Journal of Engineering Faculty

| cumfad.cumhuriyet.edu.tr | Founded: 2023 Available online, ISSN Publisher: Sivas Cumhuriyet Üniversitesi

Fast And High Preciously Estimator Design With Differential Evolution Algorithm For Shaking Table

Serdar Koçkanat[1,a]

[1]*Department of Electrical and Electronics Engineering, Cumhuriyet University, 58140, Sivas, Türkiye*
**Corresponding author*

Research Article

History

Received: 14/07/2023
Accepted: 24/07/2023

ABSTRACT

The shaking table is an experimental system in which the behavior of buildings and vehicles against ground shocks can be examined. A shaking table consists of electrical, mechanical and hydraulic parts to provide the desired technical specifications. In particular, harmonics are inevitable in the nonlinear shaking table system designed by these aforementioned parts. Harmonic is an undesirable disturbing signal that reduces the control performance of a system and distorts the output signal obtained from the system. Therefore, the identification and elimination of harmonics is an important design problem. In this paper, an acceleration harmonic estimator based differential evolution algorithm has been designed to determine the harmonics that occur especially in sinusoidal vibration tests. The proposed estimation approach was analyzed with both simulation and real-time harmonic signals including six harmonics. In addition, the amplitude and phase estimation results were compared with the results obtained by the simulated annealing algorithm. In short, fast and high preciously estimator design was realized by using differential evolution algorithm and its advantages were demonstrated with the obtained estimation results in literature.

Keywords: estimation; acceleration harmonics; shaking table; differential evolution; optimization.

[a] *skockanat@cumhuriyet.edu.tr* *https://orcid.org/0000-0001-6415-0241*

How to Cite: Koçkanat S. (2023) Fast And High Preciously Estimator Design With Differential Evolution Algorithm For Shaking Table, Journal of Engineering Faculty 1(1): 17-29

Introduction

In earthquake and civil engineering, the experimental system, in which the performance analyzes of structures and vehicles in low, medium and high intensity shocks can be examined and simulated, is called a shaking table [1]. In addition, the shaking table can be used successfully to simulate earthquakes that have occurred or are expected to occur.

The shaking tables can be designed up to 3 axes to simulate the desired or previously occurred earthquake motions. Also, shaking table designs including electrical, mechanical and hydraulic components have been developed. Thus, shaking tables can be produced to efficiently work at the desired load, precision and speed and they can also be used for different aims such as small scale structural mechanics, earthquake, ground and geological engineering experiments [2].

The electrical, mechanical and hydraulic components used in the design of the shaking table form a nonlinear control system and due to the aforementioned nonlinear factor, unwanted harmonics were especially shown in sinusoidal vibration tests. Harmonics are disturbing signals that negatively affect both the control performance of the system and the acceleration output signals generated by the system. Therefore, the identification and elimination of these disruptive harmonics arising from the internal components of the shaking table is an important engineering design problem [3, 4]. The key solution of this design problem is crucial for improving the control performance of the system and trustworthiness of the analysis results obtained from the aforementioned experiments [5]. Therefore, the greatest focal point of the design problem is to estimate the amplitude and phase values of each harmonic with high accuracy and to quickly perform the estimation process. As a result, the fast execution time and high accuracy in harmonic estimation will positively affect the control performance of the system and the reliability of the experimental analysis results.

In recent years, optimization algorithms have rapidly gained importance in solving many linear and nonlinear, one-dimensional or multi-dimensional, discrete or continuous engineering problems. Especially, suggested approaches based optimization algorithms provide fast computation and high accuracy for the estimation of amplitude and phase values of harmonics occurring in complex and nonlinear systems such as electrical power systems and shaking table. So, they have come to the fore with the aforementioned advantages. The well-known basic optimization algorithms such as least mean square (LMS), normalized LMS and recursive least square (RLS) algorithms have been used for acceleration harmonic estimation problems of the shaking table system [6-8]. However, when the harmonic order increases and the problem becomes nonlinear and more difficult, a deterioration in the estimation performance is observed. Also, the relative error in the phase estimation increases and the estimation speed slows down. In order to overcome the disadvantages of the aforementioned classical approaches and to obtain better estimation results, new estimation approaches have been proposed using metaheuristic algorithms that have better convergence rate in solution space and are more robustness in the solutions of nonlinear problems.

Particle swarm optimization (PSO) algorithm has been successfully applied for the harmonic estimation in power systems and PWM inverter systems [9, 10]. Therefore, an acceleration harmonic estimation approach based PSO algorithm has been proposed and better results have been obtained compared to the method reported in literature [11]. In addition, both the estimation and convergence performances of the PSO algorithm were compared with those of the LMS algorithm. A new approach for acceleration harmonic estimation was proposed using water cycle algorithm (WCA), and the performance criteria of the real-time calculation, convergence rate and estimation accuracy were analyzed [12]. Also, in order to improve the estimation results of the previously reported PSO algorithm, two suggested approaches based bat algorithm (BA) and artificial bee colony (ABC) algorithm have been applied for acceleration harmonic estimation problem and the results have been compared. Thus, the estimation results obtained in the literature have been improved [13, 14]. An approach based ABC algorithm has been proposed to solve the high-order acceleration harmonic estimation problem and the effect of increasing nonlinearity on estimation performance has been investigated [15]. The RLS method and the simulated annealing (SA) algorithm were used for the acceleration harmonic estimation approach and compared in practice [8]. The harmonic estimation accuracy and real-time convergence rate of the SA algorithm against the RLS algorithm were evaluated. Metaheuristic algorithm versus classical algorithm has been analyzed using performance criteria in multidimensional and nonlinear estimation problem.

From the discussions mentioned above, it is seen that the problem of acceleration harmonic estimation is an important design problem in electrical, mechanical or hydraulic systems and the estimation and elimination of harmonics have positive effects on the shaking table systems. Therefore, it is important to develop fast and accurate harmonic estimation approaches. In this study, to the best of our knowledge, differential evolution (DE) algorithm, that has fast convergence rate and powerful search ability, was used and analyzed for the first time ever in the acceleration harmonic estimation approach. It is also an important advantage that the proposed approach does not require any prior knowledge as with Kalman filters. For estimating the amplitude and phase values of the acceleration harmonics occurring in the shaking table system, the suggested approach based DE algorithm was examined for a literature test signal and an experimental signal with 6 harmonics. In both simulation and experimental study, the estimated amplitude and phase values were compared with the estimation approach based on the latest reported SA algorithm. Calculation time, convergence rate and estimation accuracy were selected as two important criteria in the simulation and experimental analyzes and the approaches were evaluated using these criteria for a fair comparison. As a result, the proposed approach based DE algorithm has shown a very accurate and rapid amplitude and phase estimation performance for both simulation and experimental acceleration harmonic signals.

