Studies on friction base isolators

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ABSTRACT

This paper deals with friction type base isolators including the pure-friction system (P-F) and resilient-friction system(R-FBI). Using the computer program DRAIN-2D for time-history dynamic analysis, various intensities and frequencies of the excitation were employed in the simulation. The peak relative displacements and the maximum accelerations of the mass were determined. Particular attention is given to the effect of the elastic stiffness of the R-FBI system. It is shown that the slip displacement decreases sharply as the elastic restoring force of the isolator increases. Several sensitivity analyses for variations in the type and intensity of the excitation were carried out, and parametric studies were performed. Preliminary laboratory tests were conducted to check the theoretical prediction.

INTRODUCTION

Base isolators can effect useful reductions in the accelerations developed in buildings due to seismic ground motions. The isolators may operate in any of several manners, or combinations thereof, which include:

a) By introducing a horizontally acting spring between the ground and the building, the natural frequency can be reduced to a value below the range of frequencies of the ground motion, thereby avoiding resonance.
b) By introducing material with a high hysteretic damping capacity, between the ground and the building, excessive motion can be prevented by damping.
c) By introducing rollers between the ground and the building, the

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transfer of ground motion to the building is prevented. By resting the rollers on dished surfaces, the action of gravity can control the displacements.
d) By supporting the building on surfaces which can slide when the earthquake intensity overcomes the friction, the force transferred, and hence the acceleration of the building, can be limited.

By combining these ideas it is possible to obtain results which are closer to some specified ideal than can be achieved by one idea alone. The aim is to reduce the maximum acceleration suffered by the building. This is evidently best achieved by introducing rollers. However, the building must resist wind forces, so a minimum lateral resistance is needed. This is most readily provided by a sliding surface with the desired coefficient of friction, but the value required tends to be low (< 0.1) with the result that the motion of the building relative to the ground during earthquake may be large, influencing the design of service connections. To reduce the displacements, the friction coefficient must be higher, but this leads to greater accelerations being transferred to the building. By adding resilient restraints as a means of controlling the relative lateral displacement, in conjunction with a low value for the friction coefficient, both the acceleration and the relative displacement can be minimized. When a spring is combined with friction, the natural frequency changes with amplitude thus resonance is not possible. Because of the low restraining force required, the natural frequency of the building is low and hence outside the range of exciting frequencies. Once sliding starts the rate of energy dissipation is high, and there is no need for any hysteretic damping from the resilient restraints.

PURE-FRICTION SYSTEM

The pure-friction system is used to support the weight of the structure and provides sliding friction, sufficiently high to withstand the wind load. For harmonic excitation, there are three ranges of building response[1]:

a) There is no sliding when $\mu g/A < 1$
b) There is a stick-slip behaviour when $0.537 < \mu g/A < 1$
c) There is continuous sliding when $\mu g/A < 0.537$
where: μ = the coefficient of friction
A = the maximum harmonic acceleration of the ground

When a body can slide on the supporting surfaces, the equation of motion during sliding, (case c), can be written as:

$$\ddot{u}_n(t) = (-1)^{n+1}\mu_d g - \ddot{x}_g(t) \qquad (1)$$

for the different time intervals, t_{n-1} to t_n, n =1,2,3,4,.., at which times, $\dot{u}$ changes sign, where:

u = displacement of the body relative to the ground = $x-x_g$
μ_d= sliding friction coefficient
g = acceleration due to gravity
x_g= horizontal ground displacement
x = absolute displacement of the body

For the initial condition at $t_0 = 0$, the body is assumed to be at rest and the ground acceleration is assumed to exceed μg, thus:

$$u(0) = -x_g(0)\ ,\ \ \dot{u}(0) = \dot{x}_g(0)\ ,\ \ \ddot{x}(0) = \mu g$$

The absolute displacement x_1 in the first time interval is then:

$$x_1 = \frac{1}{2}\mu_d g t^2 \tag{2}$$

where $0 \leq t \leq t_1$

At subsequent times t_{n-1}, n=2,3,4..., the relative velocity between body and ground is taken as zero, thus the initial conditions for each time interval are:

