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A NOVEL HYBRID ALGORITHM FOR ACCELERATION HARMONIC ESTIMATION AND ELIMINATION IN SHAKE TABLE

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ABSTRACT

Shake table tests instantly submits structure models for seismic excitation and evaluates its overall performance. However, inconsistencies in the amplified seismic output will undoubtedly exist and the desired signals cannot be precisely achieved. The ability to accurately estimate and analyze system harmonics is necessary for building control filters that hinder harmonic levels in the signals. This paper initially focus on studying the key techniques such as time integration algorithms, filtering techniques and metaheuristic optimization methods to understand its applications, and their implementation in shake tables. Then, a novel hybrid algorithm that has the capability of regulating the weights of the unknown parameter of harmonic signal arising in the table is formulated. A simulation and experimental study is carried out and the developed algorithm is also compared to Artificial Bee Colony (ABC) algorithm, Particle Swarm Optimization (PSO) algorithm and Modified Ant Bee Colony-Recursive least squares (MABC-RLS) algorithm, and studied in terms of performance. Finally, future research and application challenges are discussed and underlined.

Keywords: Shake table, numerical techniques, filtering techniques, meta heuristic techniques, LabVIEW

1. INTRODUCTION

Shake tables play a critical role in earthquake-resistant design of structures. These experimental facilities were used as a design tool to corroborate a theoretical investigation. The concept was originally investigated around 1890s. Eventually, the practical needs in civil engineering sector resulted in a wide range of shake tables between 1890s and 1950s. Japan was the first to suggest
shake table testing to explore the seismic response and subsequently the United States started investigations followed by Europe and Canada. In Japan, the progress began when a small-scale model testing of a graphite core of the nuclear power plant in Tokai Mura on the SDOF shake table (Severn 2010). It produced 2g acceleration by releasing an array of compressed springs at one end and responding with an identical set at the other. Despite its simplicity, it was claimed to provide useful information on the graphite block arrangement.

In the same decade, the test system was maneuvered to and forth along a predetermined track to produce harmonic motion. A realistic motion was noticed when a significant peak followed by descending vibration was produced by a swinging pendulum striking at one hand of the table. This was repelled by a set of springs at the other hand. Later, this version was featured with springs on both ends, with one pair compressing and releasing. However, the concept of a positively charged piston that functioned against an oil-filled cylinder proposed at the beginning of 1930s, stood as a milestone in the modern era. It was never fully engineered since the war between 1939 and 1945 hampered the development of the necessary supporting technologies (Severn 2010). On the other hand, the war resulted in significant advancements in the control of mechanical systems by the military forces (e.g., oil-filled actuator).

In the early 1960s, initiatives were taken to test buildings of full scale in Jassy, Romania. A 10 m x 10 m shake table with input from two Electro-Hydraulic Actuators (EHAs) capable of accelerating up to 0.4g was built to test civil engineering structures (Lu et al. 2007). Owing to increase advancement in computer technologies, electro-hydraulic servo-system began to dominate motion simulation vibration systems after the mid-1960s. The University of Illinois calibrated a 1-DOF table attached to a firm foundation with the help of the newly founded MTS System Corporation (1966). It was driven by a single actuator that would produce constant motion with real and arbitrary seismic waveforms (Darby et al. 1999). The control variables were displacement, velocity, or acceleration, but the preferred option for eliminating table damage was identified to be displacement. In order to avoid the absorption of the input energy data and to minimize the excitation of the other DOFs, the size of the test setup was carefully chosen. This qualified the Illinois table as a step forward in shake table development in that decade. But the critical question, which was never distinguishably answered was the degree to which the motion imparted to the test piece matched that of the actual earthquake. Most large Japanese corporations continued to construct their own, perhaps larger tables, until the mid-1980s based on the same concepts and to overcome the above disadvantages. A platform size of 7.6 m x 12 m constructed in San Diego, that could
test completely scaled constructions, and the 20 m x 15 m table by National Research Institute for Earth Science and Disaster Prevention (NIED), Japan at E-Defence Network seemed to be a more notable example (Okazaki 2012). It was competent in testing a full-scale 5-story building in all three dimensions to a short pulse or continuous time history of acceleration simulating the earthquake ground motion. Nearly 47 constructions had been tested since it opened in 2005, which also included full-scale RC structures, foundations, wooden dwellings, steel skeleton buildings, and bridges.

Due to a shortage of oil capacity in shake tables, long-period motion was difficult to replicate. This caused major damage to several large buildings in Tokyo during the Tohoku earthquake on March 11, 2011. In the mid of 2017, Hamayoon Kheradi (Kheradi et al. 2018) used a unidirectional shake table with a maximum weight of 16 KN to study the mechanical properties of subsurface buildings subjected to earthquake loading. Furthermore, box culverts in active-seismic areas that do not fulfill current seismic design criteria were also surveyed.

