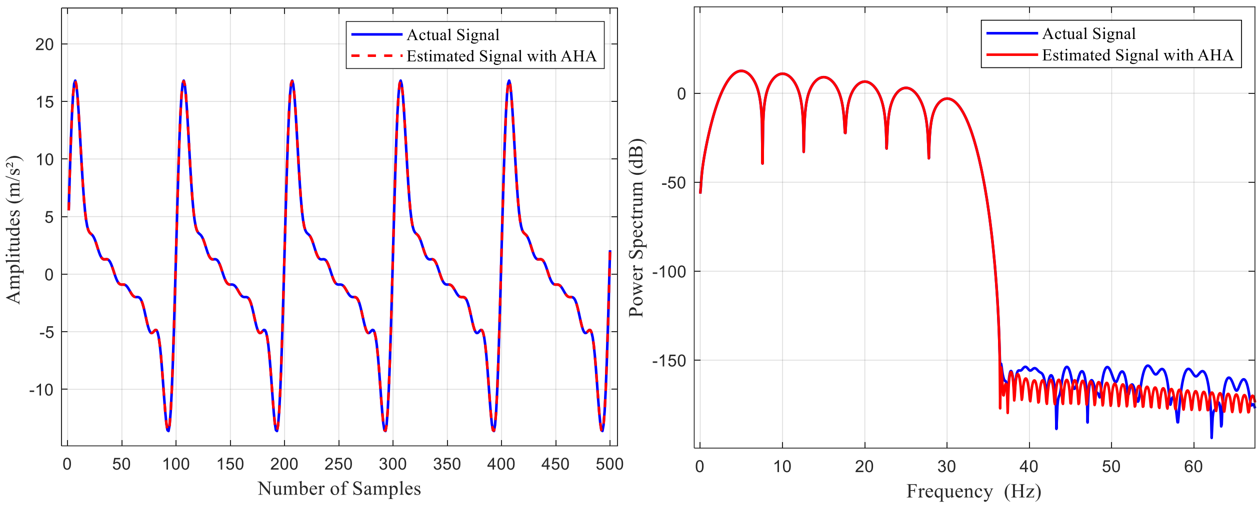


**Figure 3.1.** Test signal and AHA-estimated signal overlap(a). Power spectra of the signals(b).

The estimation was obtained by running the AHA algorithm 30 times in MATLAB R2024a. The algorithm used in the estimation was run for 2400 iterations with a population of 24 individuals. In the model, a total of 12 parameters (amplitude and phase) of 6 harmonic components were optimized. Parameter boundaries were set in the range [0,10] for amplitudes and [0,1] for phases. As a result of the estimation, the mean value was 2.234188e-04, the standard deviation was 8.860556e-04, the worst value was 4.456473e-03 and the best value was 6.834596e-12. The amplitude and phase values corresponding to the best value are shown in Table 2. In Table 2, the comparison of the amplitude and phase values obtained as a result of estimation with some optimization algorithms in the literature and their error rates are also given. Figure 3.2 shows the convergence curves of the phase (left) and amplitude (right) parameters with the AHA algorithm depending on the iterations. It is observed that the parameters reach stable values after a certain number of iterations.

