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INTERPRETATION OF EARTHQUAKE EFFECTS ON MECHANISM OPERATION: AN EXPERIMENTAL APPROACH

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Abstract

This paper investigates the characteristics of the effects of earthquakes on the operation of mechanical systems with the help of a 3 DoF robot (CAPAMAN) that can simulate 3D earthquake motion properly. Characteristics of the reaction of machinery operation to earthquake disturbance are identified through experimental tests. These tests have been carried out by using two slider crank linkages with DC and servo motors as test bed mechanisms that have been equipped with acceleration sensors. Results are reported and discussed to show characteristic seismic effects on mechanism operations.

DEPREM TİTREŞİMLERİNİN MEKANİZMA İŞLEYİŞİNE ETKİLERİNİN ÇIKARIMI: DENEYSEL BİR YAKLAŞIM

Özetçe

Bu çalışmada depremlerin mekanik sistemler üzerine etkilerini karakteristikler incelenmişti. Üç boyutlu deprem etkilerini simule edebilen üç serbestlik dereceli bir robot (CaPaMan) kullanılmıştır. Makine işleyişinin deprem etkisine tepkisinin karakteristiği deneysel olarak incelenmiştir. Bu deneylerde örnekleyici sistem olarak DC ve servo motorlara sahip iki tane krank-biyel mekanizması kullanılmıştır. Bulunan sonuçlar incelenmiştir.

Keywords: Experimental Mechanics, Mechanisms, Earthquake effects.
Anahtar Kelimeler: Deneysel mekanik, Mekanizmalar, Deprem etkileri.

1. INTRODUCTION

Earthquake simulators are commonly used for the experimental tests in the field of Civil engineering for investigating the earthquake characteristics and earthquake resistant constructions. Small-scale uni-axial servo-hydraulic seismic simulators have become popular [1, 2] for dynamic testing of structures subjected to earthquake accelerations and for experimenting effects on structures. A number of new large-scale seismic simulator facilities [3,4,5] and some exceptional simulators made for outdoor [6] and even with 6 DoF motion [7] for shaking tables are presented in the literature. Reproducing three main real characteristic of the earthquakes is most challenging effort for these simulators. Most of the earthquake simulators have high payload capacity, high motion speeds, and high accelerations, which are shaking tables which refer only to translational motions of the earthquakes.

Earthquake simulator is a suitable application for CaPaMan which can simulate not only translational motion but also three dimensional waving motions of earthquakes. Theoretical investigations and experimental validations in [8-10] present performances and suitable formulation for the operation of CaPaMan. The operation of CaPaMan can be easily adjusted to obtain any kind of earthquake in terms of magnitude, frequency and duration by giving suitable input motion. Although the effect of vibrations on machinery and their isolations are well known, the specific characteristics of earthquake actions on machinery are not yet fully explored. In previous works [11] the effects of earthquakes on mechanism operation are shown with experiments on a slider-crank mechanism and a robotic hand. In this paper the effects of earthquake on the operation of mechanical systems have been investigated by an analysis and reproduction of an earthquake motion. This paper illustrates a specific activity that has been focused in determining experimentally the effects of earthquake motion on mechanism operation. Experiments are widened by using a servo motor and some weights on the slider, not only acceleration but also torque data is taken from slider crank linkage with the servo motor.

2. EARTHQUAKE MOTION CHARACTERISTICS

A sudden and sometimes catastrophic movement of a part of the surface of the Earth is called an earthquake, which results from the dynamic release of elastic strain energy that radiates seismic waves. Large earthquakes can cause serious destruction and massive loss of life through a variety of types of damage such as fault rupture, vibratory ground motion, inundation, various kinds of permanent ground failure, and fire or a release of hazardous materials, but even buildings/ constructions collapses and vehicles/ machinery operation crashes. Ground motion is the dominant and most widespread cause of damages. [12]. Main characteristics of an earthquake are frequency, amplitude and acceleration magnitude, since the resonance of a system is determined by frequency value, duration of the stress action due to a seismic motion, amplitude and acceleration magnitude of an earthquake. Period of a seismic cycle and characteristic length for each seismic wave must be identified to define the seismic motion. Usually, critical resonant motion is analyzed in terms of translational seismic components, but even angular motion can strongly contribute to the resonant excitation. Thus, unlike most of the simulators where the 3D motion of the terrain due to earthquake waves has not been taken into account in this paper 3D motion capability of CaPaMan parallel manipulator has been used to simulate earthquake motion with its full motion effects.