In 2017, Shimizu Corporation in Singapore installed the E-beetle and E-spider, the most advanced large-scale and large-stroke shake tables in the construction area. The maximum payload capacity of the 7 meters long and 7 meters wide, large table was 70 tonnes. It could realistically check a building’s seismic performance during earthquake, including how a building responded up until the brink of collapse, the interior and external wall facings and machinery equipment inside the building (Phyu et al. 2018). In the University of Engineering and Technology (UET) Taxila, Pakistan, a one dimensional, electro dynamically operating shake table of 3 x 3 inch, that could operate at an acceleration of 0.3 to 0.4 m/s$^2$ was constructed, and installed on 2019. It was powered by a mechanical linear drive, motion controller, and 3 HP servo motor with encoder (Danish et al. 2019). In the same year, the uniaxial shake earthquake simulation equipment of 250 KN servo-hydraulic actuator that moved a 6 m x 6 m aluminum platform was utilized to conduct a dynamic test on a timber-framed house in the Institute of French Mechanical Laboratory (IFMA) to investigate the hysterical reaction of a building to seismic loading (Vieux-Champagne et al. 2017). On the other hand, to gain the transfer functions and to achieve desired accelerations on the table, a low-amplitude signal is used in the shake table setup. However, inconsistencies in the amplified seismic output will undoubtedly exist and the desired signals cannot be precisely achieved. Thus, the study on real-time control with the abilities to reproduce earthquake acceleration is an area that requires adequate attention and consideration.
Although loading devices relied on numerical simulations for target values, the ability of the numerical simulation to produce such a target value had accurately become critical. Hence, an efficient time integration technique was always desired. A wide range of topics, including various approaches of numerical time integration, appropriate methods for error corrections in experiments, and the use of pseudo-dynamic and real-time distributed hybrid testing methodologies were discussed by researchers. The backward Euler integration method in the experimental study of liquid storage tanks under seismic excitation (Igarashi et al. 2000), implicit Hilber-Hughes-Taylor (HHT) with predetermined number of sub-step iterations to account for nonlinearity in real time hybrid experimentation (Chen and Ricles 2012), 4th order Runge-Kutta (RK) integration method to account for external experimental time delay (Ou et al. 2014) and explicit unconditionally stable HHT-α method to account for stiffness hardening and softening in hybrid simulation (Wang et al. 2018) were few of the areas the time integration techniques were implemented in simulation studies. Even though there were many effective time integration strategies available for it, the numerical simulation might still be unable to discover the accurate state in time.

A polynomial function was frequently used in shake table tests, although in a subtle manner for identifying absolute value by incorporating it in the inherent delay. Methods such as the polynomial least chi-square distribution test and hypothesis testing identification were utilized to effectively identify the Frequency Response Function (FRF). The minimum control synthesis (MCS) technique (Wang et al. 2019) an innovative model reference adaptive control scheme that required no off-line controller gain computation. The researcher also devised an extension to the adaptive form of former MCS algorithm to account the shake table control using a traditional fixed-gain controller. The Feed Forward Minimal Control Synthesis (FFMCS) was a novel classification of control algorithm (Lu et al. 2021). Some of the commonly used delay compensating approaches were polynomial extrapolation approach (Horiuchi, T., Inoue, M., Konno, T. 1999) ,the force based unified formulation (Reinhorn et al. 2003), force feedback technique Lee et al., (Lee et al. 2007), feed-forward technique (Liang et al. 2016), Smith Predictor Controller (SPC) technique (Ahmadizadeh 2015), model-based feed forward compensator (Carrion et al. 2009), Rosenbrock-W integration technique Lamarche (Lamarche et al. 2010), 3rd degree polynomial function analysis (Zhu et al. 2017), proportional-integral (PI) controller (Silva et al. 2020), Adaptive Forward Prediction proposed adopting a polynomial parameter estimation technique (Wallace et al. 2005), generic adaptive stochastic approximation (SA) (Spall 2009), Minimal Control Synthesis
added with Error Feedback (MCSEF) sub structuring controller approach (Eamcharoenying 2015) etc., The resonant response of the specimens, the internal friction of the actuators and actuator force control became a challenge while merging large-scale physical subcomponents into complete virtual systems of indefinite size and design. Such procedures and set-ups considerably expanded testing possibilities, by refining these models to cascade the delay impulse, and the application in hybrid simulations of multi degree of freedom (MDF) systems (Yuan et al. 2013). The constraint that the measurement noise variance had to be significant in these techniques were overcome by several filtering and metaheuristic techniques. An identification strategy based on the Kalman Filter (KF) was introduced directly to compute the harmonics in online from the reflected cyclic response (Yao et al. 2013). Unlike the Discrete Fourier Transform (DFT), the formulated functions in the time - frequency domain performed well in real-time, demonstrating the feasibility in shake table system (Masoumnezhad et al. 2015). The experimental work was in continuous-time, whereas the measurements were taken at discrete time instants. There were several significant filtering challenges in which both continuous and discrete observations must be combined optimally. Jianjun Yao et al. (Yao et al. 2015) devised an acceleration harmonic detection method based on extended Kalman filter. The harmonic information was directly obtained from the estimated states, including the change in single period and angular phase of each harmonic. The solution of the state equation was linear, whereas the function that described the measurement process was nonlinear, which was one of the features of the algorithm. It also benefitted from the standard linear Kalman filter’s advantages thus overcoming a heavily damped experimental substructure in STST.

The search capabilities of the computational intelligence technique could also be increased, and the optimal locations could be obtained by applying several metaheuristic techniques. A metaheuristic algorithm could solve the discrete and continuous domain optimization problem. It included ways for guiding the search process, ranging from simple local searches to complicated adaptive learning systems. It could be used in conjunction with an exact approach to effectively explore the state space in order to locate near-optimal potential solutions. This could mainly be classified as trajectory (S-metaheuristic) that yielded single solution and population-based (P-metaheuristic) that yielded multiple solutions. The other classifications were iterative- based, stochastic-based and deterministic-based. The population-based could be further classified into (P-metaheuristic), Evolutionary Computation Evolutionary Programming (1962), Evolutionary Strategies (1973), Genetic

