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# MIMO System Identification of Machine Foundation Using N4SID

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**ABSTRACT**

***In this paper, a new structural identification tool is proposed to identify the modal properties of structures. At last, after collecting modal responses from the available sensors, the mode shape vector for each of the decomposed modes in the system is identified from all obtained modal response data. To demonstrate the efficiency of the algorithm, a series of numerical, and laboratory studies were evaluated.***

***In this study, machine foundation pile was used. In this study, Multi input- multi output (MIMO) system identification method was used. The modal properties of the machine foundation pile were computed using analytical approach for a comparison with the experimental modal frequencies. Results demonstrated that N4SID multi input-multi output (MIMO) system identification method is efficient and accurate in identifying modal data of the foundations.***

***Keyword:*** ***MIMO, N4SID, System Identification, Numerical Algorithms, Foundations***

## 1. INTRODUCTION

Most of structures located in regions prone to earthquake hazards suffer from various types of destruction caused by seismic loads. Under such earthquake occurring, the parts (especially the columns) of building structures suffer damage. Looking on the other side, especially considering the performance of such buildings under seismic occurrence, there is a great need to strengthen the columns even without changing their building masses; this clearly shows that there is a need to investigate the connection between technical repairing or strengthening procedures and the column capacity. In this understanding, more researches are being conducted to get required performance of structures under seismic loading, by means of looking at different point of view and directions [2].

System identification (SI) is a modeling process for an unknown system based on a set of input outputs and is used in various engineering fields. (Sirca and Adeli, 2012). Subspace system identification is introduced as a powerful black-box system identification tool for structures. The application of the method for supporting excited structures is emphasized in particular. The black- box state- space models derived from the identification of subspace systems are used to estimate the modal properties (i.e. modal damping, modal frequency and mode shapes) of the structures [10].

In engineering structures, three types of identification are used: modal identification of parameters; structural-modal identification of parameters; control model identification methods. In the frequency domain the identification is based on the unique value decomposition of the spectral density matrix and it is denoted Frequency Domain Decomposition (FDD) and its further development Enhanced Frequency Domain Decomposition (EFDD) [1].

In the time domain there are three different implementations of the Stochastic Subspace Identification (SSI) technique: Unweight Principal Component (UPC); Principal component (PC); Canonical Variety Analysis (CVA) are used [1].

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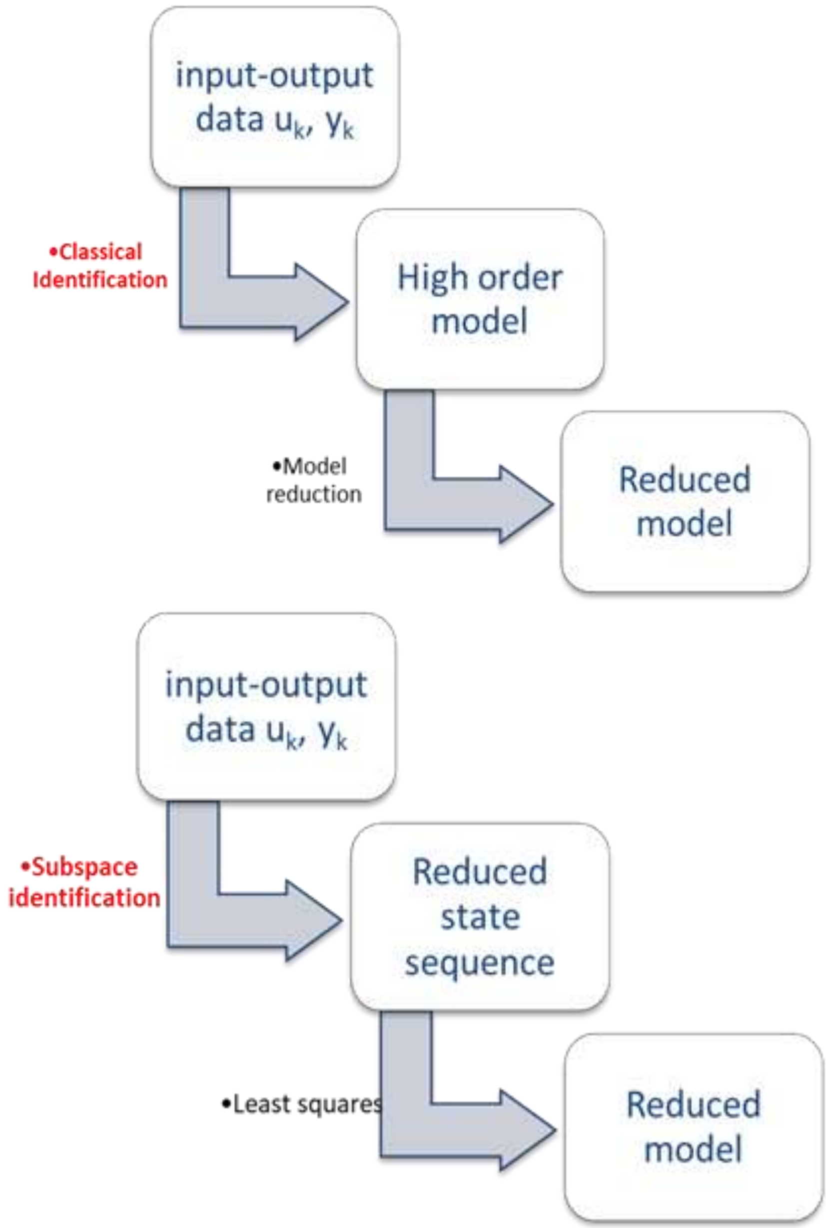