Servo Electro-Mechanical Shaking Table

In Figure. 1, the servo electro-mechanical shaking table is shown. It is a single-axis shaking table and its size is 50x50 cm. This portable shaking table is often preferred in many university research laboratories or company research offices, because it has the ability to simulate recorded earthquakes and to apply defined waves such as sine, cosine and triangle signals and any acceleration or position profile defined by the user. The aforementioned system has a servo motor, closed loop PID controller, analog to digital converter, accelerometer sensors and a mechanical platform where vibration occurs. In addition, this system is a servo electro-mechanical shaking table with a weight of 45 kg, 1000 N power, 500 mm/s speed and operating frequency up to 20 Hz.

In this study, the performance of the proposed approach based DE algorithm is analyzed for acceleration harmonic estimation problem in servo electro-mechanical shaking table. The analyzes were carried out in two stages. At the first stage, the preferred simulation signal with 5 Hz fundamental frequency in the literature was used. And, at the second stage, the experimental signal with 3 Hz fundamental frequency was produced using the servo electro-mechanical vibration table in Figure. 1.

Figure. 1. Servo Electro-Mechanical Shaking Table

Differential Evolution

Differential evolution (DE) algorithm is a metaheuristic algorithm which is accepted in the class of population-based and evolutionary algorithms. Its mechanisms are mutation, crossover and selection and they are very similar to genetic algorithm (GA). The DE algorithm is a powerful population-based algorithm developed by Storn and Price between 1996 and 1997 [16].

In the DE algorithm, crossover, mutation and selection operators are used as in GA algorithm. In addition, the DE algorithm uses a mutation operator based on the difference of randomly selected solutions, while applying each operator to the whole population respectively in order to obtain better solutions. Through mutation and crossover processes, new individuals are formed by selecting three randomly selected chromosomes individually. By comparing the suitability values of the new chromosome obtained with the existing chromosome, the individual with the better fit is transferred to the next population as the new individual. Thus, the selection operator is also used. The quality of each solution is measured by the fitness value obtained by replacing it in the objective function. The basic steps of the DE algorithm are given as follows.

Step 1: Producing the initial population according to the objective problem.

Step 2: Evaluation of randomly generated population and determination of fitness values.

Step 3: repeat

Step 4: Mutation

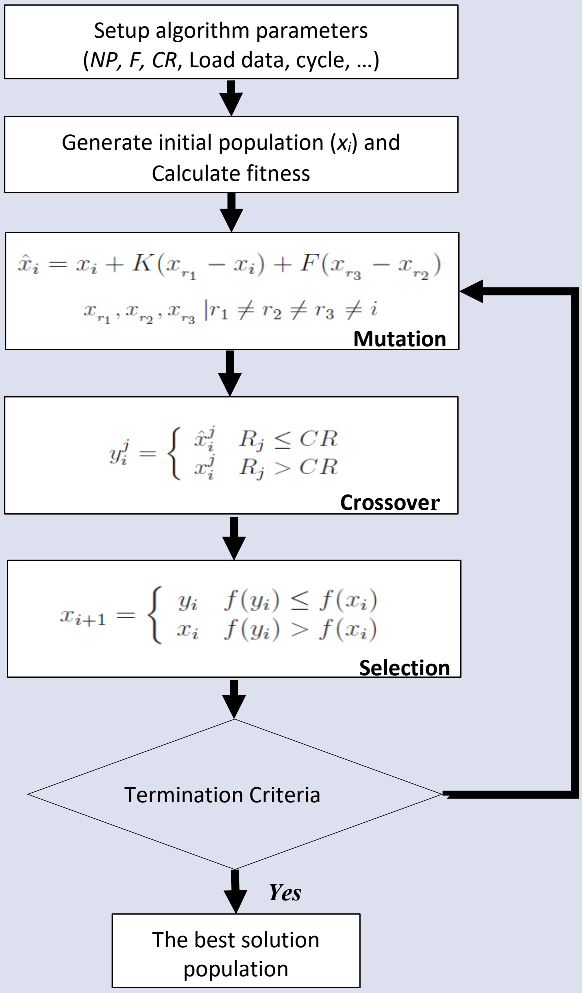
Step 5: Crossover (Recombination)

Step 6: Evaluation the population

Step 7: Selection

Step 8: until (cycle = maximum number of cycles)

The basic control parameters of the DE algorithm can be expressed as population size (NP), scaling factor (F), crossover ratio (CR) and maximum number of cycles. The basic flowchart of differential evolution algorithm is shown in Figure. 2.



Figureure. 2. The basic flowchart of differential evolution algorithm

Acceleration Harmonic Estimation Problem

In shaking table design problem, an acceleration harmonic signal can be modeled as the sum of the higher degree harmonics of the unknown amplitude and phase values and it is shown as

$$a(t) = \sum_{n=1}^{N} A_n \sin(2n\pi f_0 t + \varphi_n) \quad (1)$$

where f_0 is the fundamental frequency, A_n and φ_n are the unknown magnitude and phase values of the n_{th} harmonic. N represents harmonic order and $\omega_n = n2\pi f_0$ is the angular frequency of the n_{th} component. Then, acceleration harmonic signal is sampled with the desired sampling period T_s. $a(t)$ continuous signal is transformed to the $a(k)$ discrete harmonic signal and it can be expressed as

$$a(k) = \sum_{n=1}^{N} A_n \sin(\omega_n k T_S + \varphi_n) \quad (2)$$

Here, discrete harmonic signal $a(k)$ can be modeled using sine and cosine functions and it can be rewritten as

$$a(k)=\sum_{n=1}^{N}\left[A_n\sin(\omega_n kT_S)\cos\varphi_n + A_n\cos(\omega_n kT_S)\sin\varphi_n\right] \quad (3)$$

Later, $a(k)$ discrete signal in Equation 3 is converted to the parametric form as

$$a(k)=H(k)\theta(k) \quad (4)$$

where $H(k)$ is given as

$$H(k)=[\sin(w_1kT_S)\ \cos(w_1kT_S)\ \ldots\ \sin(w_NkT_S)\ \cos(w_NkT_S)]^T \quad (5)$$