Lu et al., (Lu et al. 2008) utilized a hybrid iteration between particle swarm optimizer (PSO) and passive congregation (PSOPC). Karaboga et al., (Kockanat and Karaboga 2015) proposed the ABC approach, which was inspired by honey bees' intelligent behavior when foraging for a high-quality food supply. Jianjun Yao et al., (Yao et al. 2018) proposed a method for estimating harmonic components in a hydraulic operated shake table based on the ABC algorithm. The results depicted the suggested method could reliably detect the harmonic component (the varying amplitude and phase), allowing the researchers to deploy it in shake table experiment acting as a new sub structuring technique. Pravat Kumar Rayn et al. (Ray and Subudhi 2012) proposed a new estimation approach that combined RLS and Bacterial Foraging Optimization (BFO) and demonstrated that it outperformed other approaches in the reliable parameter estimation of harmonics in sinusoidal waveforms. Santosh Kumar Singh et al., (Singh 2018) introduced a novel GSA-RLS hybrid algorithm. In his paper, Y. Kabalci (Kabalci et al. 2018) employed the MABC algorithm to propose a solution to the harmonic estimation problem. The findings of K. Z. S. M. Mahaei et al., (Hagh et al. 2011) suggested that weighted least square estimation could accurately estimate the system and measurement data, and the states of control devices. According to B. M. Phillips et al., (Carrion et al. 2009) computational restrictions induced inaccuracies and possible instability by causing delays and lags. As a result, the researcher suggested a new model-based compensator for evaluating the semi-active control of the structure. Z. S. Hou et al. (Hou and Wang 2013) showed that data-driven optimization and modelling theories were the two essential theoretical foundations of the data-driven controller (DDC) theory, that was paired with either of the discussed algorithms to implement it online to avoid the estimation of non-adaptive gradient estimation in on-line and off-line data driven technologies.

However, the aforementioned harmonic estimation methods either converge slowly, like GA algorithm, or need prior knowledge to detect the amplitude and phase of each harmonic, like the kalman filter. As a result, employing classic analogue methods to create a continuous discrete kalman filter and combining them with MABC leads in a simpler and more practical evolutionary algorithm, allowing for the rapid development and use of evolutionary computation in uniform harmonic estimation. The population-based metaheuristics
algorithms have attracted a lot of attention in recent times. Studies from literature suggests that metaheuristic algorithms are one of the best-known approaches, that provide a quick and effective response that overcome acceleration harmonic distortion in vibration tests. The reasons are as such:

(a) It involves a robust statistical approach for fine-tuning of parameters, which can summarize the search process and exercise a positive influence in the solutions.
(b) The search for the best-fit that is carried out iteratively through exploration on all the search space improves the convergence rate.

Despite the advantages, precise estimation and elimination of error harmonics is still an open issue. The study detailed in this article concentrates mainly on answering the crucial question, “How closely a shake table could represent a real ground acceleration?”.

A novel signal processing algorithm named as the Multi-Layer Modified Artificial Bee Colony (MMABC) technique is developed using swarm intelligence computation-based technique at the first stage. It is used for estimating the phase and amplitude of the error harmonic components at varying frequencies. At the next stage, it is further hybridized with the Extended Kalman Filter (EKF) technique to eliminate the error harmonics. These two algorithms complement each other and incorporate new Evolutionary Algorithms (EA) to facilitate in developing evolutionary computation in harmonic estimation and elimination. The focus of this chapter is using the MMABC and EKF paradigms to obtain uniform harmonic motion.

The primary goals of the study are as follows:

(a) MMABC-EKF algorithm is developed. The developed MMABC-EKF algorithm is compared to the Artificial Bee Colony (ABC) algorithm, Particle Swarm Optimization (PSO) algorithm and Modified Ant Bee Colony-Recursive least squares (MABC-RLS) algorithm, and studied in terms of performance.
(b) Simulation studies and experimental results are demonstrated to present a high precision and good convergence performance.

This article includes following steps:

(a) Mathematical modeling of the acceleration harmonic estimation that addresses the nonlinearity in the sinusoidal model.
(b) Explaining the detailed procedure of MMABC-EKF algorithm that has the feature of controlling the weights of the unknown parameters of the harmonic signal.
Solving the harmonic estimation and elimination approach using MMABC–EKF algorithm under simulation and its performance analyses in real time environment.

The findings, discussion and summary.

2. METHODOLOGY

2.1 Acceleration harmonic estimation-its mathematical model

A distorted acceleration signal is an integral multiple of the fundamental frequency with unknown values of amplitude and phase values. Hence, the acceleration harmonic response \( a_h(t) \) of uniaxial shake table can be written as the sum of the higher degree harmonics of the unknown amplitude and phase values. It is given as

\[
a_h(t) = \sum_{n=1}^{N} A_n(t) \sin[2n\pi f_0 t + \phi_h(t)]
\]  

(1)

where \( N \) is the number of harmonics, \( f_0 \) is the frequency of the fundamental signal, \( A_n(t) \) and \( \phi_h(t) \) are the unknown amplitude and phase values of the \( n \)th harmonic.

The new modeled signal \( h(t) \) can be obtained by adding direct current component \( A_0 \) and additive random noise \( r(t) \) which is stated as

\[
h(t) = \sum_{n=1}^{N} A_n \sin(2\pi f_0 t + \phi_h) + A_0 + r(t)
\]  

(2)

Thus, the direct current component in the signal is exponentially expanded, \( h(t) \) and can be rewritten as

\[
h(t) = \sum_{n=1}^{N} A_n(t) \sin[2\pi f_0 t + \phi_h(t)] + A_0 e^{\exp(-\infty) t} + r(t)
\]  

(3)

where \( A_0 e^{\exp(-\infty) t} \) denotes probable decaying term. Following that, the harmonic signal is sampled for the chosen sampling period with the discrete harmonic signal \( T_s \). Hence, \( h(d_k) \), the discrete form of the signal can be represented as

\[
h(d_k) = \sum_{n=1}^{N} A_n(t) \sin[2\pi f_0 d_k T_s + \phi_h(t)] + A_0 \exp(-\infty d_k T_s) + r(d_k)
\]  

(4)

The discrete harmonic signal \( h(d_k) \) in Eq. (4) is modified by approximating the decaying term using Taylor series expansion.