Fig-1: System İdentification Aims to Create İnput - Output Data State Space Models

When a reduced order model is required, one first identifies a high order model in some classical approaches (on the right) and then applies a model reduction technique to obtain a low order model. The left side shows the subspace identification approach: first we obtain a "reduced" status sequence, after which a low order model can be identified directly. (Overschee and Moor, 1996).

In this paper, the problem of multiple degrees of free structural systems without a limited number of elements was investigated. As known for similar type systems the system matrices [m], [c], [k] may be built only by FEM and the equation of motion for a finite-dimensional linear-dynamic system a set of n2 second-order differential equations are arranged as

$$[m]\{\ddot{u}(t)\} + [c]\{\dot{u}(t)\} + [k]\{u(t)\} = [d]\{f_{\oplus}\,(t)\} \qquad \text{(Eq. 1a)}$$

Here the direct stiffness method was used for implementation in the finite element method and appropriately was build system mass, damping and stiffness matrices ($[m]$; $[c]$; $[k]$). For example, The FEM implementing system stiffness matrix [k] is shown as follows by the direct stiffness method:

$[\bar{k}_r] -> [\bar{\bar{k}}_r] = [C_r][\bar{k}_r][C_r]^T -> [\bar{\bar{k}}_{r+}] = [\tau_r]^T[\bar{\bar{k}}_r][\tau_r] -> [k_{\cdot}] = \sum_{r=1}^{r_{\cdot}}[\bar{\bar{k}}_{r+}] -> a.b.c. -> [k]$ (Eq. 1b)

where, $[\bar{k}r]$ is the element stiffness matrix in local coordinate system (c.s.) for *r*-th finite element, $[\bar{\bar{k}}r]$ is the element stiffness matrix in global coordinate system for *r*-th finite element,

$[Cr]$ is the coordinate transformation matrix from local to global c.s. for *r*-th finite element,

$[\tau_r]$ is the topology matrix for *r*-th finite element, *a.b.c.* is abbreviation "mean after application of boundary conditions", $r_*$ is a number of identical finite elements examined system,

$[k]$ is the stiffness matrix of the in examined system in global c.s. The main relationships of the FEM are based on the Lagrange principle of variation.

The equation of motion (1) are transformed to the state-space former of first order equations-i.e., a continuous-time state-space model of the system are evaluated as

$$\{\dot{z}(t)\} = [A_c]\{z(t)\} + [B_c]\{f_\oplus(t)\} \quad \text{(Eq. 2a)}$$

$$[A_c] = \begin{bmatrix} [0] & [I] \\ -[m]^{-1}[k] & -[m]^{-1}[c] \end{bmatrix} \quad \text{(Eq. 2b)}$$

$$[B_c] = \begin{bmatrix} [0] \\ [m]^{-1}[d] \end{bmatrix} \quad \text{(Eq. 2c)}$$

$$\{z(t)\} = \begin{bmatrix} u(t) \\ \dot{u}(t) \end{bmatrix} \quad \text{(Eq. 2d)}$$

If the response of the dynamic system is measured by the $m_1$ output quantities in the output vector $\{y(t)\}$ using sensors (such as accelerometers, velocity, displacements, etc.,), for system model represented by the equations (2), appropriate measurement-output equation become as

$$\{y(t)\} = [C_a]\{\ddot{u}\} + [C_v]\{\dot{u}\} + [C_d]\{u\} = [C]\{z(t)\} + [D]\{f_\oplus(t)\} \quad \text{(Eq. 3a)}$$

$$[C] = [\,[C_d] - [C_a][m]^{-1}[k], \qquad [C_v] - [C_a][m]^{-1}[c]\,] \quad \text{(Eq. 3b)}$$