$\dot{u}_n(t_{n-1}) = 0$, $u_n(t_{n-1}) = u_{n-1}(t_{n-1})$

Solving equation (1) by incorporating these initial conditions leads to an expression for the absolute displacement of the body at time t, for continuous sliding:

$$x = \frac{(-1)^{n+1}}{2}\mu_d g t^2 + \mu_d g[(-1)^n \cdot t_{n-1} + \sum_{k=1}^{n-1}(-1)^{k+1} \cdot (t_k - t_{k-1})]t - \dot{x}_g(t_1) \cdot t$$

$$+ \mu_d \cdot g \cdot \sum_{k=2}^{n-1}(-1)^k \cdot t_k^2; \qquad for \quad t_{n-1} < t < t_n;\ n = 2,3,4, \quad .$$

This is represented in Fig.1 (a), where the velocities of the ground and the body are plotted against time.
To include stick-slip behaviour, an additional term is required and the final expression becomes:

$$x = \frac{(-1)^{n+1}}{2}\mu_d g t^2 + \mu_d g[(-1)^n t_{n-1} + \sum_{k=1}^{n-1}(-1)^{k+1}(t_k - t_{k-1})t - \dot{u}_g(t_1)t_1$$

$$+ \mu_d g \sum_{k=2}^{n-1}(-1)^k t_k^2 + \sum_{s=1}^{m}\int_{t_s}^{t_s'} \dot{u}_g(t)\,dt \tag{3}$$

where t_{n-1} is the time when stick starts in each cycle, s and s' are the points at the beginning and end of the stick interval, respectively, and m is the number of reattachments that have taken place (Fig.1 (b)).

<u>Computer simulation</u>

A program of tests on a shaking table is in progress. The model is a 2025kg concrete block resting on four sliding bearing plates, on which different materials can be mounted. The analyses have been conducted for this model.

The computer program DRAIN2D was used to study the dynamic behaviour of the body supported on a sliding surface. The uppermost curve in Fig.2 is the relationship between the maximum relative displacement and the friction coefficient, for EL-CENTRO 1940 NS ground motion. It shows how the increase of the friction coefficient has a significant effect in reducing the peak relative displacement in the range of higher friction coefficients.

The lowest curve in Fig.3 represents the maximum acceleration of the body vs. the friction coefficient. The results show that the maximum acceleration increases as the friction coefficient increases, eventually the acceleration approaches that of the fixed-base case.

Relative displacement is quite sensitive to variations in the intensity of excitation for the pure friction system, especially for lower friction coefficients, becoming less sensitive as the friction coefficient increases. This is shown in Fig.4.

The frequency content was varied by changing the duration of the earthquake record. Fig.5 illustrates the sensitivity of the displacement to this variation, and how the sensitivity is less as the friction coefficient increases.

R-FBI SYSTEM

In R-FBI systems[2], a resilient restraint is added to a friction isolator. The resilient elements provide a horizontal restoring force but carry no gravity load. The sliding surface supports the vertical load, and the interfacial friction acts both as the structural fuse and as an energy absorber.

The resilient element has a spring constant, k, giving a natural frequency, for a mass M, of $f = \omega/2\pi$, where $\omega^2 = k/M$. The acceleration of the mass due to the action of the spring for a relative displacement u is: $ku = M\omega^2 u$. In a non-sliding phase, $(\dot{u} = \ddot{u} = 0)$:

$$\mu g - | \ddot{x}_g + \omega^2 u | > 0$$

At the start of a sliding phase:

$$\mu g - | \ddot{x}_g + \omega^2 u | = 0$$

In a sliding phase ($\dot{u} \neq 0$):

$$\mu g - | \ddot{x}_g + \omega^2 u | \leq 0$$

When sliding, the equation of motion of the body can be expressed as:

$$\ddot{u}(t) + \omega^2 u(t) = (-1)^{n+1} \mu_d g - \ddot{x}_g(t) \qquad (4)$$

Using the same initial conditions as before leads to the expressions of u_1 and u_n:

$$u_1(t) = \int_0^t \omega^{-1} \sin\omega(t-\tau) [\mu_d g - \ddot{x}_g(\tau)] d\tau - x_g(0) \cos\omega t - \dot{x}_g(0) \frac{\sin\omega t}{\omega} \qquad (5$$

where $0 \leq t \leq t_1$; $0 \leq \tau \leq t$, and:

$$u_n(t) = \int_{\tau = t_{n-1}}^{t} \omega^{-1} \sin\omega(t-\tau) [(-1)^{n+1} \mu_d g - \ddot{x}_g(\tau)] d\tau + u_{n-1}(t_{n-1}) \cos\omega(t - t_{n-1})$$

(6)

where $t_{n-1} \leq t \leq t_n$; $t_{n-1} \leq \tau \leq t$; $n = 2,3,4,\ldots$

This relationship is used to provide a check of the results given by DRAIN-2D.

Computer simulation

Time-history dynamic analyses were made for a body on a sliding surface with a spring restraint. Varying the friction coefficient, μ, and the spring constant, k, represented by the natural frequency, f, the behaviour was determined in each case.

Fig.2 represents the relation between the peak relative displacement and the friction coefficient for different spring constants. The results show that only in the range of lower friction coefficients, does the addition of a spring usefully decrease the peak relative displacement.

Fig.3 represents the relationship between the maximum acceleration of the body and the friction coefficient, showing that an increase in the spring constant leads to an increase in the acceleration of the body. The greater the friction coefficient, the less sensitive is the acceleration of the body to a change in the spring constant.

Fig.6 shows that the acceleration response for various intensities of excitation. After sliding has started, the R-FBI system is not very sensitive to variations of intensity.

To study the dynamic behaviour of the isolator for different frequency contents, the accelerogram of the EL-CENTRO 1940 earthquake was modified by multiplying the time scale by factors of 0.5 and 2.0. Fig.7 show that the relative displacement is somewhat insensitive to the frequency content.

The time-history analysis of the R-FBI system with a weak restoring force shows, for a given excitation, that the spring force after the start of motion is smaller than the friction force in almost the whole time history. This means that the R-FBI system is still a friction-type isolator, and that the energy dissipation is a primary action.

Laboratory test

In a typical test on the shaking table, the concrete block(2025kg) rested on four bearings of unfilled Teflon sliding on polished stainless steel (μ=0.06), with resilient restraints of rubber giving a natural frequency of 0.4 Hz. Sinusoidal signals sweeping through frequencies from 1 to 9 Hz, in varying times, were used as excitation. After the start of motion (>3 Hz), the block slides continuously at all frequencies, and the relative displacement, peak to peak, is less than 0.03" (Fig.8). Results of the tests will be reported later.

CONCLUSION

For a pure friction base isolator, μ = 0.2 provides a balance between acceleration and displacement. To reduce acceleration, a low coefficient of friction (<0.1) is used, with a relatively weak elastic restoring force (<0.4 Hz), to prevent excessive displacement between the building and the ground. Such a system resists resonance and can be designed to respond in a predictable manner, for a wide range of earthquake motions.

REFERENCES

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[2] Mostahgel, N.,1986, "Resilient-friction Base Isolator", Proceeding Base Isolation and Passive Energy Dissipation, ATC-17, p.221-230.