Also, the vectors of unknown parameters is presented as

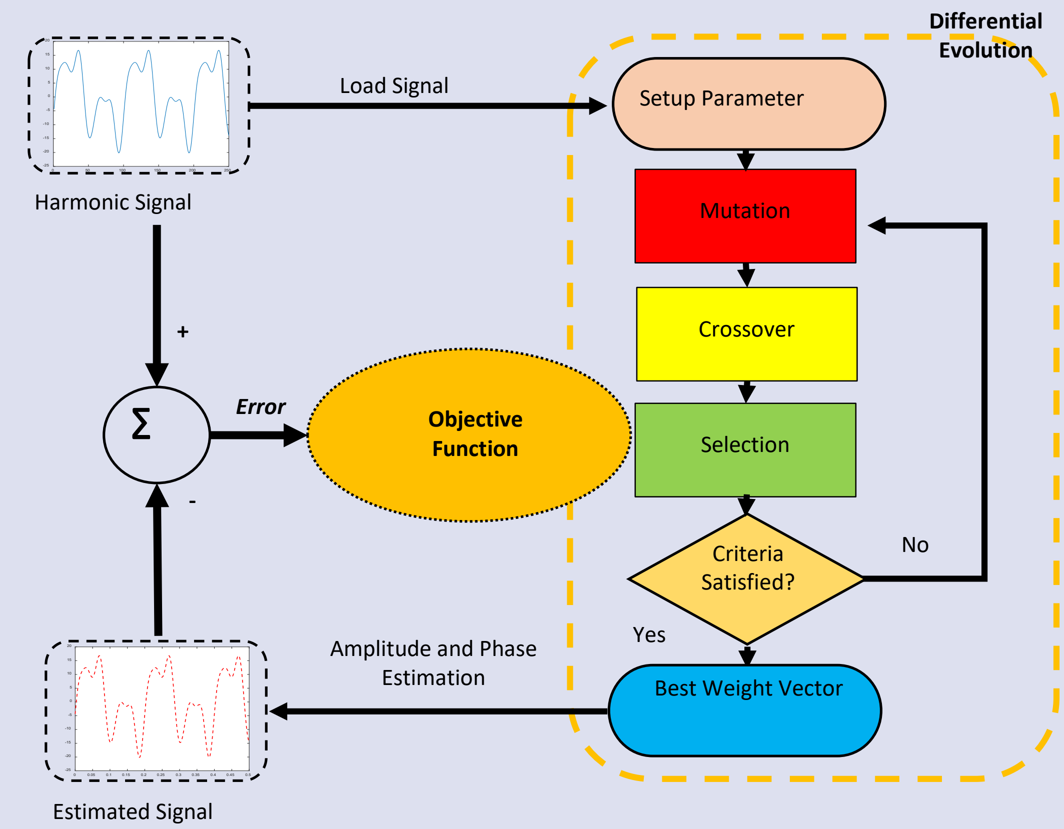
$$\theta(k)=[A_1\cos\phi_1\ A_1\sin\phi_1 \ldots A_N\cos\phi_N\ A_N\sin\phi_N\ ]^T \quad (6)$$

Using estimation vector in Equation 6, A_n and φ_n of the nth harmonic can be calculated.

An objective function in optimization is an important part of minimization or maximization operation and it is employed for optimizing the weight vector of the problem. In the acceleration harmonic estimation problem, the objective function is modeled as the mean square error between a_k and $\hat{a}_{k_{estimated}}$ signals and expressed as

$$J=\min\left(\sum_{k=1}^{K}e^2(k)\right)=MSE\left(a_k-\hat{a}_{k_{estimated}}\right) \quad (7)$$

where, a_k is the simulation or experimental harmonic signal and $\hat{a}_{k_{estimated}}$ represents the estimated harmonic signal by the proposed approach based DE algorithm. Also, k is the sample number. In Figure. 3, the flowchart of suggested approach based DE algorithm for acceleration harmonic estimation is represented.



Figureure 3. Block diagram of the acceleration harmonic estimation approach based DE algorithm

The block diagram of the acceleration harmonic estimation approach based DE algorithm can be illustrated with Figure. 3. Harmonic signal represents the sinusoidal acceleration output in shaking table system and estimated signal is generated by the estimated amplitude and phase values. The difference between harmonic signal and estimated signal is error signal and it is used to drive objective function for error minimization. In the flowchart, firstly, the initial setup parameters are determined and harmonic signal is loaded. Then, initial population is passed through mutation, crossover and selection mechanism. Each candidate solution is evaluated and calculated fitness value using objective function driven by error signal. At the end, the best weight vector is achieved and memorized. Amplitude and phase estimation is realized and estimated signal is produced. So, the estimation steps are successfully completed.

Simulation and Results

Firstly, at the simulation step, a simulation harmonic signal including six harmonics are generated according to the estimation approaches in literature [8]. The simulation harmonic signal is given as

$$a(t) = 10\sin(10\pi t) + 8\sin(20\pi t - 1.2) + 6\sin(30\pi t + 0.55) + 4\sin(40\pi t - 0.8) + 2\sin(50\pi t + 1.4) + 1\sin(60\pi t + 1) \quad (8)$$

The simulation signal contains 6 harmonics and the fundamental signal is at 5 Hz. The frequencies of other harmonics are at 10, 15, 20, 25 and 30 Hz, respectively.

For the DE algorithm, population size (*NP*), scaling factor (*F*), crossover ratio (*CR*) and cycle number were experimentally determined as 24, 0.5, 0.8 and 250, respectively. Also, for achieving the best solution, the strategy is selected as DE/rand/1/bin from all strategies. For a fair and accurate assessment, DE algorithm was run 30 times with different initial seeds and the mean values of these multiple runs were evaluated and compared.

After determining the setup parameters, the simulation signal is applied to the suggested approach based DE algorithm for the amplitude and phase estimation. At the end of the calculation process, estimated amplitude and phase values using DE algorithm are listed in Table 1 for 6 harmonics. The harmonic estimation results obtained by DE algorithm are very close to the actual values and the relative errors are very small compared with those of the SA algorithm. When the reported harmonic estimation results taken into account, it is concluded that proposed approach based DE algorithm is a high preciously estimator design for acceleration harmonic estimation in shaking table system. Also, it has superior performance than that of the SA algorithm.

In Figure. 4, harmonic estimation period is observed and the overlap between the actual simulation signal suggested in literature and estimated signal by DE algorithm is analyzed. In the initial estimation, the fluctuation decreases within 0.05 seconds and the actual and estimation signals overlap in complete agreement. After 0.1 seconds, a perfect agreement between two signals is occurred.

Table 1. Harmonic estimation results of SA and DE algorithms

Algorithms	Parameters	Harmonics Degree					
		Fund.	Second	Third	Fourth	Fifth	Sixth
Actual	Frequency (Hz)	5	10	15	20	25	30
	Amplitude (m/s^2)	10	8	6	4	2	1
	Phase (radian)	0	-1.2	0.55	-0.8	1.4	1
SA Algorithm [8]	Amplitude (m/s^2)	9.9998	8.0004	5.9999	4.0007	1.9993	0.9998
	Error (%)	0.0018	0.0052	0.0025	0.0172	0.0358	0.0224
	Phase (radian)	-0.0000	-1.2000	0.5500	-0.7998	1.4000	0.9997
	Error (%)	0.0000	0.0008	0.0064	0.0238	0.0002	0.0272
DE Algorithm	Amplitude (m/s^2)	10.0000	8.0000	6.0000	4.0000	2.0000	1.0000
	Error (%)	0.0004	0.0001	0.0002	0.0000	0.0001	0.0012
	Phase (radian)	0.0000	-1.2000	0.5500	-0.8000	1.4000	1.0000
	Error (%)	0.0000	0.0000	0.0004	0.0000	0.0001	0.0008

