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SEISMIC MOTION SIMULATION BASED ON CASSINO PARALLEL MANIPULATOR

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Abstract. *In this paper we present a study of feasibility by using Cassino Parallel Manipulator (CaPaMan) as an earthquake simulator. We propose a suitable formulation to simulate the frequency, amplitude and acceleration magnitude of seismic motion by means of the movable platform motion by giving a suitable input motion. In this paper we have reported numerical simulations that simulate the three principal earthquake types for a seismic motion: one at the epicenter (having a vertical motion), another far from the epicenter (with the motion on a horizontal plane), and a combined general motion (with a vertical and horizontal motion).*

Keywords: Parallel manipulator, Earthquake, Earthquake simulation, Seismic motion.

1. INTRODUCTION

Parallel structures have characteristics such as high stiffness and load capacity and can operate at high velocities and accelerations with high precision. This justifies the great number of theoretical and experimental studies with the aim to use them more than serial manipulators. It has been found applications for flight simulators, milling machines, toys, load cells, packing and assembly.

At the Laboratory of Robotics and Mechatronics in Cassino, Italy, a novel parallel structure with 3 d.o.f., named as CaPaMan – Cassino Parallel Manipulator – has been conceived and suitable formulation for kinematics and dynamics has been developed by theoretical investigations.

Earthquakes are well known from the destruction and lost lives due the failing of buildings. In general a combined horizontal and vertical ground motion characterizes an earthquake, and it can be conveniently simulate by using a suitable parallel structure. The simulation of a seismic motion has great interest because it helps to understand the earthquake effects and helps to solve problems in predicting the behavior of buildings and civil engineering structures in general.

In this paper we present a study of feasibility for an earthquake simulator by using the CaPaMan structure. The frequency, amplitude and acceleration magnitude of seismic motion are simulated by the movable platform motion by giving a suitable input motion.

In particular we propose a specific formulation in order to simulate the three principal types of seismic motion and by considering the position related to the epicenter. If the earthquake is considered in the epicenter the seismic motion takes place along the vertical direction. By considering the seismic motion far from the epicenter, the motion ground occurs preferentially in a horizontal plane, and otherwise takes place a general motion, i.e. a vertical motion that is combined with a horizontal motion.

2. CAPAMAN STRUCTURE

CaPaMan (Cassino Parallel Manipulator) structure is characterized by three 4-bar articulated mechanisms AP disposed in an equilateral triangle of the fixed base FP as shown in Fig.1. On the coupler link of each 4-bar mechanism is installed a prismatic joint SJ that is connected with the movable platform MP by a rod CB and a spherical joint BJ. The kinematic variables are the input crank angles α_k (k=1,2,3) of each 4-bar mechanism.

In order to describe the CaPaMan kinematic and dynamic behavior, an inertial frame OXYZ has been assumed fixed to FP and a moving frame $HX_pY_pZ_p$ has been attached to the platform. The kinematic feasibility of CaPaMan was analysed by Ceccarelli (1997) and Ceccarelli and Figliolini (1997). The position and orientation of MP has been expressed as function of the coordinates y_k and z_k of the articulation points H_k that can be easily expressed as a function of the AP input angles α_k (k=1,2,3). Since the motor units for robotic applications are usually controlled in position and velocity, the input motion can be given by a cubic function of time t between given initial α_{ki} and final α_{kf} angles at initial t_{ki} and final t_{kf} times, respectively. An analytical model for dynamics of CaPaMan by using the Newton-Euler approach has been formulated to compute the input torques which are necessary for a given trajectory of movable platform (Carvalho and Ceccarelli, 1999). Experimental tests has been confirmed the kinematic feasibility and actuation efficiency of CaPaMan (Ceccarelli et al., 1999a).