ACKNOWLEDGEMENTS

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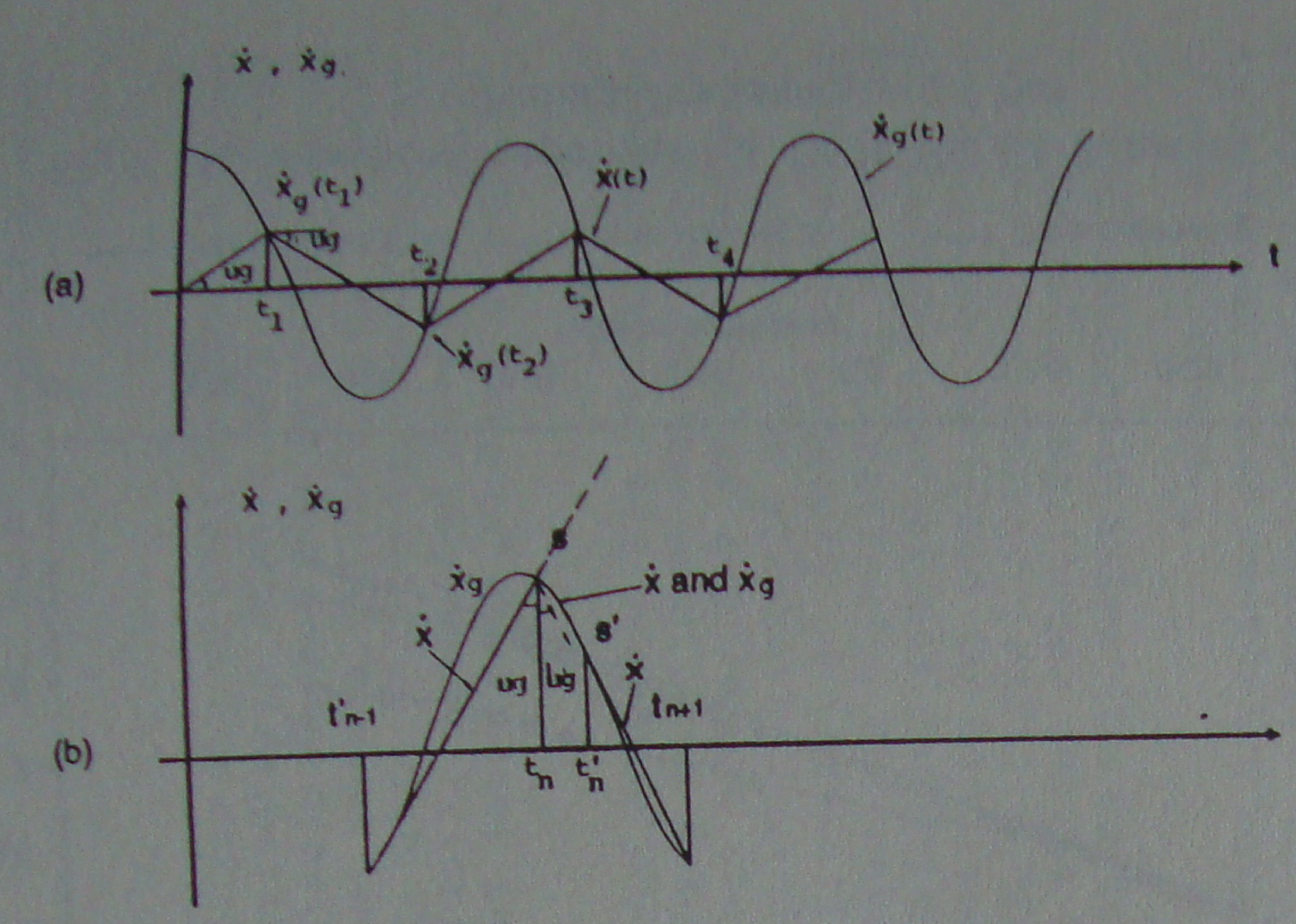