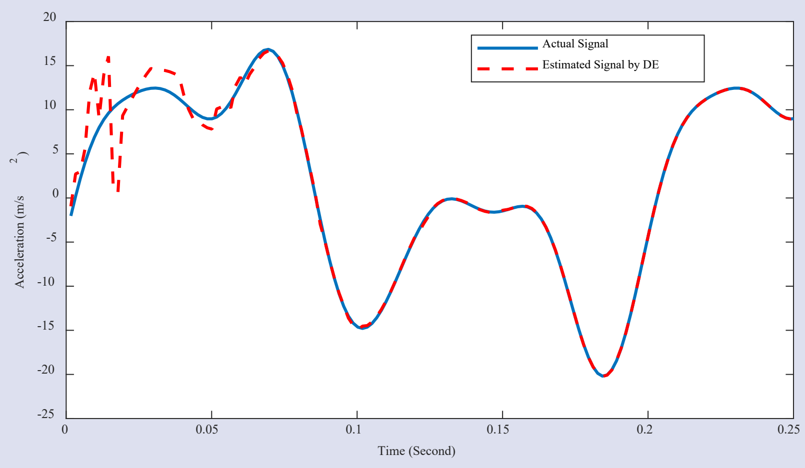


Figure 4. Actual signal and estimated signal by DE algorithm

In Figure. 5 and 6, the estimated amplitudes and phases by applying DE algorithm are shown in detail. For each harmonic, amplitude-time and phase-time curves are drawn. In the initial estimation interval for both amplitude and phase, random fluctuations can be observed. As mentioned above, the randomly generated weight vector causes this change. But, after about 0.1 seconds, the estimated amplitude and phase values of each harmonic converge to the predefined actual values. The convergence time is very small compared with that of the SA algorithm, because SA algorithm completes the optimization within about 0.4 seconds.

In Figure. 7, for each harmonic, generated waveform by generating estimated amplitude and phase values is shown. From this Figureure, it is shown that acceleration harmonic estimation problem in shaking table system is solved and computed with 0.1 seconds using proposed approach based DE algorithm.

When the reported harmonic estimation results in simulation taken into account, it is obvious that fast and high preciously estimator design with differential evolution algorithm is realized and efficiently applied at the simulation stage.