$$[D] = [C_a][m]^{-1}[d] \quad \text{(Eq. 3c)}$$

Where $\{u\}$ is the vector of displacement; $[Ac]$, is an $n_1$ ($n1 = 2n_2$; $n_2$ is the number of independed coordinates) by $n_1$ state matrix ; $[d]$ is an $n_2$ by $r_1$ input infuence matrix, characterizing the locations and type of known inputs $\{f_\oplus(t)\}$ ; $[Ca]$ ; $[Cv]$ ; $[Cd]$ are output influence matrices for acceleration, velocity, displacement for using sensors (such as accelerometers, tachometers, strain gages, etc.,) respectively; $[C]$ is an $m_1\ x\ n_1$ output influence matrix for the state vector $\{z\}$ and displacement only; $[D]$ is an $m_1\ x\ r_1$ direct transmission matrix; $r_1$ is the number of inputs; $m_1$ is the number of outputs.

In the output - only modal analysis environment, the main assumption is that input force $\{F(t)\} = [d]\,\{f_\oplus(t)\}$ comes from white noise or time impulse excitation. Under this hypothesis discrete-time stochastic state {space model may be written as:

$$\{z_{k+1}\} = [A]\{z_k\} + [B]\{f_{\oplus k}\} + \{w_k\} \quad \text{(Eq. 4)}$$

$$\{y_k\} = [C]\{z_k\} + [D]\{f_{\oplus k}\} + \{v_k\} \quad \text{(Eq. 5)}$$

where $\{z_k\} = \{z(k\Delta t)\}$ is the discrete-time state vector; is the process noise due to disturbance and modeling imperfections; $\{v_k\}$ is the measurement noise due to sensors' inaccuracies; $\{w_k\}, \{v_k\}$ vectors are non-measurable, but assumed that they are white noise with zero mean.

If this white noise assumption is violated, in other words if the input contains also some dominant frequency components in addition to white noise, these frequency components cannot be separated from the eigen frequencies of the system and they will appear as eigenvalues of the system matrix $[A]$.

In the real structures, exited by ambient vibration, the input $\{f_\oplus(t)\}, \{f_{\oplus k}\}$ remains unmeasured and therefore it disappears from the equations (2)-(5) respectively. Then to take into consideration this fact, the input is implicitly modeled by the noise terms $\{\underline{w}_k\}\{\underline{v}_k\}$, which are indirectly contain no measurable input from ambient vibration and mentioned relation became as:

$$\{z_{k+1}\} = [A]\{z_k\} + \{\underline{w}_k\} \quad \text{(Eq. 6)}$$

$$\{y_k\} = [C]\{z_k\} + \{\underline{v}_k\} \quad \text{(Eq. 7)}$$

## 2. DESCRIPTION OF MACHINE FOUNDATION PILE

In this study, the foundation with an area of 18 * 18 m and a thickness of 50 cm was used. 12 m in length and 40 cm in diameter were added to this foundation. The material used is reinforced concrete. Spring stiffness coefficient $k_s$ ,U1 and U2 are 2000 KN/$m^3$ . Machine Foundation is shown in Figure 2, Figure 3. The acceleration values were taken from the ends of the two piles. Two inputs and two outputs were taken. As a result of this data, multi input multi output system definition was realized with matlab 2018b program.