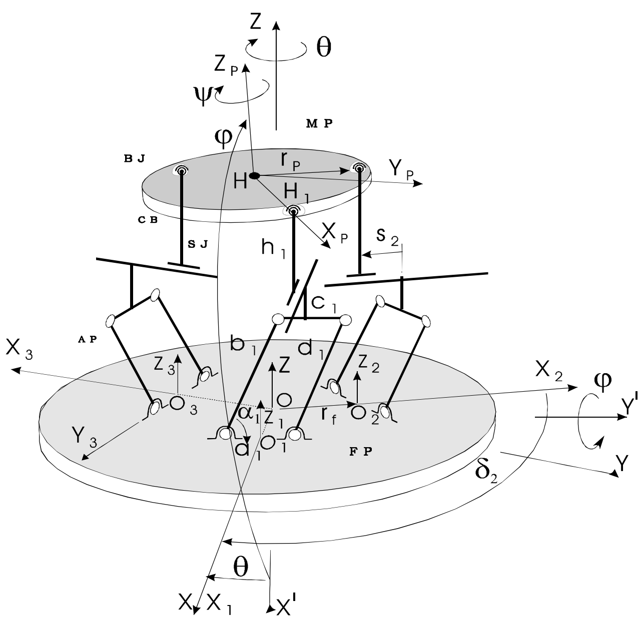

Figure 1. Kinematic chain and parameters of CaPaMan.

3. EARTHQUAKE CHARACTERISTICS

The intensity, shape and duration, that are functions of the terrain properties, can characterize an earthquake. Newmark-Rosenblueth, as cited in Gavarini (1984), classifies earthquakes in three types :

- Type 1 - Type 1 earthquake is characterized by a single shock. Generally occurs no long of the epicenter and in a compact soil as those that has been occurred in Agadir in 1960, Skopje in 1963 and Port Hueneme in 1957 (Gavarini, 1984; Sarà, 1985). An example is shown in Fig.2.

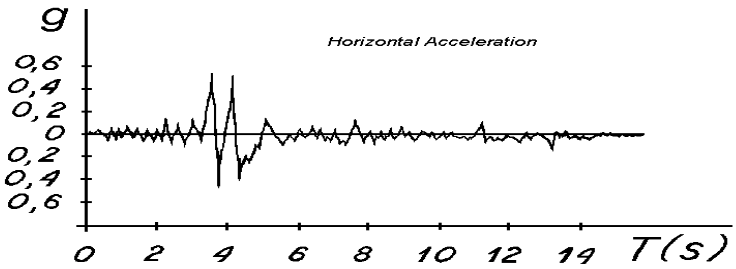

Figure 2. Single shock earthquake (Sarà, 1985).

- Type 2 – It is an earthquake characterized by a long duration, and is very irregular with a large frequency spectrum. Generally occurs at a medium distance of the epicenter and in a compact soil as the El Centro earthquake (California/USA) that has been occurred in 1940 as shown in Fig.3.

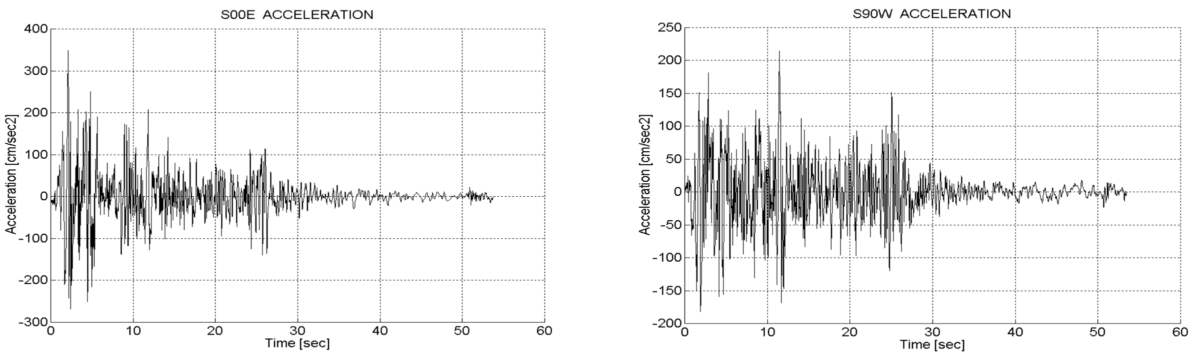

Figure 3. The El Centro Earthquake (May 18, 1940).

- Type 3 – This earthquake type is characterized by a predominant frequency as the Mexico City earthquake occurred in 1964, shown in Fig.4. The terrain acts as a filter for the reflection waves of the seismic motion.