Now Eq. (4) becomes

\[
h(d_k) = \sum_{n=1}^{N} A_n(t) \sin[2\pi f_0 d_k T_s + \phi_h(t)] + A_0 - A_0 e^{\exp(-\infty) d_k T_s} + r(d_k)
\]  

(5)

Therefore, the sine and cosine functions can be used to model the sinusoidal signal.

\[
h(d_k) = \sum_{n=1}^{N} [A_n(t) \sin(2\pi f_0 d_k T_s) + \cos(\phi_h(t)) +
\]
\[ A_n(t) \cos(2n\pi f_0 d_k T_s)(\sin \varphi_h(t)) + A_0 - A_0 \infty_0 d_k T_s + r(d_k) \]  

(6)

The sum of higher order harmonics of uncertain amplitude and phase can be used to describe a distorted acceleration signal, as shown in Eq. (6). For any sinusoidal vibration tests, the weights of all the harmonic signals acquired from the accelerometer can be successfully modeled using the aforementioned mathematical model. But, the error in the amplitude and phase estimate of the harmonic signal recorded from the specimen, results in distorted sinusoidal model. Therefore, there raised a necessity to formulate and introduce MMABC-EKF algorithm.

2.2 MMABC - EKF algorithm for amplitude and phase estimation

The work initially started by understanding the shortcomings in basic ABC algorithm. In the basic ABC algorithm, the randomly chosen signal is alone modified while the other parameters are kept unaltered. Even though it achieved a better performance, the premature, low precision and slow convergence rate for constraint problems leads to the need for modification of the ABC algorithm. Researchers focused on improving the search strategy affecting the performance, but other important factors such as initialization method, selective strategy and fitness value are insufficient. In order to overcome the inefficient optimization, modification is done on all phases of ABC.

A new solution \(v_{ij}\) (neighborhood food source) is produced by the following equation:

\[
v_{i,j} = \begin{cases} x_{best,j} + \varphi_{ij}(x_{i,j} - x_{k,j}), & j = j^* \\ x_{i,j}, & j \neq j^* \end{cases}
\]

(7)

where \(k\) is randomly chosen from 1 to \(NP\) such that \(k \neq i\), \(j^*\) is randomly chosen from 1 to \(D\) and \(\varphi_{ij}\) is a random number in \([-1, 1]\). \(NP\) is the number of bees and \(D\) is the number of variables or dimension. In the proposed approach, \(h(d_k)\) is converted to a parametric form as

\[ h(d_k) = x(d_k)\varphi(d_k) \]

(8)

where \(x (d_k)\) is given as

\[ x(d_k) = \begin{bmatrix} \sin(\omega_1 d_k T_s) \cos(\omega_1 d_k T_s) \\ \sin(\omega_2 d_k T_s) \cos(\omega_2 d_k T_s) \\ \vdots \\ \sin(\omega_n d_k T_s) \cos(\omega_n d_k T_s) (1 - d_k T_s) \end{bmatrix}^T \]

(9)

\[ \varphi(d_k) = \begin{bmatrix} \varphi_{1k} \varphi_{2k} \cdots \varphi_{(2n-1)k} \varphi_{2nk} \varphi_{(2n+1)k} \varphi_{(2n+2)k} \end{bmatrix}^T \]

(10)

\[ \varphi = [A_1 \cos \varphi_1 A_1 \sin \varphi_1 \ldots A_n \cos \varphi_n A_n \sin \varphi_n A_0 A_0 \infty_0]^T \]

(11)
The amplitude and phase values ($A_n$ and $\phi_n$) of the $n^{th}$ harmonic and the decaying terms $A_0$ and $\alpha_0$ can be calculated using Eq. (11).

\[ A_n = \sqrt{\phi_{2n}^2 + \phi_{2n-1}^2} \]  \hspace{1cm} (12)

\[ \phi_n = tan^{-1} \frac{\phi_{2n}}{\phi_{2n-1}} \]  \hspace{1cm} (13)

\[ A_0 = \phi_{2n+1} \]  \hspace{1cm} (14)

\[ \alpha_0 = \frac{\phi_{2n+2}}{\phi_{2n+1}} \]  \hspace{1cm} (15)

The objective function of harmonic estimation for MMABC algorithm is expressed as

\[ M = min(\sum_{k=1}^{k} e^2(k)) = MSE(h_{dk} - \hat{h}_{d_{estimated}}) \]  \hspace{1cm} (16)

$h_{dk}$ = simulated or experimental harmonic signal

$\hat{h}_{d_{estimated}}$ = estimated harmonic signal

This Eq. (16) is used for minimization process between both the signals.

In the proposed approach, the EKF algorithm is applied to solve for the acceleration harmonic elimination.

2.2.1 Numerical modeling of EKF

The EKF is an extension of the Kalman Filter (KF) implemented for nonlinear dynamic systems. Consider a nonlinear system that is subjected to deterministic input $u(t)$, unmeasured zero mean white Gaussian disturbances $w(t)$ with a covariance $Q_c$ described by

\[ \dot{x}(t) = f(x,u,w,t) \]  \hspace{1cm} (17)

where $f \in \mathbb{R}^{nxn}$ is an arbitrary vector valued function. Measurements are assumed to be linearly related to the state vector $x(t)$ and available at discrete time steps and contaminated by a realization of white noise $v_k$ with a covariance $R$, namely

\[ y_k = Cx_k + v_k \]  \hspace{1cm} (18)

Here, unmeasured stochastic disturbance and measurement noise are assumed to be mutually uncorrelated. Hence, given the nonlinear equations of motion and measurement data, the EKF is used to calculate the minimum variance estimate of $x(t)$. The main purpose of applying the
EKF is linearization of the nonlinear equations of motion using Taylor series expansion, and
calculation of the KF estimate based on the linearized system. Hence in EFK algorithm, \( u(t) \)
the input vector is generated using the produced acceleration harmonic signal of MMABC
algorithm. The simplified flowchart diagram showing the solution steps adapted for MMABC-
EKF is expressed in Figure 1.