Fig.1 Ground Motion and Response

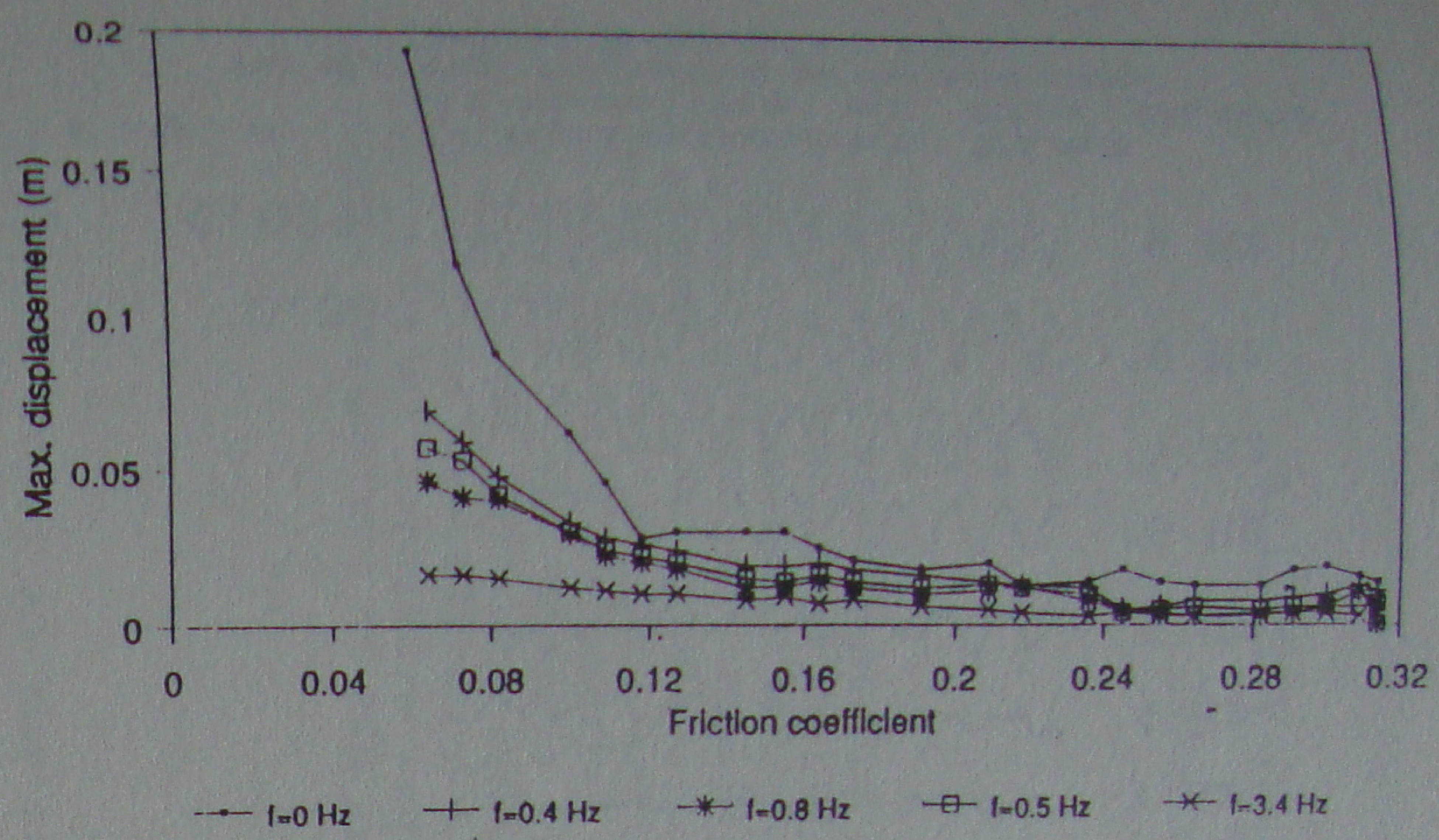

Fig.2 Displacement Responses of P-F and R-FBI Systems (EL-CENTRO Earthquake)