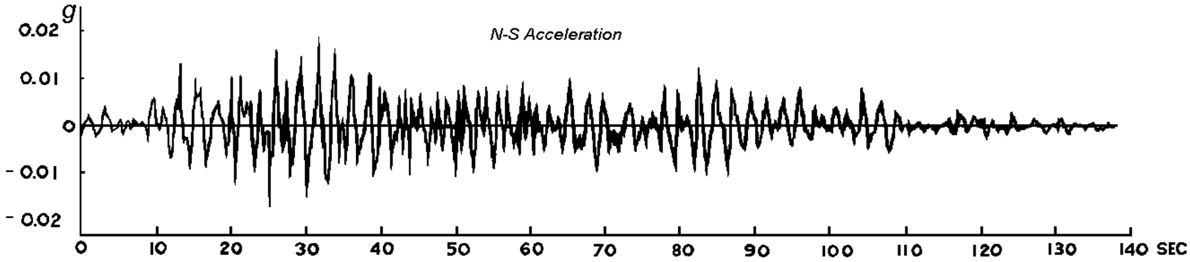

Figure 4. The Mexico City earthquake occurred in 06.08.64 (Gavarini, 1984).

There is a fourth earthquake type that is characterized by an important deformation on the ground (with a magnitude of a meter) that we do not consider in this paper.

A typical acceleration seismogram is characterized by an initial phase that corresponds to the beginning of the seismic motion; an intermediate phase during which occurs the maximum acceleration peaks and displacements, and a final phase that represents the end of the earthquake as shown in Figs. 2, 3 and 4. Characteristics of the terrain and distance of the epicenter can give to seismic motion a preferential direction: along a vertical line, on a horizontal plane, or both horizontal and vertical directions.

The feasibility of use CaPaMan as an earthquake simulator is shown through results of numerical simulations of three earthquake types, and by considering a vertical, or a horizontal or a vertical and horizontal motion.

4. EARTHQUAKE SIMULATION BY CAPAMAN

An earthquake simulation by using CaPaMan can be performed by properly giving an input motion to links b_k (k=1,2,3). Crank angles α_k (k=1,2,3) give the amplitude of seismic motion, and acceleration peaks for the displacement of MP. The random characteristics of an earthquake give the possibility to define limits for maximum and minimum intervals for input angles α_k and time cycle.

In order to obtain a general earthquake shape, the initial and final phases of an accelerogram has been divided in two parts as shown in Figs. 5 and 6.

Figure 5 represents a typical shape of an earthquake defined by limits of input angles. The beginning of the seismic motion is limited by cycle i_2; and the final phase from cycle i_3 to cycle i_f . Between cycles i_2 and i_3 occurs the acceleration peaks of earthquake.

In order to simulate a single shock earthquake, a maximum and minimum shock input angle $\alpha_{shock\_\max/\min}$ has been defined between cycles i_2 and i_3 as shown in Fig.6.

Acceleration peaks for earthquakes of types 1 and 2 have been obtained from cycle time as shown in Fig.7. Small cycle times associated with large input angles at interval $i_2 i_3$ correspond to large accelerations peaks. Type 3 earthquake has a constant frequency.

Referring to Figs. 5 and 6 each input angle α_k (k=1,2,3) has been given according to the following expressions:

$$\alpha_k = \alpha_{k0} + (\alpha_{ki1\max} - \alpha_{ki1\min})\frac{i}{i_1} R + (\alpha_{ki1\min} - \alpha_{k0})\frac{i}{i_1}; \quad i \in [0, i_1) \tag{1}$$

$$\begin{aligned}\alpha_k = \alpha_{ki1\min} + \left[(\alpha_{ki2\max} - \alpha_{ki1\max} - \alpha_{ki2\min} + \alpha_{ki1\min})\left(\frac{i - i_1}{i_2 - i_1}\right) + \alpha_{ki1\max} - \alpha_{ki1\min} \right] R + \\ + (\alpha_{ki2\min} - \alpha_{ki1\min})\left(\frac{i - i_1}{i_2 - i_1}\right); \quad i \in [i_1, i_2)\end{aligned} \tag{2}$$

$$\begin{aligned}\alpha_k = \alpha_{ki2\min} + \left[(\alpha_{ki4\max} - \alpha_{ki2\max} - \alpha_{ki4\min} - \alpha_{ki2\min})\left(\frac{i - i_3}{i_4 - i_3}\right) + \alpha_{ki2\max} - \alpha_{ki2\min} \right] R + \\ + (\alpha_{ki4\min} - \alpha_{ki2\min})\left(\frac{i - i_3}{i_4 - i_3}\right); \quad i \in [i_3, i_4)\end{aligned} \tag{3}$$

$$\alpha_k = \alpha_{k0} + (\alpha_{ki4\max} - \alpha_{ki4\min})\left(\frac{i_f - i}{i_f - i_4}\right) R + (\alpha_{ki4\min} - \alpha_{k0})\left(\frac{i_f - i}{i_f - i_4}\right); \quad i \in [i_4, i_f] \tag{4}$$