![Flow chart diagram of MMABC-EKF algorithm](image)

Figure 1 - Flow chart diagram of MMABC-EKF algorithm

3. RESULT AND DISCUSSION

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The simulation or experimental harmonic signal is loaded into the estimation and elimination program based on the above procedure. After initialization, a randomly distributed initial population of NP/2 solutions (food source positions), where NP denotes the size of the generated population is generated. Each solution $x_i^j$ (i=1, 2, ..., NP/2) is a D-dimensional vector. Here, D is the number of optimization parameters. After choosing a random value between the lower bound and the upper bound for initialization, the population is evaluated. A uniformly distributed random real number is produced and if the real number is less than the control parameter value, the parameter $x_i^j$ is modified in the employed bee phase. The probability value is set based on the feasibility condition to make decision in the onlooker bee phase. Thus, a new solution is generated for the new food source. In the scout bee phase, firefly algorithm is applied to construct new position, by moving an unaudited position to a new position based on the distance, to obtain a better solution. It is subjected to repeated cycles of search process through employed, onlooker and scout bee phases respectively. The output population from the MMABC algorithm produces the best estimates. But, the uncertainties in the process input are unknown. Hence, obtaining optimal estimates of the system is carried out using EKF. The value is loaded into EKF through input control vector. The prediction time update is performed followed by Kalman gain calculation. The measurement noise covariance matrix is calculated and the corrected signal is reproduced.

### 3.1 Simulation study

In this section, a series of analytical simulation studies are conducted to verify the effectiveness of the proposed MMABC–EKF using a classical benchmark frequency given by (Yao et al. 2017) [178]. The chosen signal has a fundamental frequency of 5 Hz with six harmonic in it. Hence, if the first harmonic occurs at 5 Hz, then the second, third, fourth, fifth and sixth occurs at 10 Hz, 15 Hz, 20 Hz, 25 Hz and 30 Hz. For acceleration harmonic estimation, the acceleration harmonic signal recommended in literature is expressed as

$$Y = y_1 + y_2 + y_3 + y_4 + y_5 + y_6$$  \hspace{1cm} (19)

where,

$$y_1 = 6 \times \sin (2 \times freq \times pi \times tt + 0.25)$$

$$y_2 = 5 \times \sin (4 \times freq \times pi \times tt + 0.27)$$

$$y_3 = 4 \times \sin (6 \times freq \times pi \times tt + 0.29)$$

$$y_4 = 3 \times \sin (8 \times freq \times pi \times tt + 0.2)$$

$$y_5 = 2 \times \sin (10 \times freq \times pi \times tt + 0.3)$$

$$y_6 = 1 \times \sin (12 \times freq \times pi \times tt + 0.4)$$
As a first step of investigation, the simulation signal formulated in Eq. (19) is loaded into the MATLAB program. The algorithm is allowed to run to the maximum limit by changing the colony size from 10 to 100. The SDD strategy divides the search space into sub spaces and obtain initial solution from each subspace, by ensuring that the initial solution is distributed relatively even across the search area based on the initialized parameters. Thus, only the random numbers generated at limited condition are used to generate different initial solutions at every run. This allows the initialized value to be accurate even though it failed in the previous one. After producing best initial solution, MMABC algorithm obtains the new food source in the employed bee phase and send to the onlooker bee phase. The second modification is done in the onlooker bee phase, by choosing 25% of the best solution based on a probability criterion and replacing the 5% of worst position based on the best solution on the next cycle. Finally, the unupdated positions in the scout bee phase are generated new positions by using firefly algorithm. The calculated values are given in Table 1. It is noticed that the best value and worst value is achieved for colony size=10.

<table>
<thead>
<tr>
<th>Colony size</th>
<th>Calculated mean</th>
<th>Calculated standard deviation</th>
<th>Best value</th>
<th>Worst value</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>1.300</td>
<td>5.523x10^-1</td>
<td>8.874x10^-6</td>
<td>1.201x10^-1</td>
</tr>
<tr>
<td>20</td>
<td>8.410x10^-1</td>
<td>6.446x10^-1</td>
<td>1.888x10^-4</td>
<td>2.174x10^-1</td>
</tr>
<tr>
<td>30</td>
<td>5.784x10^-1</td>
<td>6.443x10^-1</td>
<td>1.541x10^-5</td>
<td>5.110x10^-1</td>
</tr>
<tr>
<td>40</td>
<td>4.364x10^-1</td>
<td>6.098x10^-1</td>
<td>2.584x10^-4</td>
<td>8.378x10^-1</td>
</tr>
<tr>
<td>50</td>
<td>3.496x10^-1</td>
<td>5.723x10^-1</td>
<td>1.879x10^-3</td>
<td>1.176</td>
</tr>
<tr>
<td>100</td>
<td>3.030x10^-1</td>
<td>4.798x10^-1</td>
<td>3.098x10^-4</td>
<td>2.498</td>
</tr>
</tbody>
</table>

In Table 2, for CS x D, minimum mean and standard deviation values are obtained. It is also observed that the best values are obtained for CS x D. According to the table, limit CS x D shows better performance.
The reproduced signal in MMABC is then filtered using EKF algorithm. The simulation analysis is performed and the robustness is realized by comparing with ABC and PSO algorithms.