3. MECHANISM OPERATION

A machine is a “mechanical system that performs a specific task, such as the forming of material, and the transference and transformation of motion and force.” and mechanism is defined as a “constrained system of bodies designed to convert motions of, and forces on, one or several bodies into motions of, and forces on, the remaining bodies” as mentioned in the terminology of IFToMM [13]. Operation of mechanisms can be described by three steps as input, task and output. Task and output of mechanisms can differ with respect to desired results which are task goals for mechanisms, which can be classified as function generation, point guidance, and body guidance, [14]. Considerations for designing mechanisms for those and other tasks are related to characteristics of operation such as general operation performance, repeatability of operation frequency, efficiency, reliability, precision and accuracy. Also vibrations that can occur during the operation can be considered and some isolation can be applied to machine basements.

Human-machine interactions will include issues on comfort and safety that can make strong constraints to machinery operations with limited range of feasible operations. Special attention is today addressed to safety as interaction with human users, even when using a machine under critical, risky situations which can be characterized by impact, high accelerations or changed operation outputs. Also efficiency in force transmission and energy consumption is of great importance in modern machinery. Unfortunately in general the effects of earthquakes are neglected during machine design. The difficulty to determine the effects of the earthquakes is due to different types of totally random waves caused by them. It is necessary to have a fixed reference for defining the motion of a mechanism. Usually ground is taken as the reference for machines and manipulators. When an earthquake occur these fixed link starts to move and even the frame applies force acting on the machines or manipulators. The effect of these unexpected random forces and motions on machines must be investigated to see the unexpected changes of the outputs. This knowledge can give useful feedback for the design and operation of machines that can work without affected by earthquakes.

3.1. AN EXAMPLE WITH A SLIDER CRANK MECHANISM

The slider-crank mechanism in Figure (2.a) is often used to convert rotary motion into alternating linear motion or vice versa. One of the four inversions of slider crank mechanism is used in internal combustion engines (automobiles, ships, etc), with application of perhaps a billion engines makes the slider crank mechanism one of the most used mechanisms in the world. In Figure (2.a) kinematic parameters of slider crank are shown, acceleration as output of the slider has been and a numerical computation is shown in Figure (2.b), which shows a nearly harmonic motion.

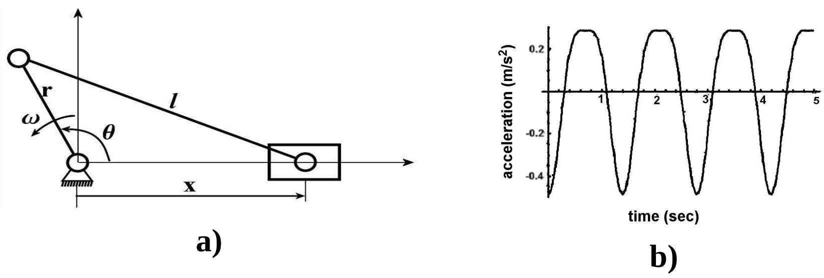


Figure 2. A test-bed slider-crank mechanism: a) Kinematic parameters, b) Slider accelerations with stationary frame (43 rpm)

4. AN EXPERIMENTAL EVALUATION

The CaPaMan prototype is shown in Figure (3). The laboratory test-bed prototype for earthquake simulator consists of CaPaMan prototype with sensors, a controller for its operation and an acquisition board connected to the computer, in order to acquire the components of the linear accelerations occurring along the axes of the reference system belonging to the mobile platform [8].