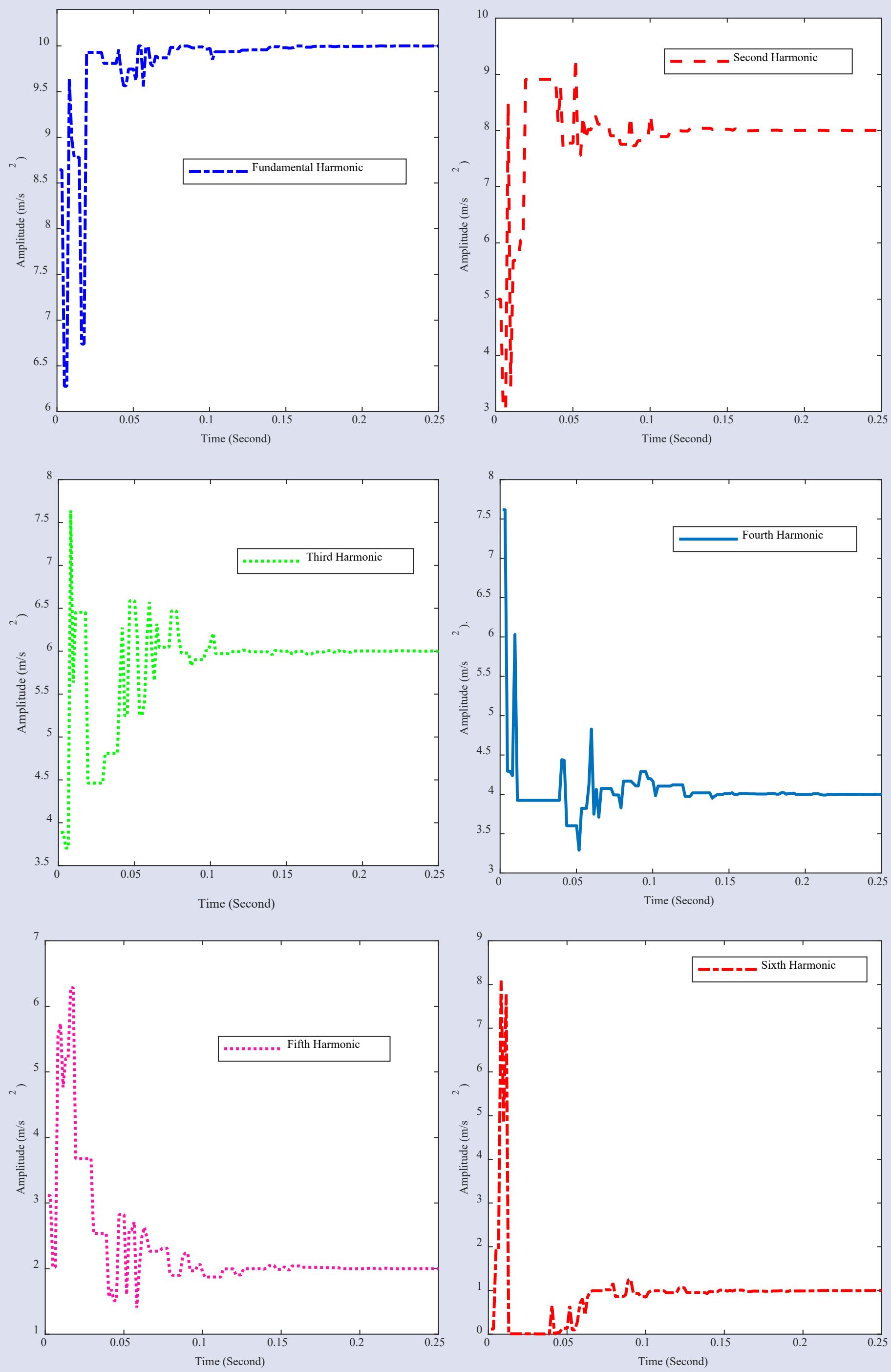


Figure 5. The estimated amplitudes by applying DE algorithm

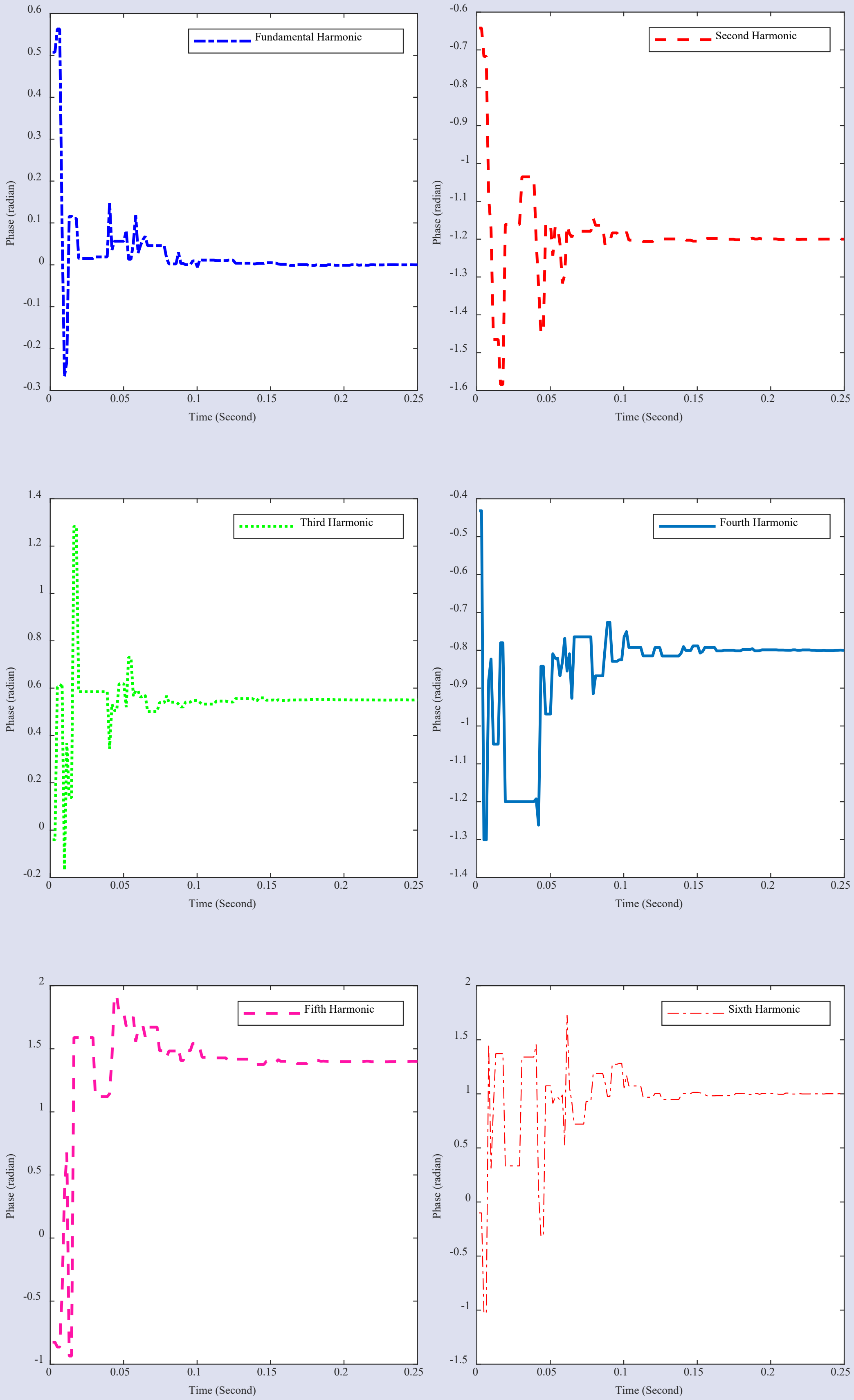


Figure 6. The estimated phases by applying DE algorithm

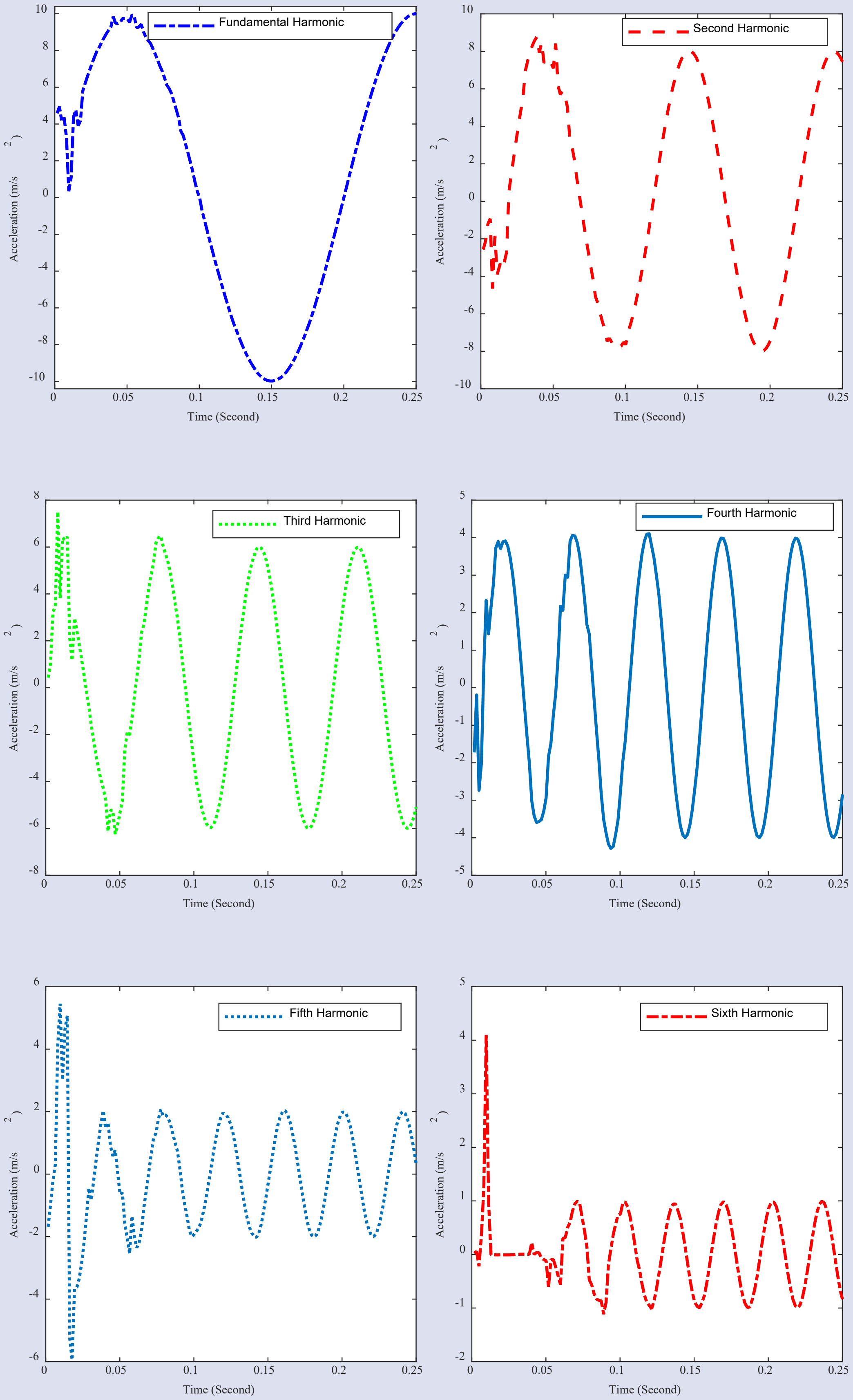


Figure 7. Harmonic waveforms by generating estimated amplitude and phase values

Experiment and Results (3 Hz)

Secondly, at the experimental stage, an experimental harmonic signal is obtained from the servo electro-mechanical shaking table in real-time. The experimental signal contains 6 harmonics and the fundamental signal is at 3 Hz. The frequencies of other harmonics are at 6, 9, 12, 15 and 18 Hz, respectively. The setup parameters are selected as previous section.