The values for the acceleration harmonics' amplitude and phase for the selected control parameters are shown in Table 3. It demonstrates the accurate estimation capability of the proposed approach.

<table>
<thead>
<tr>
<th>Limit</th>
<th>Calculated mean</th>
<th>Calculated standard deviation</th>
<th>Best value</th>
<th>Worst value</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1 x CS x D</td>
<td>4.205x10^{-2}</td>
<td>3.223x10^{-2}</td>
<td>1.180x10^{-5}</td>
<td>1.358x10^{-2}</td>
</tr>
<tr>
<td>0.2 x CS x D</td>
<td>1.091x10^{-2}</td>
<td>1.524x10^{-2}</td>
<td>1.009x10^{-6}</td>
<td>3.272x10^{-3}</td>
</tr>
<tr>
<td>0.3 x CS x D</td>
<td>4.888x10^{-3}</td>
<td>8.958x10^{-3}</td>
<td>2.880x10^{-8}</td>
<td>1.171x10^{-3}</td>
</tr>
<tr>
<td>0.4 x CS x D</td>
<td>3.019x10^{-3}</td>
<td>5.937x10^{-3}</td>
<td>2.733x10^{-7}</td>
<td>5.266x10^{-4}</td>
</tr>
<tr>
<td>0.5 x CS x D</td>
<td>3.030x10^{-3}</td>
<td>4.798x10^{-3}</td>
<td>3.100x10^{-8}</td>
<td>2.498x10^{-4}</td>
</tr>
<tr>
<td>0.6 x CS x D</td>
<td>3.272x10^{-3}</td>
<td>4.574x10^{-3}</td>
<td>8.000x10^{-10}</td>
<td>1.286x10^{-4}</td>
</tr>
<tr>
<td>0.7 x CS x D</td>
<td>2.436x10^{-3}</td>
<td>3.741x10^{-3}</td>
<td>1.800x10^{-9}</td>
<td>8.671x10^{-5}</td>
</tr>
<tr>
<td>0.8 x CS x D</td>
<td>1.871x10^{-3}</td>
<td>3.139x10^{-3}</td>
<td>4.800x10^{-9}</td>
<td>6.127x10^{-5}</td>
</tr>
<tr>
<td>0.9 x CS x D</td>
<td>1.531x10^{-3}</td>
<td>2.659x10^{-3}</td>
<td>5.000x10^{-10}</td>
<td>8.576x10^{-5}</td>
</tr>
<tr>
<td>1 x CS x D</td>
<td>1.515x10^{-3}</td>
<td>2.399x10^{-3}</td>
<td>5.000x10^{-10}</td>
<td>7.718x10^{-5}</td>
</tr>
</tbody>
</table>

Table 2 – Efficiency of MMABC algorithm at various limit values
Table 3 – Comparative study of the proposed algorithm with peer algorithms

<table>
<thead>
<tr>
<th>Algorithms</th>
<th>Parameters</th>
<th>Harmonic Degree</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>First</td>
</tr>
<tr>
<td>Benchmark Problem</td>
<td>Frequency (Hz)</td>
<td>5</td>
</tr>
<tr>
<td>(Yao et al. 2017)</td>
<td>Amplitude (m/s^2)</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>Phase (radian)</td>
<td>0.25</td>
</tr>
<tr>
<td>PSO Algorithm</td>
<td>Amplitude (m/s^2)</td>
<td>5.837</td>
</tr>
<tr>
<td></td>
<td>Phase (radian)</td>
<td>0.244</td>
</tr>
<tr>
<td>ABC Algorithm</td>
<td>Amplitude (m/s^2)</td>
<td>5.829</td>
</tr>
<tr>
<td></td>
<td>Phase (radian)</td>
<td>0.245</td>
</tr>
<tr>
<td>Proposed MMABC-EKF</td>
<td>Amplitude (m/s^2)</td>
<td><strong>5.981</strong></td>
</tr>
<tr>
<td></td>
<td>Phase (radian)</td>
<td><strong>0.253</strong></td>
</tr>
</tbody>
</table>

In Figure 2, the produced harmonic signal with proposed algorithm is compared at sample number. The plot shows six peaks at each Hz with several more spurious peaks caused due to random noise in the signal. Figure 3 shows the precise synchronization of the signals in frequency domain.

![Figure 2 - Actual vs produced harmonic signal with MMABC-EKF algorithm at various sample number](image-url)
Figures 4 shows the synchronization of the amplitude and phase values of the 6 harmonics which are estimated by the MMABC algorithm in a selected population. As it can be seen from Figures 5 and 6, unwanted harmonics is eliminated and the desired signal at 5 Hz is achieved or varying sample number and frequency.

The synchronization of the amplitude and phase is also realized for PSO and ABC algorithms and is shown in Figures 7 and 8. These values serve as a tool to prove the efficiency of the proposed algorithm.
Figure 4 - Synchronization of amplitude and phase at each harmonic using MMABC algorithm (5 Hz)

Figure 5 - Produced vs reproduced signal with MMABC-EKF algorithm in amplitude-sample number curve
Figure 6 - Reproduced signal with MMABC-EKF algorithm in power spectrum-frequency curve

Figure 7 - Synchronization of amplitude and phase at each harmonic in ABC algorithm (5 Hz)
It can also be seen that the estimated values for both amplitude and phase at each frequency shows the estimation capability of the proposed algorithm when compared with those of the ABC and PSO algorithms in Table 4. In addition, the estimated values of amplitude converge to the nominal values.