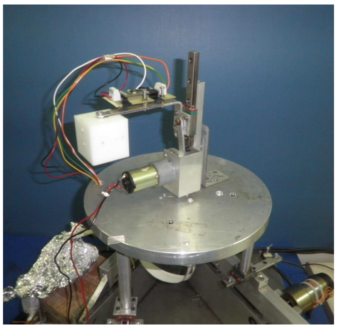
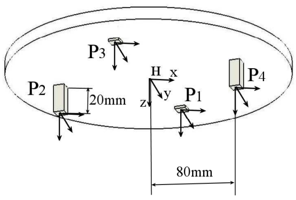
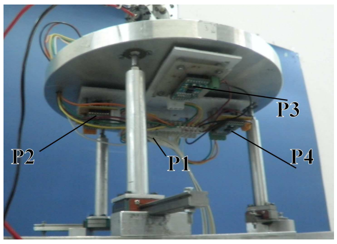


Figure 3. An experimental setup at LARM with the slider-crank mechanism.

The minimum numbers of accelerometers need to directly calculate the angular velocity for a 3D motion of a rigid body is twelve. In this research four of three axis accelerometers are placed in the corners to keep symmetry and using the mathematical calculations in [15] this configuration of 4 sensors is used to keep the replacement errors of sensor minimum. Accelerometers are placed under the platform of the CaPaMan as shown in Figures (4.a-b). The control system scheme layout for CaPaMan manipulator is shown in Figure (5).



a)



b)

Figure 4. Sensored CaPaMan platform with accelerometers: a) a scheme, b) sensor installation & test lay-out

For characterization of earthquake effects on mechanism two types of earthquakes are simulated. Characteristic phases of the simulated earthquakes are given in Table (1) and a reference earthquake simulation Figure (6) is given for defining parameters for earthquake characteristics.

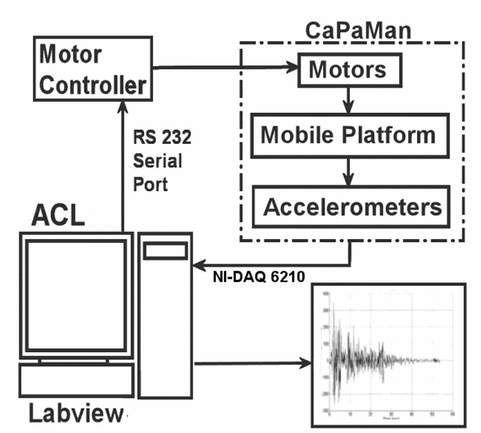


Figure 5. Control system layout for CaPaMan as earthquake simulator.

Table 1. The characteristics of simulated earthquakes

	Total Time (sec)	ΔT_{max} (sec)	ΔT_{min} (sec)	Number of oscillations	Maximum Frequency (Hz)
Earthquake Type 1	45	2.0	0.8	30	1.2
Earthquake Type2	50	2.0	1.5	30	0.8

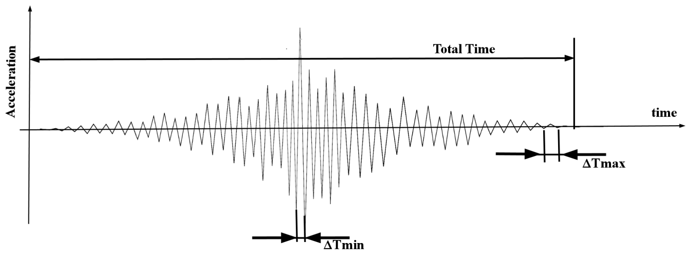
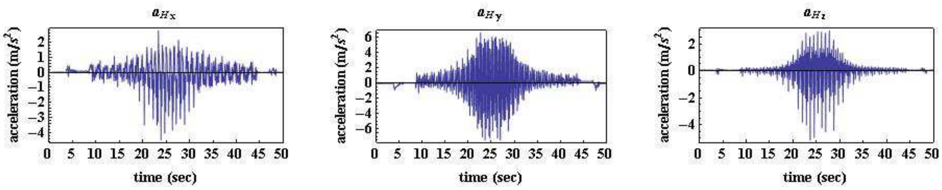
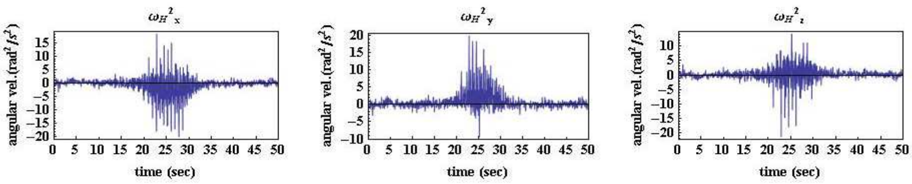