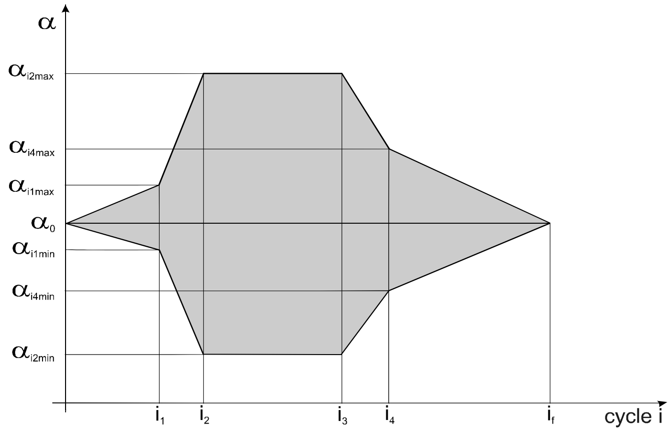

Figure 5. Domain for input angles in order to obtain earthquakes of types 2 and 3.

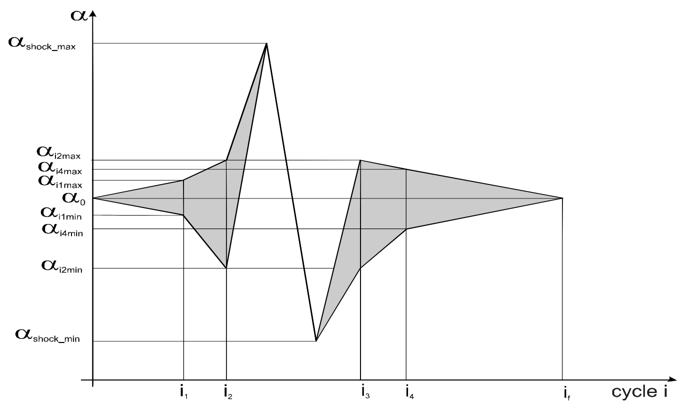

Figure 6. Feasible domain for the input angles in order to obtain single shock earthquake.

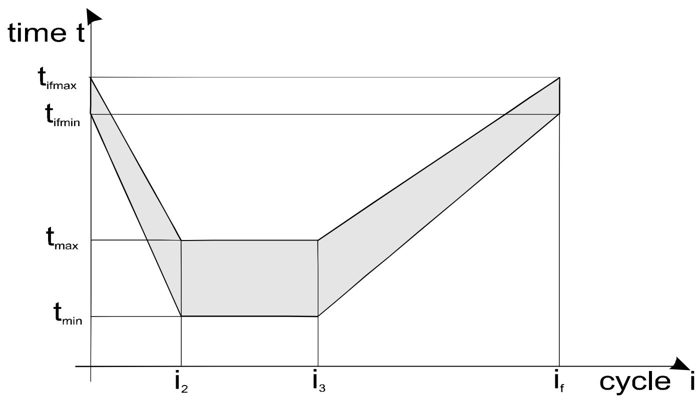

Figure 7. Domain for input time of a cycle in order to obtain earthquakes of types 1 and 2.

For earthquakes of types 2 and 3 the expression of each input angle in the interval i_2 and i_3 takes the form:

$$\alpha_k = \alpha_{ki2\min} + (\alpha_{ki2\max} - \alpha_{ki2\min})R; \quad i \in [i_2, i_3) \tag{5}$$