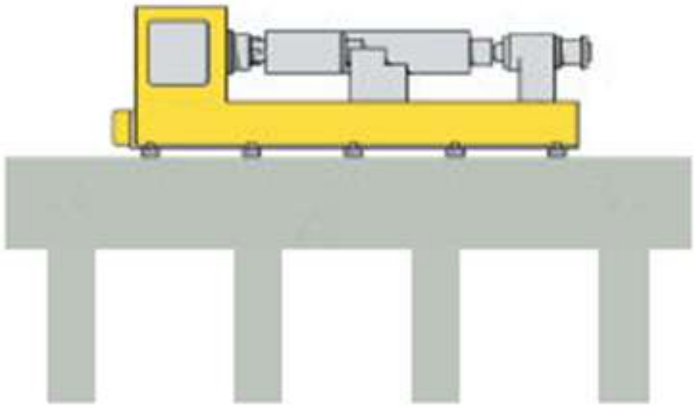

Fig-2: Machine Foundation Model

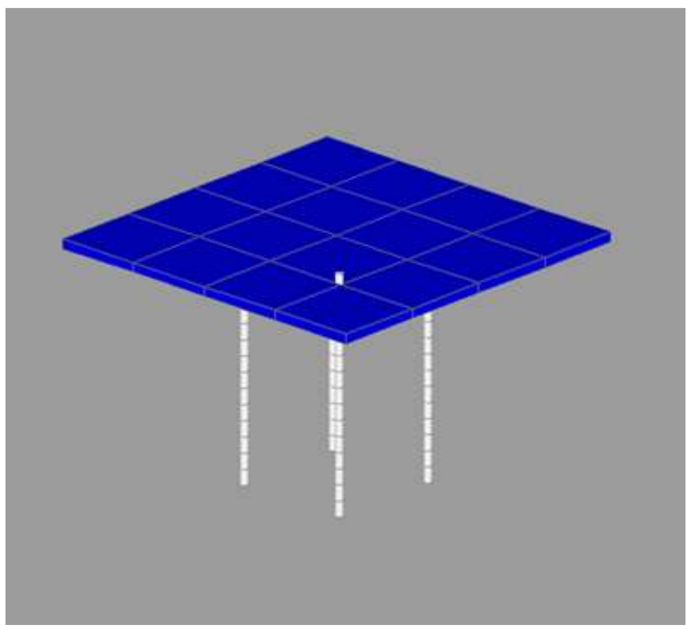

Fig-3: Machine Foundation 3D View

## 3. N4SID RESULTS

If After analyzing the data in MATLAP using N4SID with multi input – multi output (MIMO) method the following results are summaries in figures 3- 14.

They were examined respectively;

- İnput and Output Signals
- Model Outputs
- A, B, C, D and K matrices
- Fit to estimation data
- Transient Responses
- Frequency Functions
- Poles and Zeros
- Noise Spectrums