Figure 6. Typical characteristics of simulate earthquake



a)



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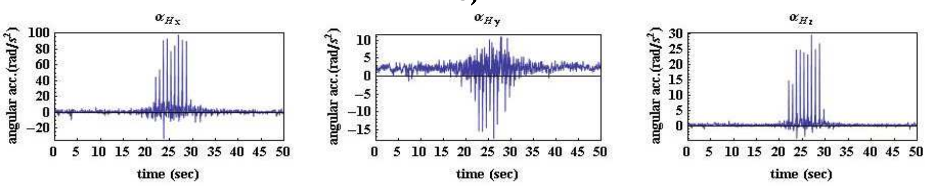


c)

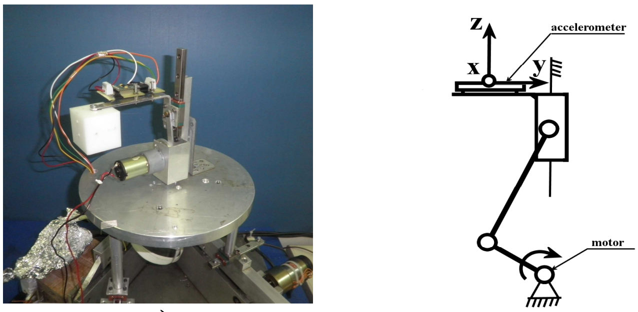
Figure 7. An example of acc. data during earthquake simulation: a) for platform center H, b) angular platform velocity, c) angular platform acc.

By using four sensors with totally twelve sensitive axes it is possible to directly compute the linear accelerations ($\mathbf{a}_H$), angular accelerations ($\boldsymbol{\alpha}_H$) and angular velocities ($\boldsymbol{\omega}_B$) around point H and shown in Figure (7).

5. EXPERIMENTAL TESTS WITH PROTOTYPES

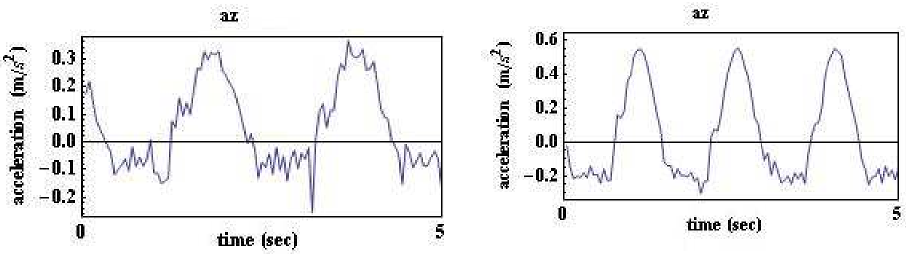
Experimental tests have been carried out by using a slider-crank linkage with DC and servo motors, a robot leg linkage, a small car model, and LARM Hand as test-bed mechanisms with acceleration or force sensors.

5.1. SLIDER CRANK ACTUATED WITH DC MOTOR



a) b)

Figure. 8. A test-bed slider-crank mechanism at LARM: a) an experimental set up with accelerometer and weight on the slider. b) sensing axes of the accelerometer.