and for single shock earthquake it holds as

$$\alpha_k = \alpha_{kshock\_\max} \qquad \text{for} \quad i = i_2 + 1 \tag{6}$$

$$\alpha_k = \alpha_{kshock\_\min} \qquad \text{for} \quad i = i_2 + 2 \tag{7}$$

Referring to Fig.7, input time for each cycle can be obtained as

$$t = t_{if\,\min} + \left[\left(t_{\max} - t_{\min} - t_{if\,\max} + t_{if\,\min} \right) \frac{i}{i_2} + t_{if\,\max} - t_{if\,\min} \right] R + \left(t_{\min} - t_{if\,\min} \right) \frac{i}{i_2}; \quad i \in [0, i_2) \tag{8}$$

$$t = t_{\min} + \left[\left(t_{\min} - t_{\max} + t_{if\,\max} - t_{if\,\min} \right) \left(\frac{i - i_3}{i_f - i_3} \right) + t_{\max} - t_{\min} \right] R + \\ + \left(t_{if\,\min} - t_{\min} \right) \left(\frac{i - i_3}{i_f - i_3} \right); \quad i \in [i_3, i_f] \tag{9}$$

Between cycles i_2 and i_3 the input time for single shock earthquake is given as

$$t = t_{min} \qquad \text{for} \quad i = i_2 + 1 \tag{10}$$

$$t = t_{max} \qquad \text{for} \quad i = i_2 + 2 \tag{11}$$

for earthquake of type 2 is given as

$$t = t_{\min} + \left(t_{\max} - t_{\min} \right) R; \quad i \in [i_2, i_3) \tag{12}$$

and for earthquake of type 3 is given by the earthquake frequency F_{req} as

$$t = F_{req}^{-1}; \quad i \in [i_2, i_3) \tag{13}$$

R in Eqs. (1) to (12) is a random function in the interval (0,1) which has been successfully used to simulate seismic motions.

Kinematics characteristics of CaPaMan have been analyzed in (Ceccarelli, 1997; Ceccarelli & Figliolini, 1997; Carvalho & Ceccarelli, 1999; Ceccarelli et al., 1999a and 1999b) and they permitted to easily simulate a seismic motion along a vertical direction, a horizontal plane and a general direction, i.e. vertical and horizontal motion by simulating the distance of the epicenter.

4.1. Numerical Simulations

In this section we have reported results for three numerical simulations: a single shock earthquake in a vertical direction that is shown in Fig.8; an earthquake of type 2 in a horizontal direction that is shown in Fig.9, and an earthquake of type 3 in a general direction that is shown in Fig.10.

Reported simulations refer to the specific dimensions of the built prototype in Cassino,

Fig.1: $c_k=a_k$=200mm; $b_k=d_k$=80mm; h_k=116mm; $r_f=r_p$=109,5mm and m=2,912kg, k=(1,2,3).

Results of the numerical simulation of a single shock earthquake in a vertical direction are shown in Fig.8 and they show accelerations of the same magnitude as those presented in Fig.2. The input parameters defining the seismic wave have been given as: α_0=90deg; $\alpha_{i1max}=\alpha_{i2max}=\alpha_{i4max}$=16,5deg; $\alpha_{i1min}=\alpha_{i2min}=\alpha_{i4min}$=-16,5deg; α_{shock_max}=20deg; α_{shock_min}=-20deg; t_{max}=0,4s; t_{min}=0,3s; $t_{ifmax}=t_{ifmin}$=0,25s; number_of_cycles=50. The vertical linear motion of MP is obtained when the input crank angles α_k (k=1,2,3) are equal as shown in Fig.8a. Figure 8b presents time history of vertical acceleration. Fig.8c gives the values of required input torques and Fig.8d gives the consequent displacement of point H of MP.