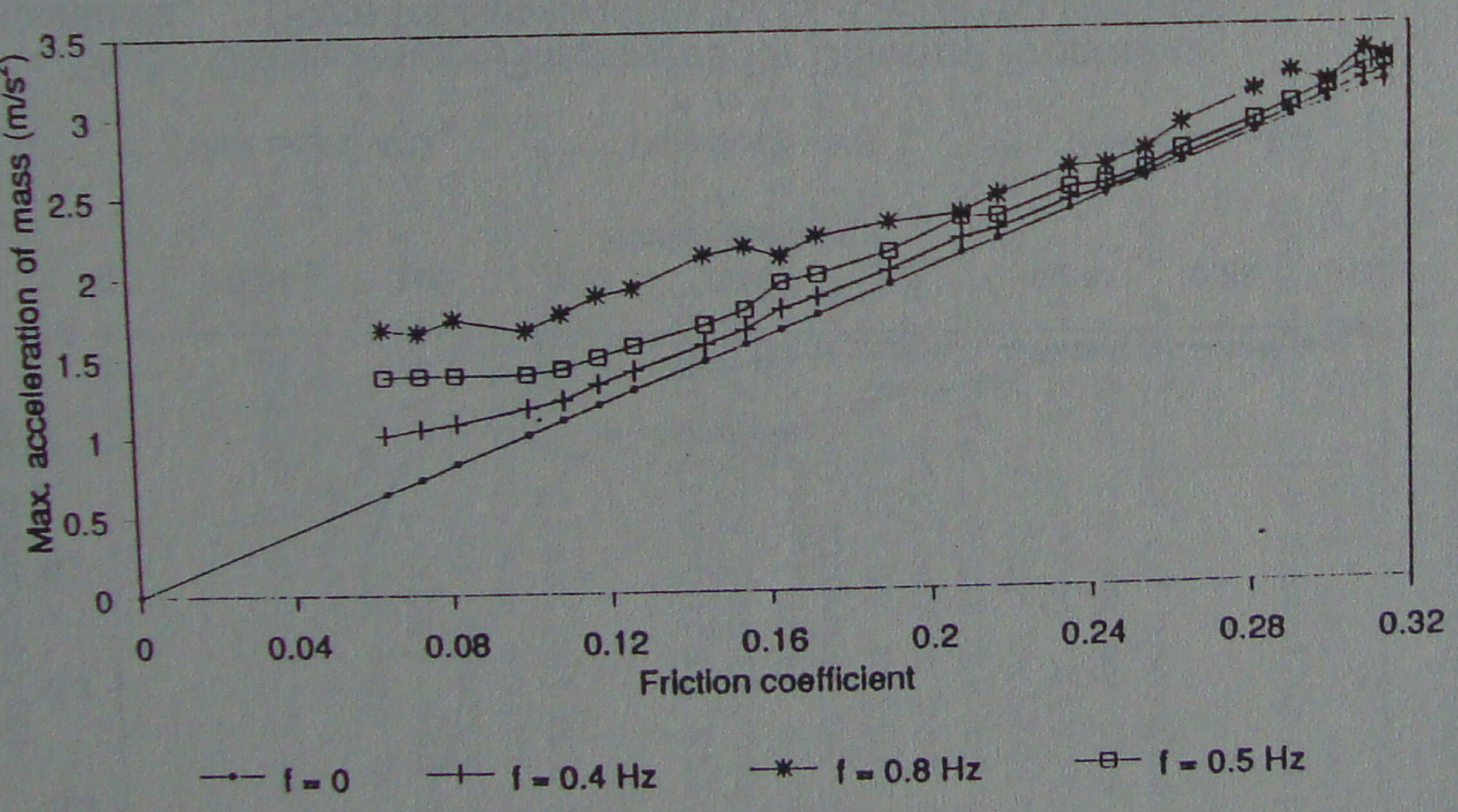

Fig.3 Acceleration Responses of P-F and R-FBI Systems (EL-CENTRO Earthquake)