In real-time application, proposed approach based DE algorithm is operated after the third seconds, because real-time data acquisition and experiment begin at this start time. Also, above aforementioned optimization steps have been realized.

In Figure. 8, the actual experimental signal and estimated signal by DE algorithm are shown. The tracking ability of the proposed approach depends on the fast and accurate estimated amplitude and phase values and it is quite satisfactory. Because, after 3.1 seconds, the agreement between two harmonic signal is growing at perfect level. The best fit is achieved within 3.2 seconds. Also, at the end of real-time estimation, the obtained results using proposed approach based DE algorithm is tabulated in Table 2. When the Figure. 8 and Table 2 taken into account, it is concluded that the high preciously estimator design computes successively the amplitude and phase values of harmonics in simulation and experimental applications.

The estimated amplitudes and phases by applying DE algorithm are given in Figure. 9 and 10 for real-time application. As can be seen from the Figureures, fluctuations continue in amplitude and phase estimation, though the estimated amplitude and phase values of each harmonic converge to their stable values. After about 3.2 seconds, amplitude estimation process is exactly completed for each harmonic. But, phase estimation process of the 2_{nd}, 4_{th} and 6_{th} harmonics is finished after about 3.4 seconds.

In Figure. 11, waveforms of all harmonics by generating estimated amplitude and phase values is presented. For real-time acceleration harmonic estimation, proposed approach based DE algorithm solves the desired results within 0.2 seconds.

To sum up, when the estimated amplitude and phase values, generated waveforms of all harmonics, and convergence times in simulation and experimental conditions taken into account, it is evident that the proposed estimator design not only has the fast and preciously solution ability, but also it is suitable for real-time application. Also, the proposed design show better estimation performance than those of the SA and RLS algorithm.

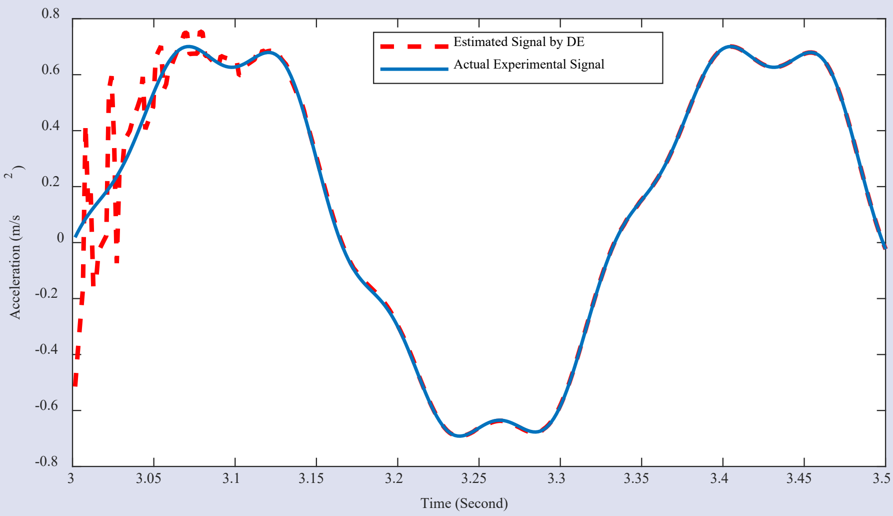


Figure 8. Actual experimental signal and estimated signal by DE algorithm

Table 2. Harmonic estimation results of DE algorithm

Harmonic Degree	Amplitude (m/s2)	Phase (radian)
Fundamental	-0.7185	3.0242
Second	-0.0033	1.0666
Third	-0.0381	-2.5075
Fourth	0.0076	-2.4615
Fifth	0.0745	1.8149
Sixth	-0.0044	1.5760