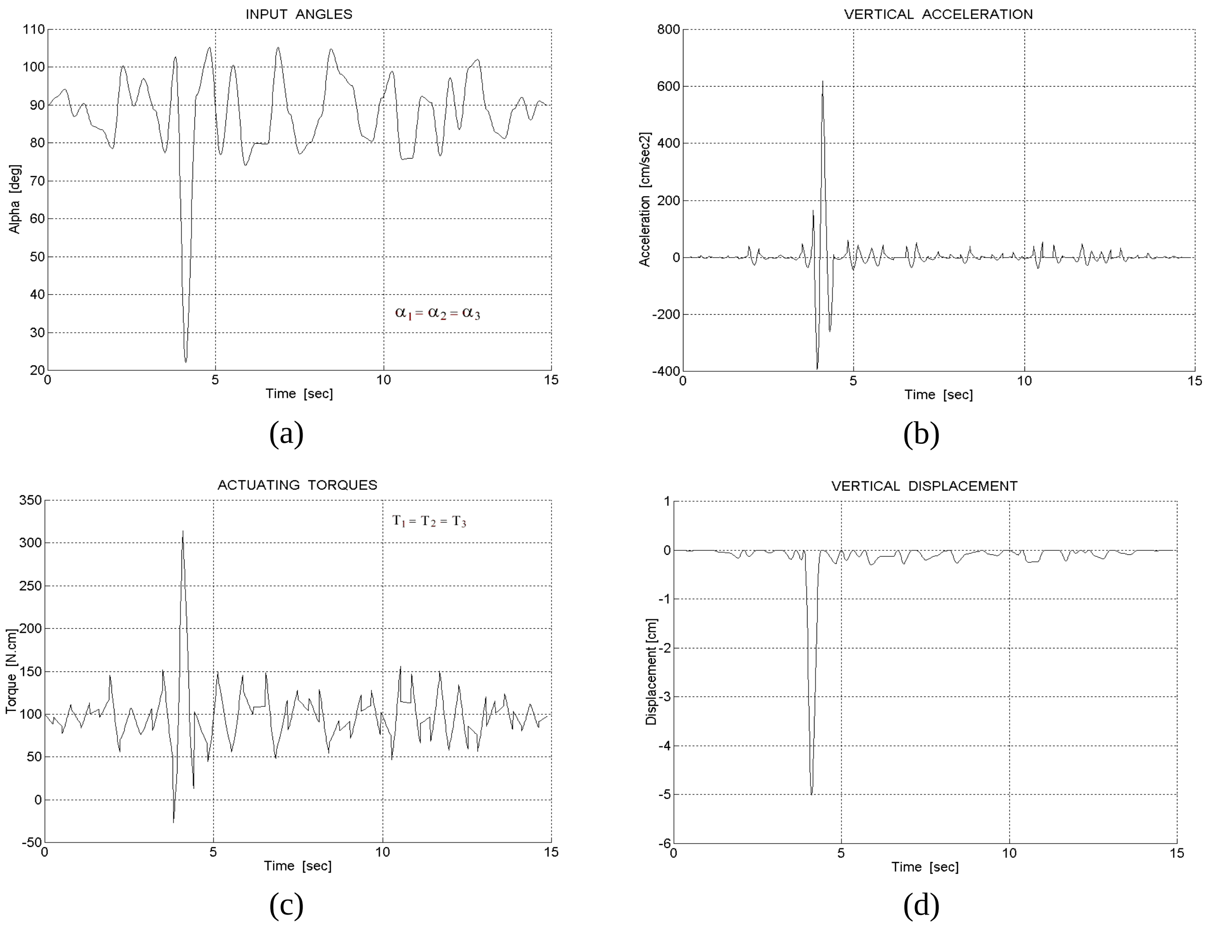

Figure 8. Numerical results of a single shock earthquake in the vertical direction.

The earthquake of type 2 has been simulated for a horizontal motion and the results are shown in Fig.9. The parameters for the seismic wave are: α_0=90deg; $\alpha_{i1max}=\alpha_{i2max}=\alpha_{i4max}$=16,5deg; $\alpha_{i1min}=\alpha_{i2min}=\alpha_{i4min}$=-16,5deg; t_{max}=0,4s; t_{min}=0,3s; $t_{ifmax}=t_{ifmin}$=0,2s; number_of_cycles=70. Figure 9 shows results for a horizontal motion of MP along the axis x when the input angle α_1 is assumed as constant, α_2 is given by Eqs. (1) to (5) and $\alpha_3 = \pi - \alpha_2$ is ensured.

The results of the numerical simulation are shown in Fig.9 and a small acceleration component in the vertical direction has been computed in agreement with what occurs in a real horizontal earthquake, Figs.9g and 9h.