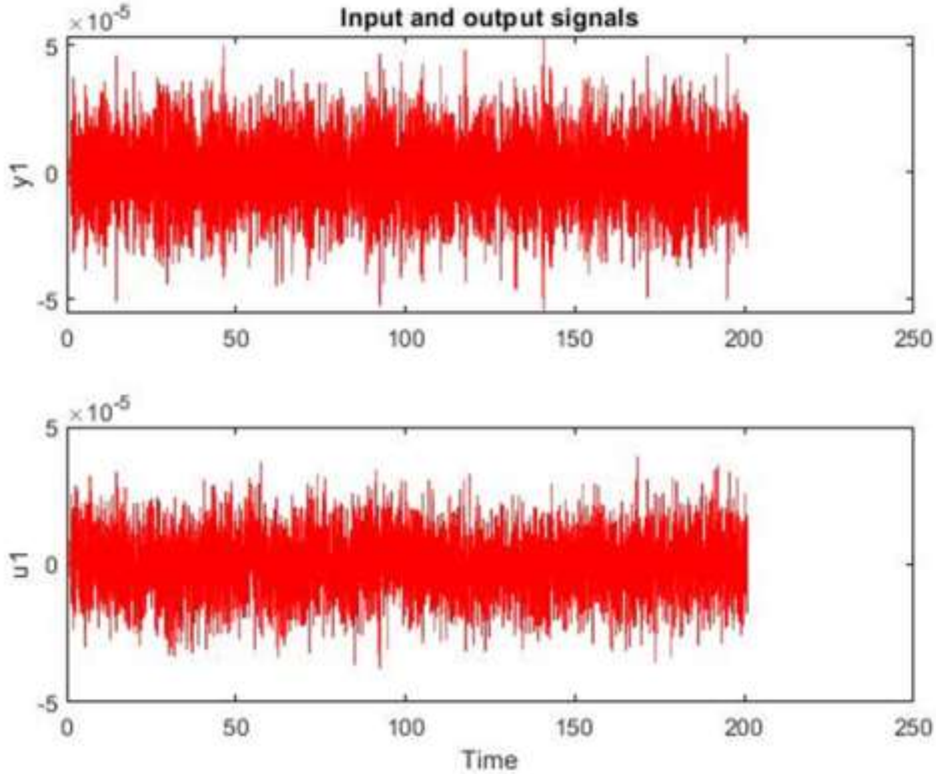


Fig-4: İnput and Output Signals u1->y1

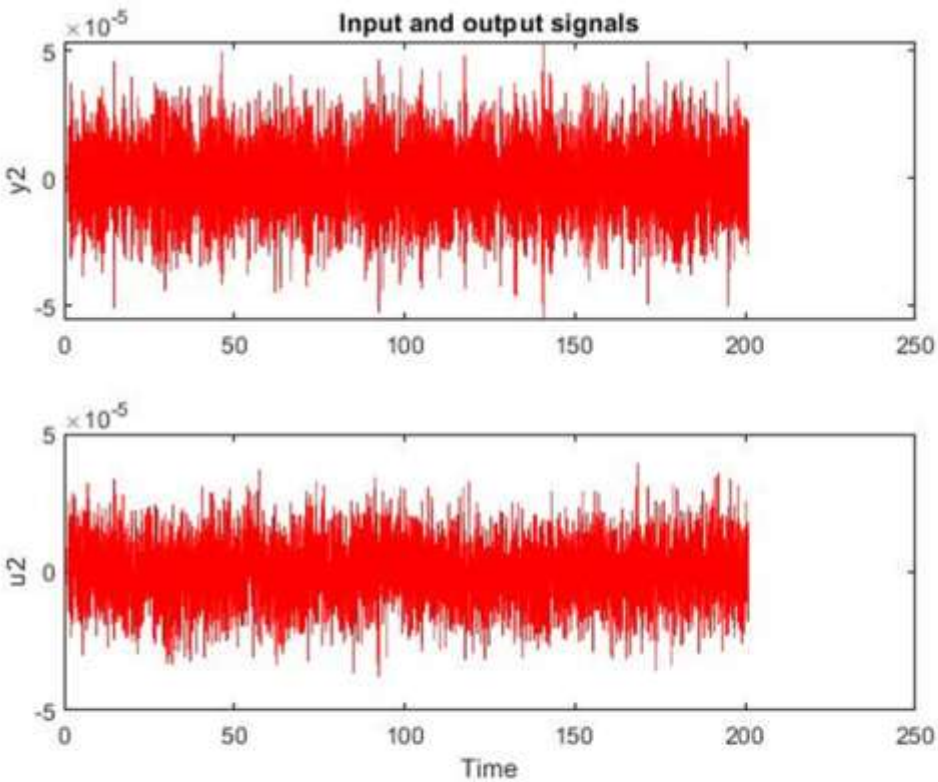

Fig-5: İnput and Output Signals u2->y2

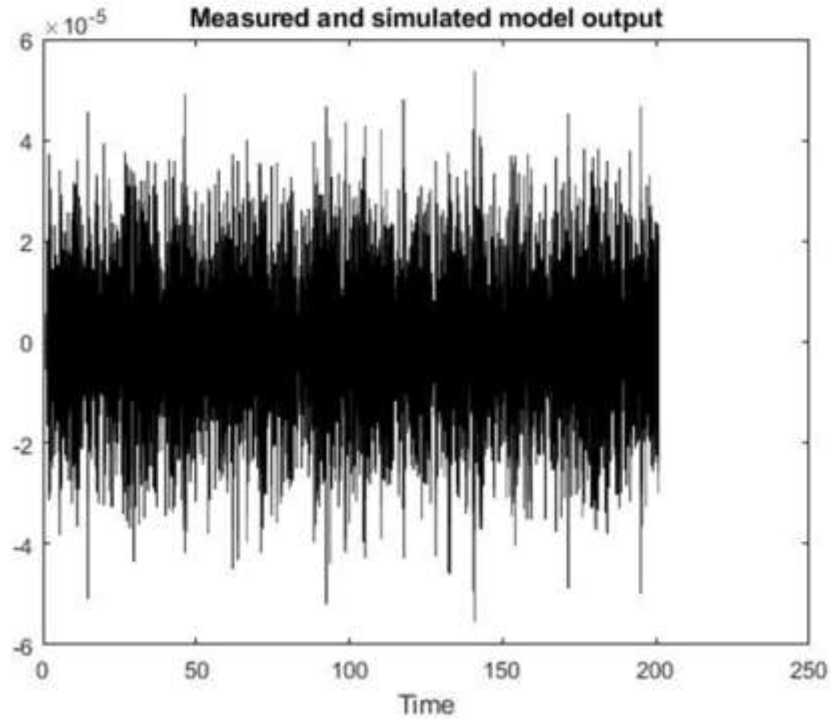


Fig-6: Model Output y1

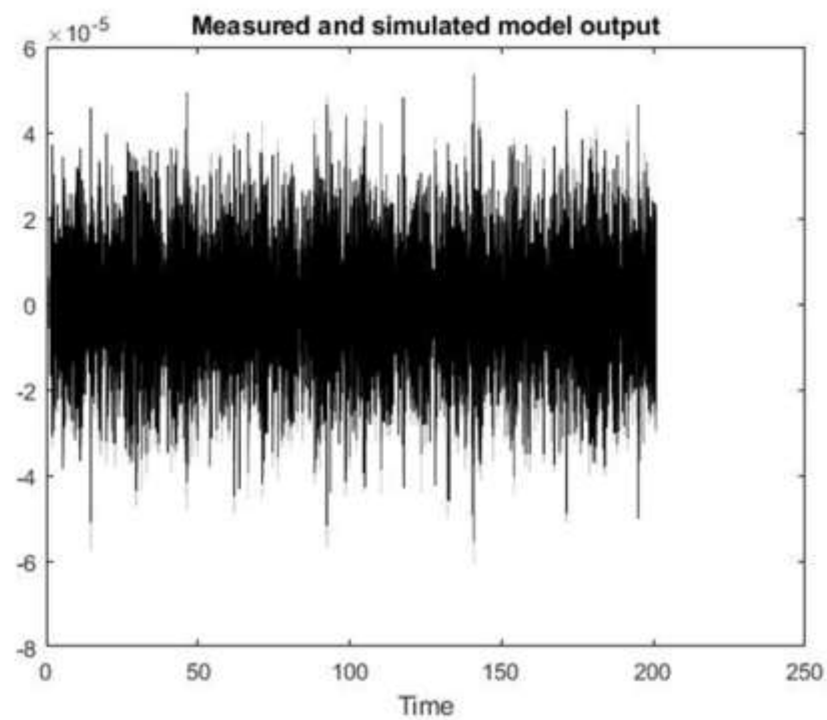


Fig-7: Model Output y2

Fit to estimation data is %99.01.