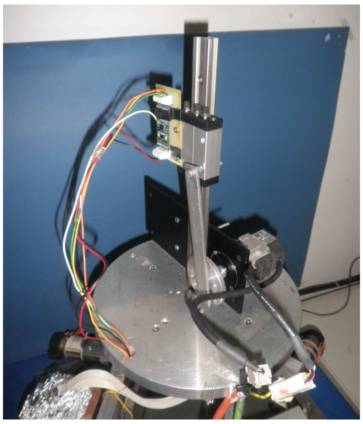
a) b)

Figure 9. An experimental measure of the typical acc. of the slider-crank with stationary frame: a) crank rotation 32 rpm, b) crank rotation 43 rpm,

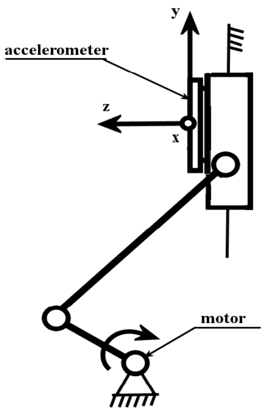
An accelerometer is attached to the slider of the slider crank mechanism as shown in Figure (8a) and accelerometers sensing axes can be seen in Figure (8b). Slider-crank mechanism with DC motor actuation is subjected to earthquake vibrations with different operating speeds. Figure (9) shows the filtered experimental measure of the acceleration of the slider as from the case in Figure (2.b). The noise in the measure is due to backlash of the components, flexibility of the links and design tolerances. Also some noise is caused by environmental waves into the frame link. Experiments are repeated with and without attached weight on the slider.

5.2. SLIDER CRANK ACTUATED BY SERVO MOTOR

An accelerometer is attached to the slider of the slider crank mechanism Figure (10.a) and accelerometers sensing axes can be seen in Figure (10.b). Usage of servo motor gives the advantage to view torque data during operation. In Figure (11.a) torque data of the motor and acceleration of the slider is given without earthquake disturbance with crank motion of 90 rpm. In Figure (11.b) same type of data with crank rotation 180 rpm is given.



a)



b)

Figure 10. Slider-crank mechanism with servo motor at LARM: a) an experimental set up with accelerometer on the slider. b) sensing axes of the accelerometer.

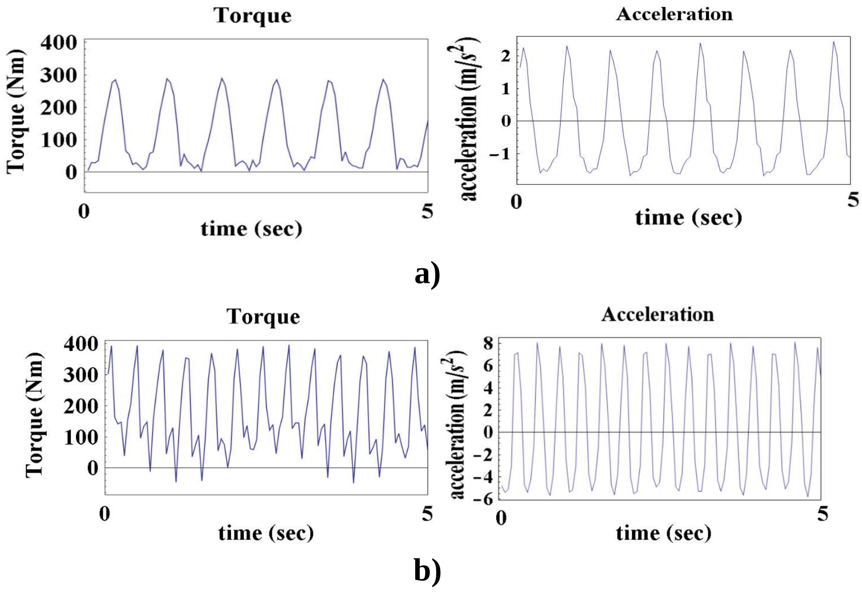


Figure 11. An experimental measure of slider crank with servo motor without earthquake effect: a) torque data of the motor, acceleration of the slider with crank rotation 90 rpm, b) torque data of the motor, acceleration of the slider with crank rotation 180rpm