It is clearly evident that estimation error is exponentially reduced in MMABC-EKF, a model that generates response and also uncertainty description such as measurement noise, stochastic disturbances or process noise, can be modeled for more convergence.
Table 4 - Comparison of MMABC-EKF algorithm in experimental study (5 Hz)

<table>
<thead>
<tr>
<th>Harmonic Degree</th>
<th>ABC</th>
<th>PSO</th>
<th>MMABC-EKF</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Estimated amplitude (m/s²)</td>
<td>Estimated phase (radian)</td>
<td>Estimated amplitude (m/s²)</td>
</tr>
<tr>
<td>1st</td>
<td>0.058</td>
<td>0.224</td>
<td>0.057</td>
</tr>
<tr>
<td>2nd</td>
<td>0.098</td>
<td>0.236</td>
<td>0.096</td>
</tr>
<tr>
<td>3rd</td>
<td>0.086</td>
<td>0.151</td>
<td>0.084</td>
</tr>
<tr>
<td>4th</td>
<td>0.082</td>
<td>0.193</td>
<td>0.000</td>
</tr>
<tr>
<td>5th</td>
<td>0.078</td>
<td>0.242</td>
<td>0.000</td>
</tr>
<tr>
<td>6th</td>
<td>0.042</td>
<td>0.304</td>
<td>0.000</td>
</tr>
</tbody>
</table>

3.2 TEST STRUCTURE AND EXPERIMENTAL PROGRAM

3.2.1 Test specimen properties and details

Figure 9 shows the plan, elevation and details of structural elements of the prototype building. The plan of the building is kept 0.69 m x 0.69 m with 2.00 m height. The vertical configuration of the building consists of a two-storey with V-type braces to brace the PS in one direction, resulting in a weak y-axis and a strong x-axis. The sectional properties of the PS are given in the Table 5. The average yield stress, $f_s$, of the reinforcing steel considered for the study is $2.5\times10^8$ MPa.
<table>
<thead>
<tr>
<th>Channel Section</th>
<th>Dimension h x b x t&lt;sub&gt;w&lt;/sub&gt; x t&lt;sub&gt;f&lt;/sub&gt; mm</th>
<th>Sectional weight kg/m</th>
<th>Length m</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>75 x 40 x 4.8</td>
<td>7.14</td>
<td>0.6</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Square Hollow Section (SHS)</th>
<th>Dimension B x B x t mm</th>
<th>Sectional weight kg/m</th>
<th>Height of the column at each floor m</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>40 x 40 x 2.6</td>
<td>2.92</td>
<td>1.2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Angle section</th>
<th>Dimension H x W x t mm</th>
<th>Sectional weight kg/m</th>
<th>Length m</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>35 x 35 x 5</td>
<td>2.62</td>
<td>0.6</td>
</tr>
</tbody>
</table>
3.2.2 Preliminary experimental program

A separate module is programmed in LabVIEW software for tracking the vibration data (see Figure 10). Sensor is placed at the base of the structure to calculate the value of base excitation at various Hz.

The dynamic behavior of test model is investigated by bolting the frame structure to the shake table. The frame model is designed to show the inelastic behaviour clearly in bolted connections.
under dynamic loads without failure in the beams and the columns. Column base connections are made as rigid as possible to avoid overturning moment with respect to platform. The errors, in this case, again come from a change in table-specimen interaction. Hence, iterative matching steps is carried out using Wilson-θ method and incorporated in the LabVIEW program.

The upper limit of the working frequency of the designed shake table is kept less than 8 Hz, and the lower limit more than 2 Hz. The accuracy in frequency is maintained up to 0.01 Hz. Low peak white noise excitation is used to assess dynamic features such as natural frequency and damping ratio. The diminishing time oscillation is recorded in data acquisition system to calculate the damping ratio. Two successive acceleration maxima are evaluated, and the result is found to vary by nearly 0.0203 (see Table 6).

Table 6 - Dynamic properties measured before experiment

<table>
<thead>
<tr>
<th>No</th>
<th>Quantity</th>
<th>Notation</th>
<th>Observations</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Amplitude at the 0(^{th}) peak</td>
<td>A(_0)</td>
<td>0.25g</td>
</tr>
<tr>
<td>2</td>
<td>Amplitude at the n(^{th}) peak</td>
<td>A(_n)</td>
<td>0.23g</td>
</tr>
<tr>
<td>3</td>
<td>Logarithmic decrement</td>
<td>(\Delta)</td>
<td>0.0203</td>
</tr>
<tr>
<td>4</td>
<td>Damping ratio</td>
<td>(\Xi)</td>
<td>2%</td>
</tr>
</tbody>
</table>

3.2.3 Harmonic base excitation test

The first series of tests performed on the shake table are harmonic base excitation tests. The main objectives of the harmonic excitation tests are to assess stability, propagation of errors, and validity of shake table testing. Controlled vibration using Variable Frequency Drive (VFD) is generated, for the purpose of studying the linear performance of the scaled frame structure. According to the dynamic characteristics of the prototype structure, frequency at 2 Hz, 4 Hz, 6 Hz, 7 Hz and 8 Hz are chosen for simulating the shake table. MPU 6050 sensor is placed at the base of the shake table to record the response at the base of the table. The accelerometers, with sensitivity around 113.8 mV/g, are further mounted on the beams of each storey using super glue and duct tape to collect the responses under different intensities. Accelerations are measured by the signal acquisition and analysis system, PC domain Data Acquisition (DAQ) developed by National Instruments (NI). Further, the test arrangement show in Figure 11, is analyzed for the applicability and efficiency of the proposed algorithm in real-time systems.
order to present the performance of the proposed approach at different frequencies, sinusoidal vibration test signals from 2 to 8 Hz are applied to the system. Then, the experimental harmonic signal is obtained from the accelerometers attached to top storey as the output response signal in real-time.