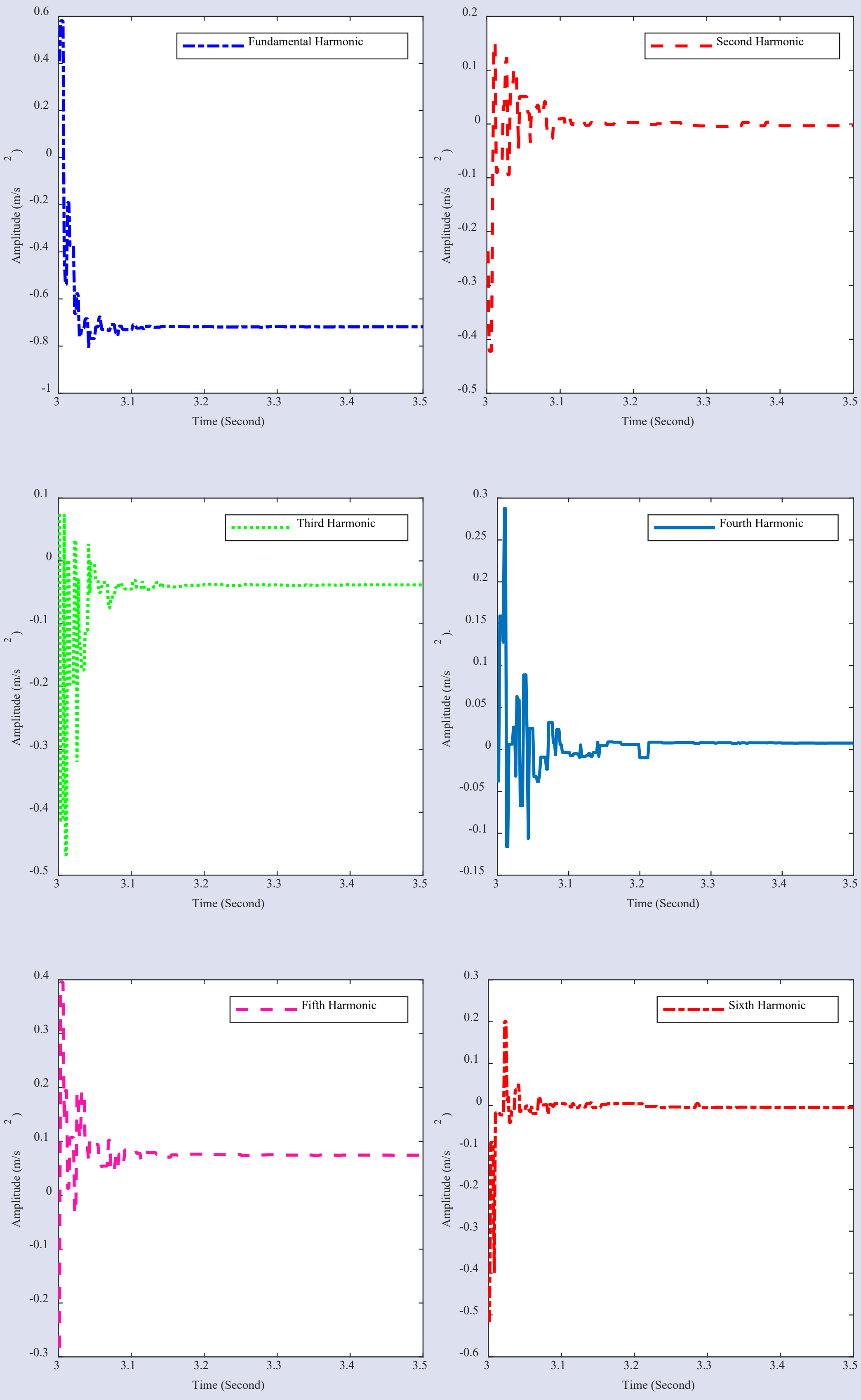


Figure 9. The estimated amplitudes by applying DE algorithm

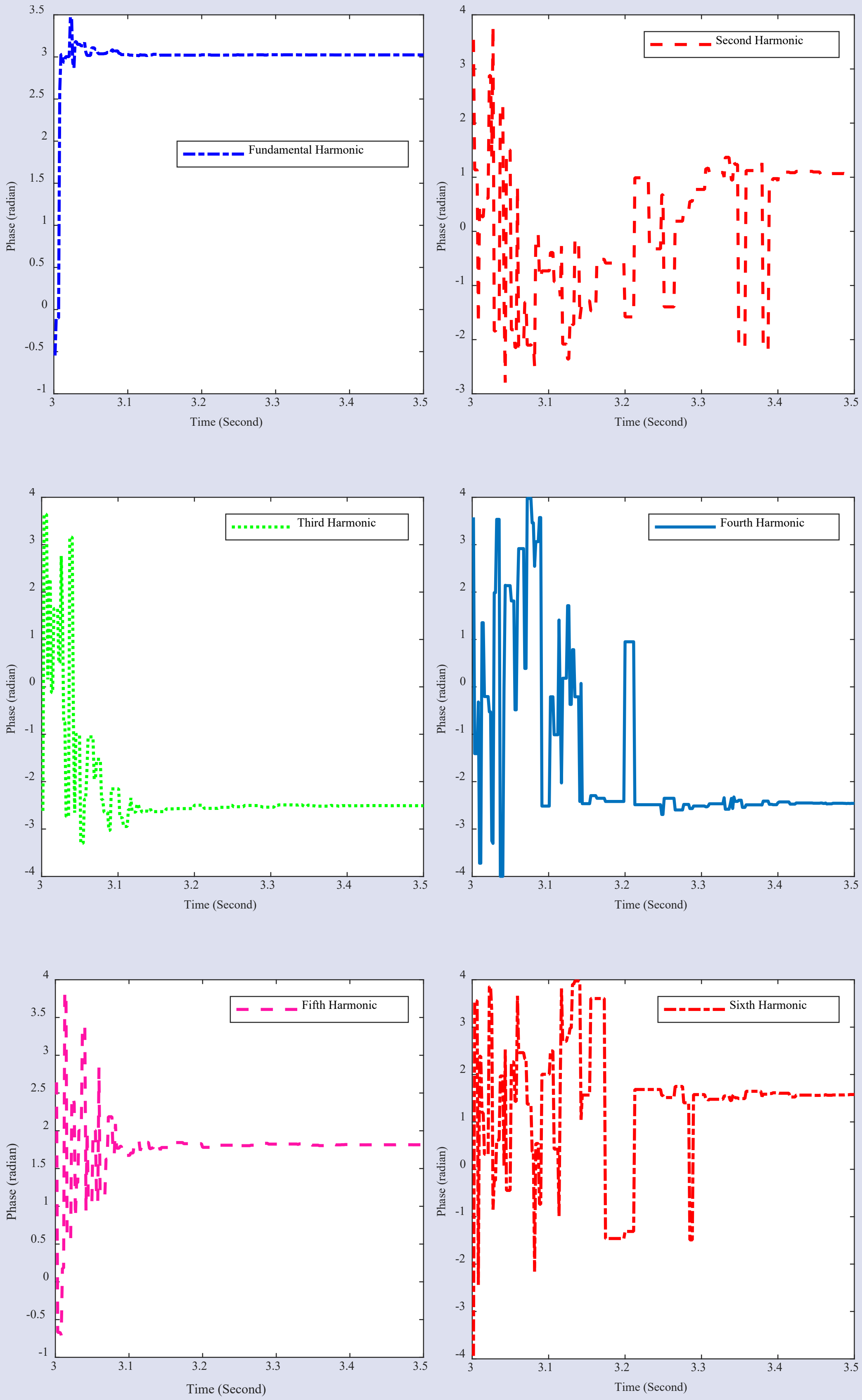


Figure 10. The estimated phases by applying DE algorithm

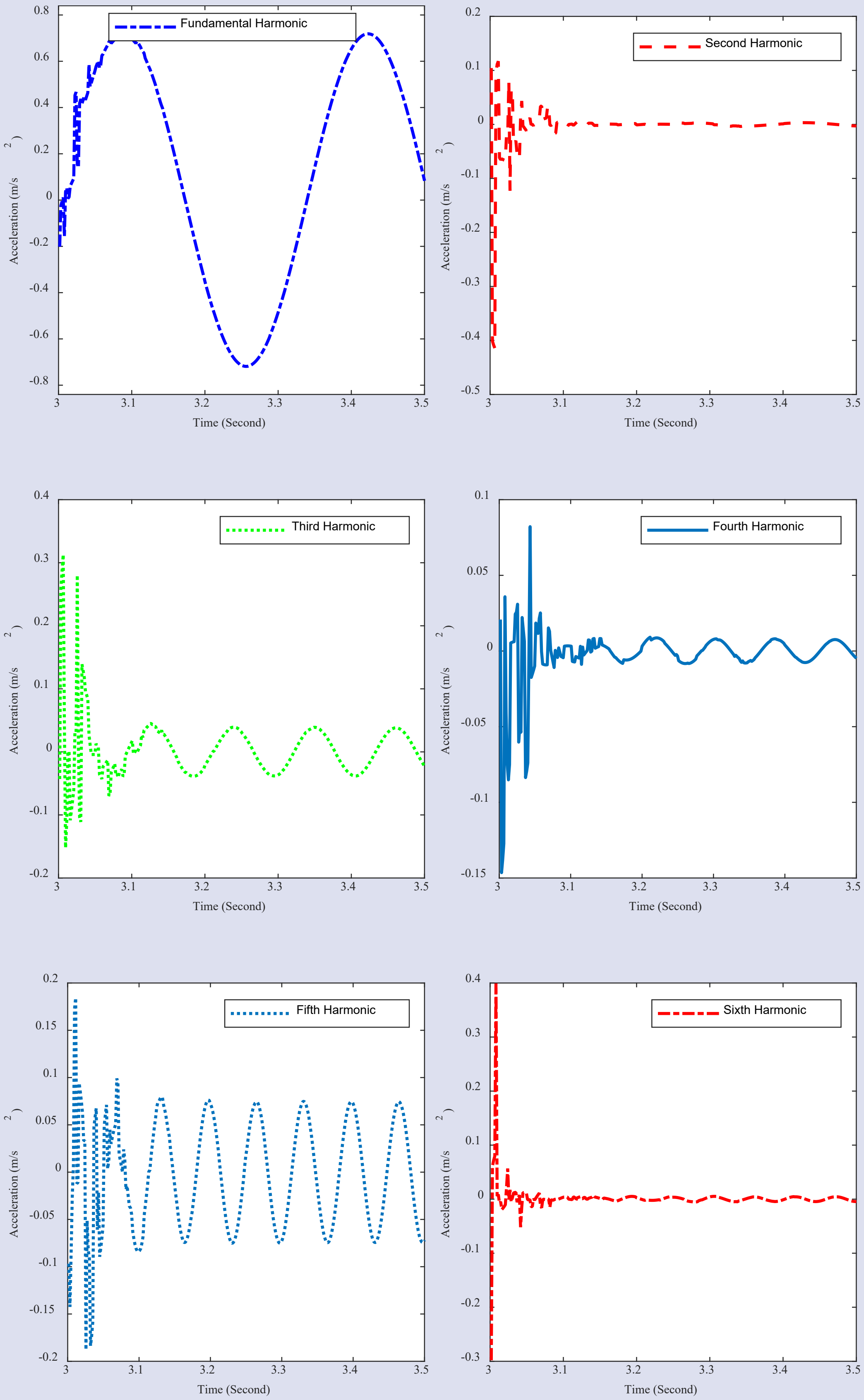


Figure 11. Harmonic waveforms by generating estimated amplitude and phase values

Conclusions

In this study, fast and high preciously harmonic estimator design with differential evolution algorithm is developed and coded. In particular, a key solution has been proposed for the determination of harmonics in the shaking table system. Unlike many solutions using optimization algorithms, the harmonic estimator design has been analyzed for both simulation and experimental cases. At the simulation stage, a simulation signal with 6 harmonics was used. The fundamental frequency is 5 Hertz. With the proposed harmonic estimator, amplitude and phase values of each harmonic in the simulation signal are estimated. All estimation results obtained by DE algorithm are shown in Table 1. The best relative error in amplitude estimation was 0.0000, while the worst relative error was 0.0012. In the phase estimation, the best relative error value was 0.0000, while the worst relative error value was 0.0008. In addition, the estimation process was completed within 0.1 seconds. When the estimation results, graphics and convergence time are taken into account, a more successful harmonic estimation was performed compared with the SA algorithm. At the experimental stage, a real-time harmonic signal with a fundamental frequency of 3 Hertz was used. Up to 6 harmonics were estimated for the experimental signal and it was obtained from servo electro-mechanical shaking table system. The estimated amplitude and phase values are given in Table 2. Relative error values could not be calculated because the actual amplitude and phase values were not known. However, the amplitude and phase estimation figures of each harmonic show that the designed harmonics estimator works successfully. In addition, the estimation process was completed in 0.2 seconds. To sum up, when the reported harmonic estimation results, figures and convergence rate in simulation and experimental conditions taken into account, it is concluded that fast and high preciously estimator design with differential evolution algorithm is efficiently realized and its performance is better than that of the SA algorithm.

References

[1] Ji X., Kajiwara K., Nagae T., Enokida R., Nakashima M., A substructure shaking table test for reproduction of earthquake responses of high-rise buildings, Earthquake Engineering and Structural Dynamics, 38 (12) (2009) 1381-1399.

[2] Shen W., Wang J.Z., Wang S.K., The control of the electro-hydraulic shaking table based on dynamic surface adaptive robust control, Transactions of the Institute of Measurement and Control, 39(8) (2017) 1271-1280.