6. RESULTS OF TESTS AND CONSIDERATIONS FOR CHARACTERIZATION

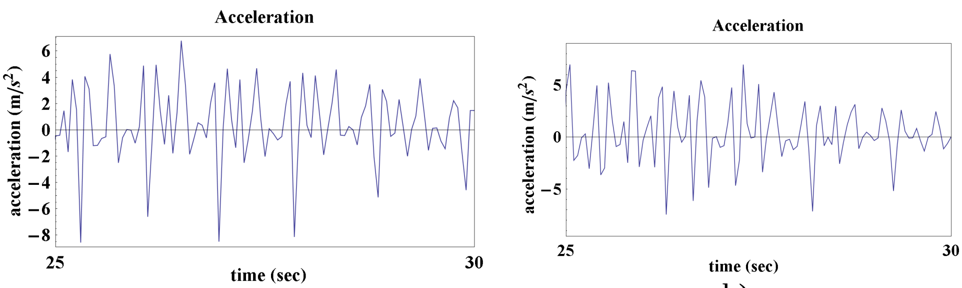
The results of simulated earthquakes can be summarized with the maximum acceleration values of center point H. For the earthquake type 1 maximum acceleration is $a_{h,max}$= 8.4 m/s^2, and for earthquake type 2 max acceleration of point H is $a_{h,max}$= 5.29m/s^2. In Table (2) maximum acceleration data for the mechanisms are given for comparison. In each sub-section experimental data from mechanism sensors are shown during earthquake disturbance

Table.2. Data from experimental tests with test-bed mechanisms.

		Exp data	Earthquake type 1	Earthquake type 2	Stationary
Slider crank With DC motor az_{max} (m/s^2)	Horizontal	24 volts 32rpm	8.575	9.160	0.452
		32 volts 43rpm	5.664	5.267	0.531
	weighted	24 volts 32rpm	9.023	8.006	0.316
		32 volts 43rpm	6.235	6.223	0.574
	Vertical	24 volts 32rpm	9.286	7.438	0.447
		32 volts 43rpm	4.390	3.829	0.587
	weighted	24 volts 32rpm	7.145	8.583	0.609
		32 volts 43rpm	3.975	4.242	0.706
Slider crank with servo ay_{max} (m/s^2)		15k-90rpm	7.530	4.15	2.508
		30k-180rpm	11.64	10.81	8.211
		60k-360 rpm	16.90	16.03	13.97

6.1. SLIDER CRANK ACTUATION BY DC MOTOR

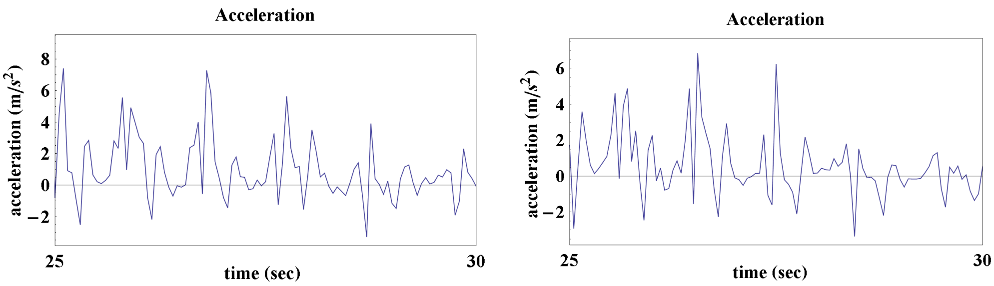
When the slider-crank is subjected to an earthquake motion the acceleration of the slider is altered up to the measured acceleration shown in Figure (12) for slider position horizontal and Figure (13) for slider position vertical. Details of these changes are visible from Figure (12) to Figure (13) with views of slider acceleration between 25 and 30 seconds of earthquake motion, when the seismic accelerations are at maximum.



a) b)

Figure 12. An experimental measure of the typical accelerations with horizontal slider under earthquake effect (type 1): a) crank rotation 32 rpm, b) crank rotation 43 rpm.