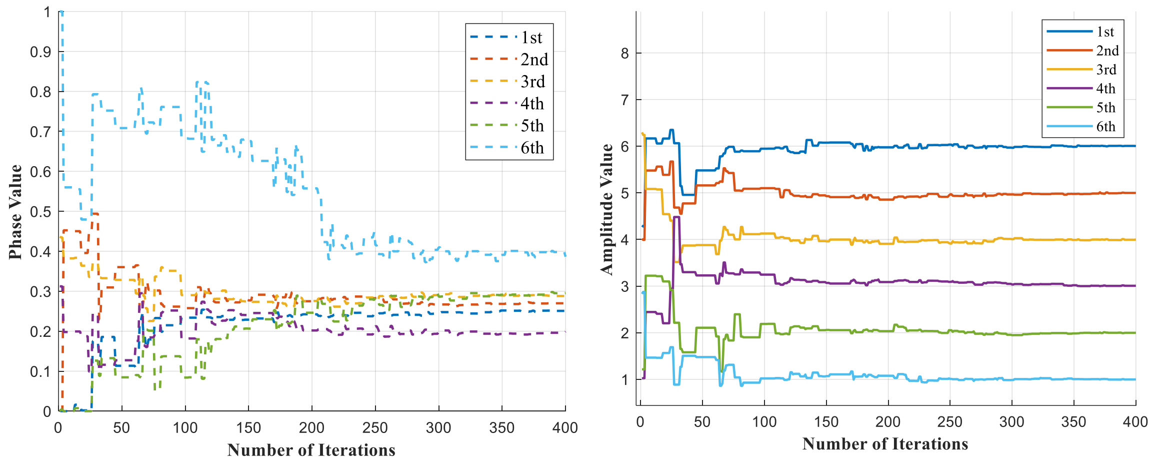


**Figure 3.2.** Convergence curves of phase (left) and amplitude (right) parameters depending on iterations

**Table 2.** Comparison of amplitude and phase values corresponding to the best error value in the estimation result

| **Algorithm** | **Parameter** | **Harmonics** | | | | | |
|---|---|---|---|---|---|---|---|
| | | **1.** | **2.** | **3.** | **4.** | **5.** | **6.** |
| **Actual Values** | **Frequencies (Hz)** | 5 | 10 | 15 | 20 | 25 | 30 |
| | **Amplitudes (m/s²)** | 6 | 5 | 4 | 3 | 2 | 1 |
| | **Phases (radians)** | 0.25 | 0.27 | 0.29 | 0.2 | 0.3 | 0.4 |
| **PSO Algorithm [9]** | **Amplitudes (m/s²)** | 6.0001 | 4.9986 | 3.9999 | 3.0011 | 2.0007 | 0.9997 |
| | **Error Rate (%)** | 0.0017 | 0.0288 | 0.0027 | 0.0357 | 0.0365 | 0.0257 |
| | **Phases (radians)** | 0.2499 | 0.2701 | 0.2901 | 0.1999 | 0.3000 | 0.4014 |
| | **Error Rate (%)** | 0.0282 | 0.0253 | 0.0430 | 0.0320 | 0.0033 | 0.3385 |
| **Bat Algorithm [17]** | **Amplitudes (m/s²)** | 6.0015 | 5.0006 | 4.0014 | 3.0010 | 2.0006 | 1.0009 |
| | **Error Rate (%)** | 0.0090 | 0.0054 | 0.0038 | 0.0109 | 0.0096 | 0.0218 |
| | **Phases (radians)** | 0.2501 | 0.2700 | 0.2901 | 0.1999 | 0.3000 | 0.4010 |
| | **Error Rate (%)** | 0.0064 | 0.0090 | 0.0032 | 0.0056 | 0.0624 | 0.0244 |
| **ABC Algorithm [18]** | **Amplitudes (m/s²)** | 6.0005 | 4.9999 | 4.0001 | 3.0001 | 2.0004 | 1.0003 |
| | **Error Rate (%)** | 0.0084 | 0.0027 | 0.0020 | 0.0030 | 0.0182 | 0.0255 |
| | **Phases (radians)** | 0.2500 | 0.2700 | 0.2900 | 0.2000 | 0.3000 | 0.4000 |
| | **Error Rate (%)** | **0.0011** | 0.0070 | 0.0050 | **0.0001** | **0.0024** | 0.0185 |
| **AHA Algorithm** | **Amplitudes (m/s²)** | 6.0000 | 5.0000 | 4.0000 | 3.0000 | 2.0000 | 1.0000 |
| | **Error Rate (%)** | **0.0001** | **0.0001** | **0.0002** | **0.0001** | **0.0001** | **0.0004** |
| | **Phases (radians)** | 0.2500 | 0.2700 | 0.2900 | 0.2000 | 0.3000 | 0.4000 |
| | **Error Rate (%)** | 0.0039 | **0.0027** | **0.0008** | 0.0047 | 0.0073 | **0.0122** |

## 4. Conclusions and Discussion

In this study, the estimation of harmonic acceleration signals on a shake table is realized with the Artificial Hummingbird Algorithm. The test signal from the literature was used to test the suggested algorithm thirty times. As a result of multiple runs, mean value 2.234188e-04, standard deviation 8.860556e-04, worst error 4.456473e-03 and best error 6.834596e-12 were obtained. Then, the precise amplitude and phase values corresponding to the best error value are compared with other algorithms in the literature. With error rates of 0.0001% in the first order harmonic, 0.0001% in the second order harmonic, 0.0002% in the third order harmonic, 0.0001% in the fourth order harmonic, 0.0001% in the fifth order harmonic and 0.0004% in the sixth order harmonic, it showed better results than other competing algorithms in all order harmonics. In the phase part, it outperformed the other algorithms with error rates of 0.0027% at second order harmonic, 0.0008% at third order harmonic and 0.0122% at sixth order harmonic. Thus, in 9 out of 12 parameters, the Artificial Hummingbird Algorithm outperformed the competing algorithms. Consequently, it is demonstrated that the suggested algorithm is a successful method for estimating harmonic acceleration signals.

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