[3] Yao J., Yan H., Xiao R., Di D., Jiang G., Gao S., Yu H., Sinusoidal acceleration harmonic estimation using the extended Kalman filter for an electro-hydraulic servo shaking table, Journal of Vibration and Control, 21(8) (2015) 1566-1579.

[4] Yao J.J., Hu S.H., Fu W., Han J.W., Impact of excitation signal upon the acceleration harmonic distortion of an electro-hydraulic shaking table, Journal of Vibration and Control, 17(7) (2011) 1106-1111.

[5] Yao J., Acceleration Harmonic Cancellation of Electro-hydraulic Servo Shaking Table, Chinese Journal of Mechanical Engineering, 46(3) (2010).

[6] Yao J., Jiang G., Di D., Liu S., Acceleration harmonic identification for an electro-hydraulic servo shaking table based on the normalized least-mean-square adaptive algorithm, Journal of Vibration and Control, 19(1) (2013) 47-55.

[7] Yao J., Hu. S, Fu. W, et al., Harmonic cancellation for electro-hydraulic servo shaking table based on LMS adaptive algorithm, Journal of Vibration and Control, 17(12) (2011) 1862-1868.

[8] Yao J., Wan Z., Fu Y., Acceleration Harmonic Estimation for Hydraulic Servo Shaking Table by Using Simulated Annealing Algorithm, Applied Sciences, 8(4) (2018) 524.

[9] Lu Z., Ji T.Y., Tang W.H., et al., Optimal Harmonic Estimation Using A Particle Swarm Optimizer, IEEE Transactions on Power Delivery, 23 (2) (2008) 1166-1174.

[10] Ray R.N., Chatterjee D., Goswami S.K., An application of PSO technique for harmonic elimination in a PWM inverter, Applied Soft Computing, 9(4) (2009) 1315-1320.

[11] Yao J., Yu H., Dietz M., Xiao R., Chen S., Wang T., Niu Q. Acceleration harmonic estimation for a hydraulic shaking table by using particle swarm optimization, Transactions of the Institute of Measurement and Control, 39(5) (2017) 738-747.

[12] Yao J., Wan Z., Fu Y., Acceleration Harmonic Estimation in a Hydraulic Shaking Table Using Water Cycle Algorithm, J Shock and Vibration, (2018) 12.

[13] Kockanat S., Acceleration Harmonic Estimation for Hydraulic Shaking Table Using Bat Algorithm, European Journal of Science and Technology, 15 (2019) 387-393.

[14] Kockanat S., Acceleration Harmonic Estimation using an Approach based Artificial Bee Colony Algorithm: A Hydraulic Shaking Table Application, 2019 27th Signal Processing and Communications Applications Conference (SIU), (2019) 1-4.

[15] Yao J., Wan Z., Fu Y., et al., An Artificial Bee Colony Algorithm for Solving Hydraulic Shaking Table Acceleration Harmonic Estimation Problem, ASME 2018 Noise Control and Acoustics Division Conference, (2018) 1-5.

[16] Storn R., Price K., Differential Evolution – A Simple and Efficient Heuristic for global Optimization over Continuous Spaces, Journal of Global Optimization, 11 (4) (1997) 341-359.