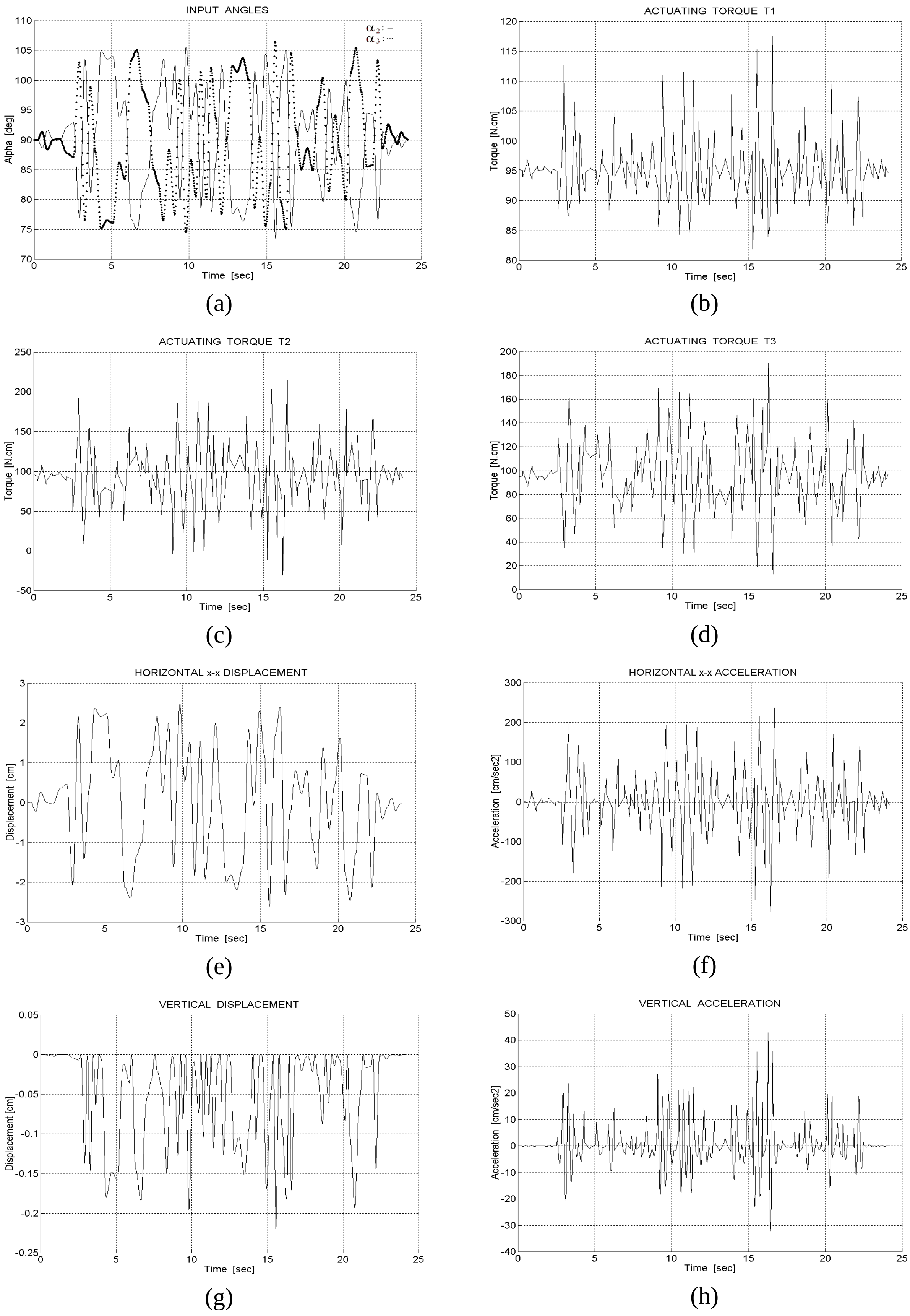

Figure 9. Numerical results of simulation for type 2 earthquake with a horizontal seismic motion.

Figure 10 shows results of a general seismic motion for the type 3 earthquake. The values of the parameters for the seismic wave are assumed as: F_{req}=2,4cycle/sec; α_0=70deg; $\alpha_{i1max}=\alpha_{i2max}=\alpha_{i4max}$=35deg; $\alpha_{i1min}=\alpha_{i2min}=\alpha_{i4min}$=-35deg; number_of_cycles=310.