It is observed from the Figures (20, 21) that the shape and amplitude of the acceleration of the slider during a simulated earthquake are strongly changed and oscillations of the slider acceleration are also vanished. It seems that the slider acceleration is fully disturbed by the earthquake effects. Considering the different speeds and different position of the mechanism the motion is affected more when crank speed is at lower speed or slider position is vertical.



a) b)

Figure 13. An experimental measure of the typical accelerations with vertical slider under earthquake effect (type 1): a) crank rotation 32 rpm, b) crank rotation 43 rpm.

6.2. SLIDER CRANK ACTUATION BY SERVO MOTOR

In Figure (14.a) and Figure (14.b) experimental data of motor torque and slider acceleration during earthquake disturbance are shown for a crank rotation of 90 rpm and 180 rpm respectively. It is recognized from acceleration data of slider shown in Figure (14) that not only shape and amplitude of the acceleration of the slider during a simulated earthquake are strongly changed but also oscillations of the slider are vanished. Meanwhile torque data of the motor has some disturbances in the amplitude, shape and oscillation can be told to be similar with the static state.

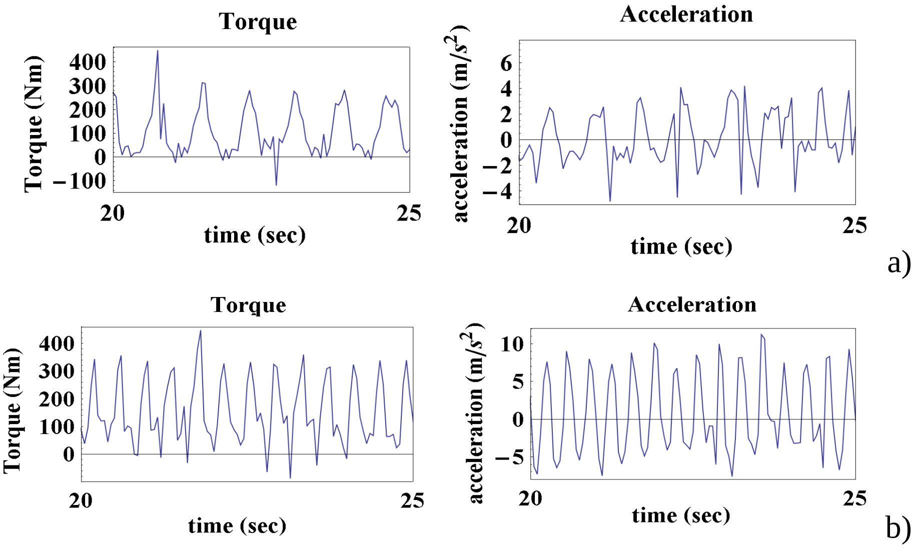


Figure 14. A measure of slider crank with servo motor with earthquake effect (type 1), torque data of the motor, acceleration of the slider with crank rotation: a) 90 rpm, b) 180 rpm

7. CONCLUSIONS

In this paper with the help of CaPaMan the effects of earthquakes on the operation of mechanical systems have been investigated by an analysis and reproduction of an earthquake motion. The sensitivity of the operation characteristics of machinery to earthquake disturbance is characterized in terms of acceleration response of output of machinery operation. Experimental tests have been carried out by using a slider-crank linkage with DC and servo motors as test-bed mechanisms with acceleration or force sensors. The results show that an earthquake will surely effect the acceleration of the mechanism operation both in shape and amplitude of the output motion. Also effect of earthquake is inverse proportional with the speed of the mechanism, in other words, the more we are approaching to the frequency of the earthquake the less mechanism is affected. Applied torque is affected during earthquake and it is observed that it is disturbed similar to the acceleration during earthquake.

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