A, B, C, D and K matrices are given below;

$$A=\begin{bmatrix} -0.3341 & -0.8322 & 0.0030 & 0.0005 & 0.0015 & -0.0003 & 0.0026 & -0.0030 \\ 0.9235 & -0.1738 & 0.0055 & 0.0015 & 0.0003 & -0.0028 & 0.0036 & -0.0006 \\ 0.1084 & -0.2388 & -0.4510 & 0.8083 & 0.4773 & -0.0307 & 0.9773 & -0.4980 \\ -0.0147 & 0.0600 & -0.7758 & -0.4296 & 0.2292 & 0.1266 & -0.1744 & -0.7047 \\ -0.0014 & 0.0230 & -0.0180 & 0.0225 & -0.2670 & -0.2786 & 1.5455 & 0.5782 \\ 0.0024 & 0.0098 & -0.0073 & 0.0095 & 0.2024 & 0.1197 & 1.4173 & -0.6627 \\ -0.0048 & 0.0032 & 0.0014 & 0.0091 & -0.1434 & -0.3556 & -0.3244 & 0.3705 \\ -0.0106 & 0.0124 & -0.0021 & 0.0242 & -0.5190 & -0.0367 & 0.8770 & 0.3718 \end{bmatrix}$$

$$B=\begin{bmatrix} 261.535089355254 & 261.535089354888 \\ -164.422872238218 & -164.422872232819 \\ -130.733097361699 & -130.733097361695 \\ -323.116648699914 & -323.116648699906 \\ -33.7184926930470 & -33.7184926930453 \\ 1.16049576937979 & 1.16049576937525 \\ 1.45170920163509 & 1.45170920163691 \\ -8.59808349158066 & -8.59808349158248 \end{bmatrix}$$

C=

$$\begin{bmatrix} 0.0008 & -0.0009 & -9.59E+08 & -2.07E+08 & -2.54E+07 & 2.41E+08 & -2.63E+08 & 3.12E+08 \\ 0.0008 & -0.0009 & -9.59E+08 & -2.07E+08 & -2.54E+07 & 2.41E+08 & -2.63E+08 & 3.12E+08 \end{bmatrix}$$