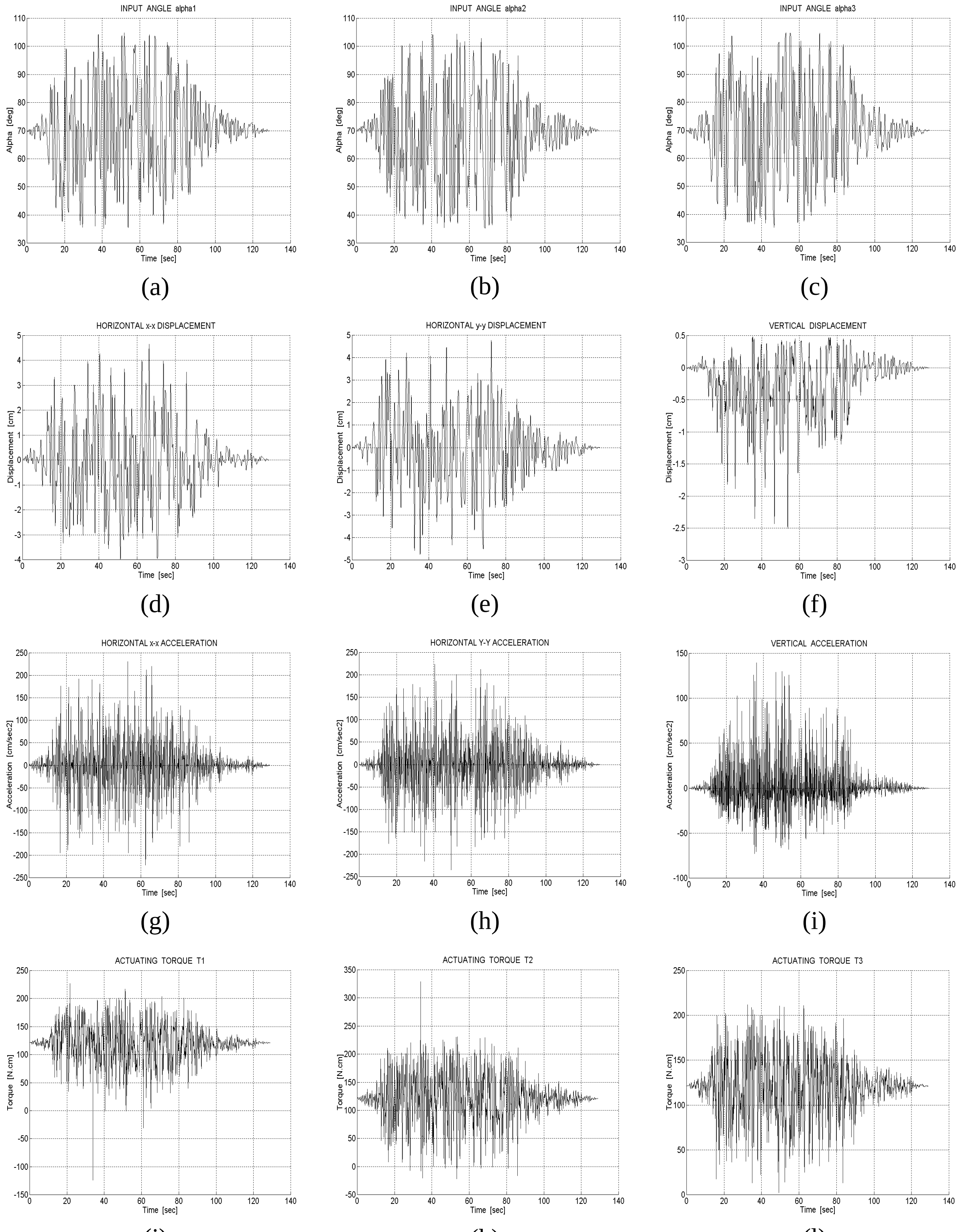

Figure 10. Numerical results of simulation for type 3 earthquake with a general seismic motion.

5. CONCLUSIONS

In this paper we have presented a study of feasibility by using CaPaMan (Cassino Parallel Manipulator) as earthquake simulator. A suitable formulation has been presented as based on seismogram of the three principal types of earthquakes that can de identified as a seismic motion along a vertical direction, a horizontal plane and a combined general motion direction.

Several numerical tests have been carried out and results prove the feasibility of CaPaMan to simulate any type of seismic motion "in" or "out" of the epicenter since a suitable actuation has been computed in the form of input torques for the three motors of CaPaMan.

Practical experiments, reported in (Ceccarelli et al., 1999b), have been shown the feasible seismic simulated motion of the mobile platform by using a simple programming of the earthquake operation.

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