4. HARMONIC ESTIMATION USING FAST FOURIER TRANSFORM
The acceleration reproducibility of experimental setup varies in every frequency due to serious harmonic distortion. Therefore, it is of great importance to estimate the harmonic information of the shake table at each frequency in a quick and accurate way. Hence the acceleration signal is reconstructed in frequency domain to identify the harmonics in the signal. Figure 12 shows the flow chart diagram for FFT analysis.
The acceleration harmonic signal calculated by FFT analysis for experimental study is expressed as

\[ Y = y_1 + y_2 + y_3 + y_4 + y_5 + y_6 + y_7 \]  \hspace{1cm} (20)

where,

\[ y_1 = 0.10 \times \sin(2 \times \text{freq} \times \pi \times t) \]
\[ y_2 = 0.09 \times \sin(4 \times \text{freq} \times \pi \times t) \]
\[ y_3 = 0.08 \times \sin(6 \times \text{freq} \times \pi \times t) \]
\[ y_4 = 0.07 \times \sin(8 \times \text{freq} \times \pi \times t) \]
\[ y_5 = 0.06 \times \sin(10 \times \text{freq} \times \pi \times t) \]
\[ y_6 = 0.05 \times \sin(12 \times \text{freq} \times \pi \times t) \]
\[ y_7 = 0.04 \times \sin(14 \times \text{freq} \times \pi \times t) \]

It is observed from FFT analysis, there exists seven harmonics in each cycle of the signal. Figure 13 a, b, c, d, e, f and g shows the results at 2 Hz to 8 Hz on the top storey of the structure using frequency-based estimation program coded in MATLAB software. It is verified that frequency domain analysis estimates more accurately the number of harmonics present in each frequency. The estimation of each noise harmonic and eliminating them, results in accurate acceleration responses.
Figure 13 - FFT analysis to identify harmonics in each frequency
The estimated harmonic signals are then estimated with MMABC–EKF algorithm and compared with the actual harmonic signal in each sample number and frequency domain respectively in Figures 14 and 15 for 5 Hz frequency.
Figure 14 - Produced harmonic signal with MMABC-EKF algorithm in experimental study

Figure 15 - Actual vs produced harmonic signal with MMABC-EKF algorithm in experimental study
It can also be seen from the Figures 14 and 15, each harmonic of acceleration response is well counteracted indicating that the estimated signals not only have the right amplitudes but also have the near accurate phases.

4.1 Analysis damage patterns

When subjected to 2 Hz frequency on the table, almost no changes occurred in the structure indicating the structure is in the elastic stage. The peak acceleration recorded was nearly 0.08 g. In the case of 4 Hz, the model responded with very less vibrations with a peak acceleration of nearly 0.15 g, which may also indicate that it is still in serviceable conditions. After moderate 5 Hz, a peak acceleration response of 0.50 g is recorded, which indicates that the prototype building is experiencing a moderate vibration. However, at 6 Hz, a peak acceleration response of 0.60 g is recorded, with some part of the prototype building undergoing severe vibrations. At 7 Hz a peak acceleration of 0.8 g is noticed with small loosening of bolts. At 8 Hz, acceleration response of the top storey of the structure is relatively large. A peak acceleration response of nearly 1 g is noticed. The model vibrated significantly, together with small deformation in the beams of the model. Self-loosening and a small backing-off of the nuts are observed in connection bolts as indicated in Figure 16.

Figure 16 - Damages in connection corresponding to 8Hz
(a) and (b) connection 1 (in the bottom storey); (c) and (d) connection 2 (in the top storey)

The time domain graph shown in the Figure 17 and Figures 18 a, b, c, d, e, f, g, and h indicate the residual error stays around zero at each time period.

Figure 17 - Acceleration time history recorded by sensor at the base.

Figure 18a - Acceleration time history on the top storey at 2 Hz

Figure 18b - Acceleration time history on the top storey at 3 Hz
Figure 18c - Acceleration time history on the top storey at 4 Hz

Figure 18d - Acceleration time history on the top storey at 5 Hz

Figure 18e - Acceleration time history on the top storey at 6 Hz
5. SUMMARY AND CONCLUSIONS

The work can be summarized as follows:

1. Estimation of acceleration harmonics and elimination with some other method t is necessary.

2. A novel algorithm named as Multilayer Modified Artificial Bee Colony (MMABC) is developed by the author. This novel optimization algorithm is hybridised with the Extended Kalman Filter (EKF) to eliminate the estimated noise harmonics and it is named as MMABC-EKF algorithm.

3. The inefficiency in the initialization strategy is overcome by novel initialization method called Search Space Division (SSD) resulting in a high-quality initial solution.

4. The definition of scout bee is changed by introducing Firefly Algorithm (FA) in the novel MMABC algorithm.
5. Therefore, the poor convergence may not be the critical disadvantage to be considered in optimization problems, when optimized using MMABC.

6. The performance of the MMABC-EKF algorithm has been compared with that of PSO and ABC for harmonic estimation and elimination.

7. The simulation experiment and the real time experiment exhort, that the proposed hybrid method outperforms the other algorithms in terms of overall performance.

8. The reproduced signal with MMABC-EKF algorithm showed desired sinusoidal characteristics for the real-time application of the shake table.

The efficiency of the same can be used in SI problems of civil engineering. An elaborate study is worked out in the next chapter using MMABC-EKF algorithm for identifying stiffness degradation in beam element.

**Authors Contribution**

All authors contributed to the study conception and design. Test setup, programming and analysis are performed by [Dr. R. B. Malathy]. The first draft of the manuscript is written by [Dr. R. B. Malathy] and authors [Dr. Govardhan Bhat] [Dr. U. K. Dewangan] commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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**Ethics declarations**

**Conflict of interest**

The authors have no relevant financial or non-financial interests to disclose.

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