$$D=\begin{bmatrix} -0.144805143 & -0.144805056 \\ 0 & 0 \end{bmatrix}$$

K= $[0]_{8*2}$

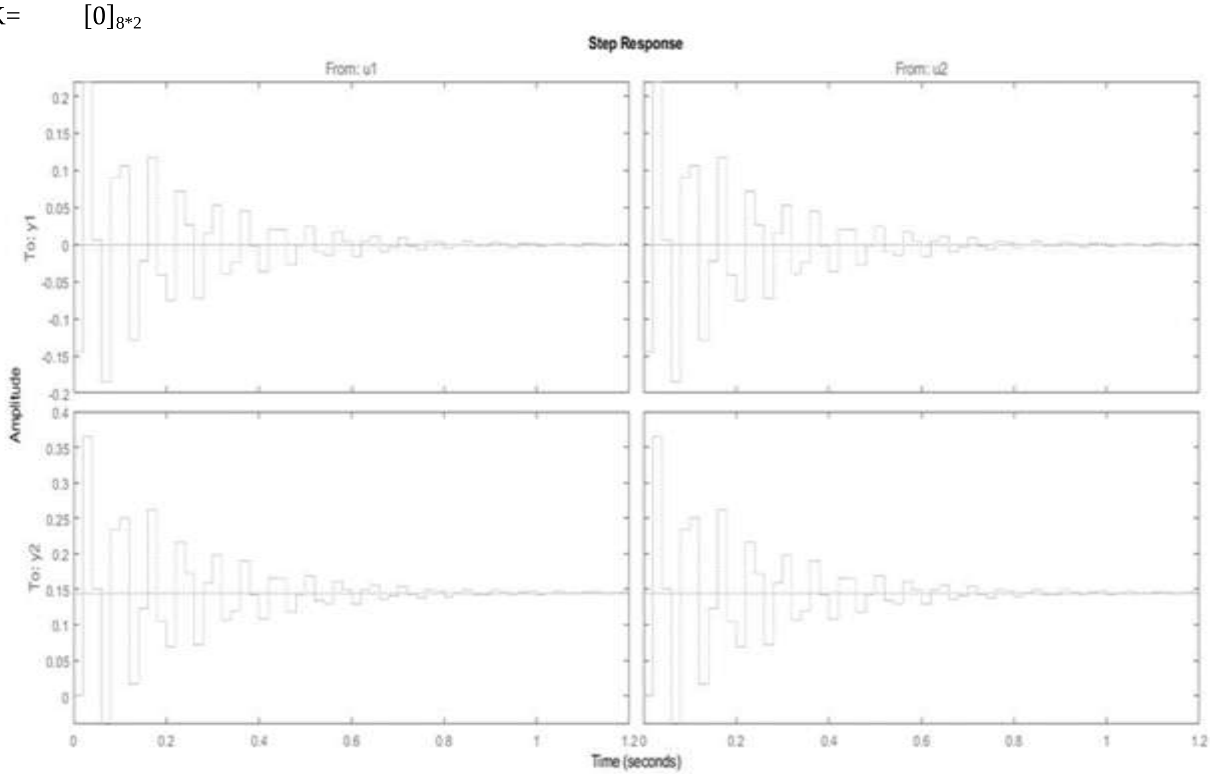


Fig-8: Transient Responses

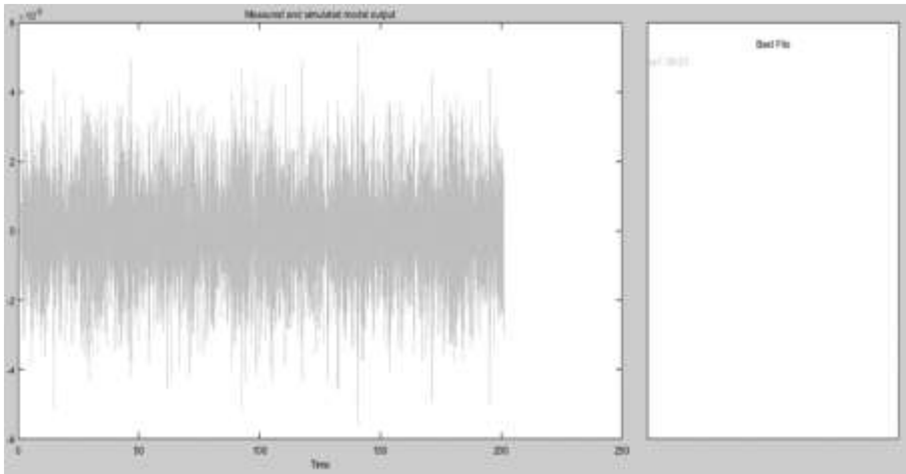

Fig-9: Fit to Estimation Data %99.01

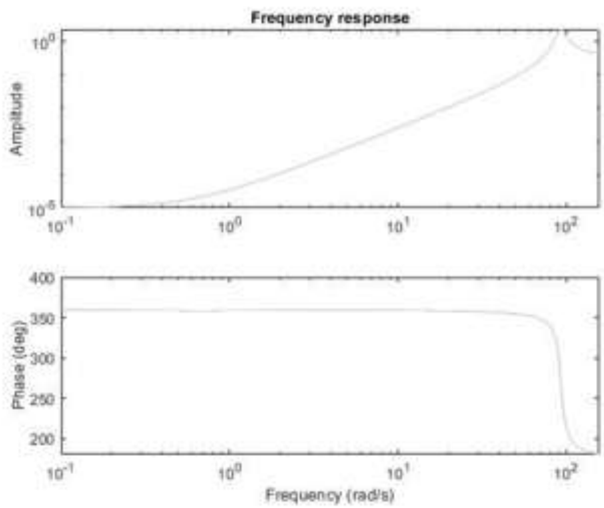


Fig-10: Frequency Function u1->y1

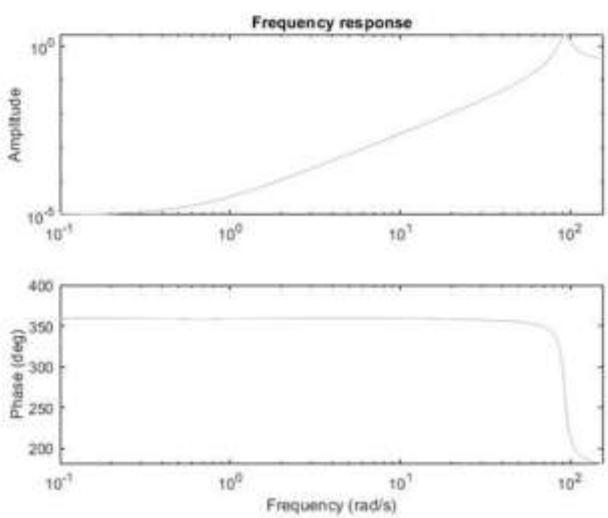

Fig-11: Frequency Function u2->y2

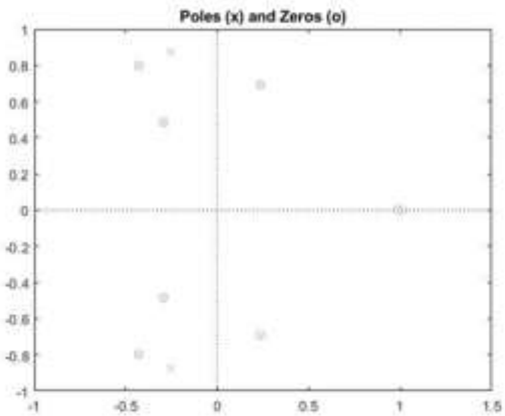


Fig-12: Poles and Zeros u1 > y1

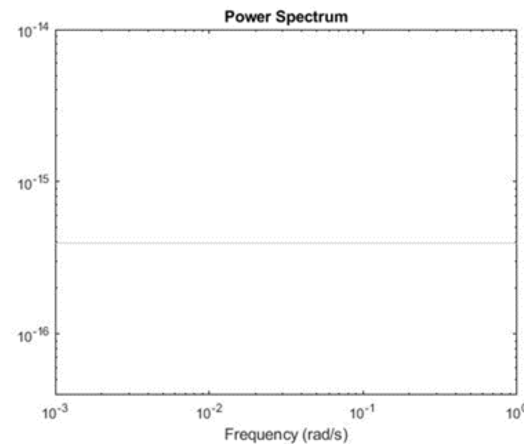


Fig-14: Noise Spectrum y1

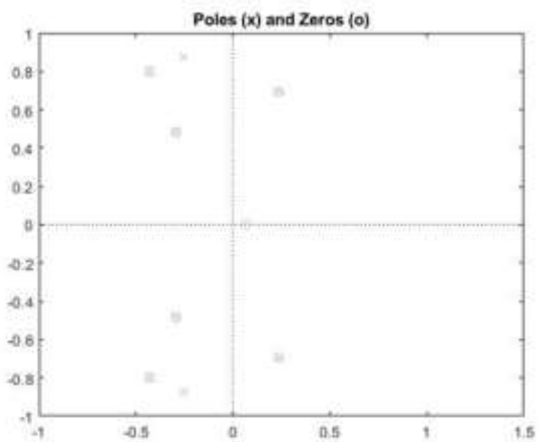


Fig-13: Poles and Zeros u2 > y2

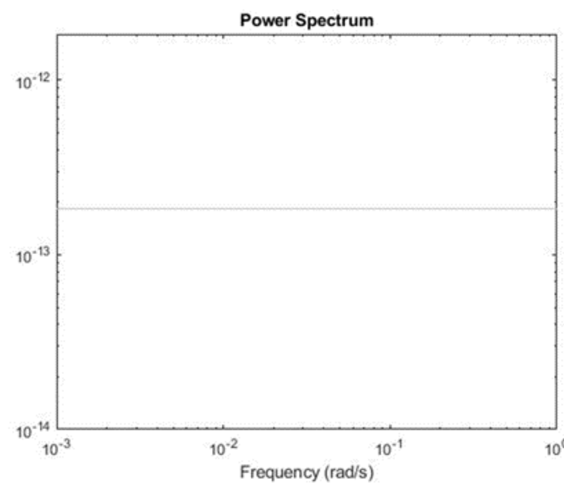


Fig-15: Noise Spectrum y2

**4. CONCLUSIONS**

In this paper reviews the theoretical principles of subspace system identification as applied to the problem of estimating black-box state-space models of support-excited structures (e.g., structures exposed to earthquakes). The work distinguishes itself from past studies by providing readers with a powerful geometric interpretation of subspace operations that relates directly to theoretical structural dynamics.

To validate the performance of subspace system identification, a series of experiments are conducted on a machine foundation pile exposed to moderate seismic ground motions; structural response data is used off-line to estimate black-box state-space models. Ground motions and structural response measurements are used by the subspace system identification method to derive a complete multi input – multi output state-space model of the machine foundation pile system. The modal parameters of the machine foundation pile are extracted from the estimated multi input – multi output state-space model. With the use of only structural response data, output-only state-space models of the system are also estimated by subspace system identification.

In this paper, a new structural identification tool is proposed to identify the modal properties of foundations and foundation pile. Results demonstrated that fit to estimation data was 99.01% and it can be concluded that N4SID multi input – multi output (MIMO) system identification method is efficient and accurate in identifying modal data of the machine foundation.

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