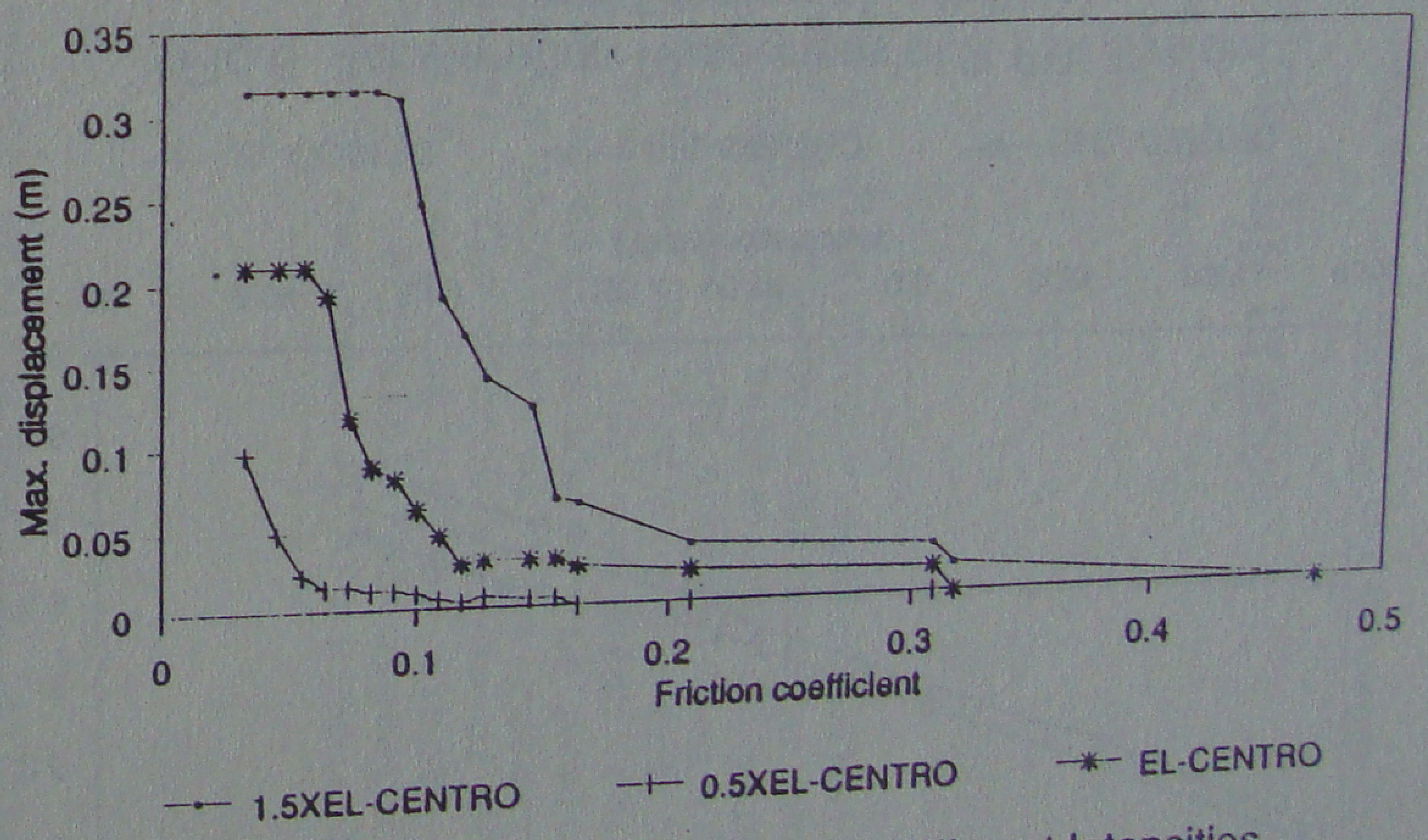

Fig.4 Displacement Responses for Different Intensities (Pure-friction System)

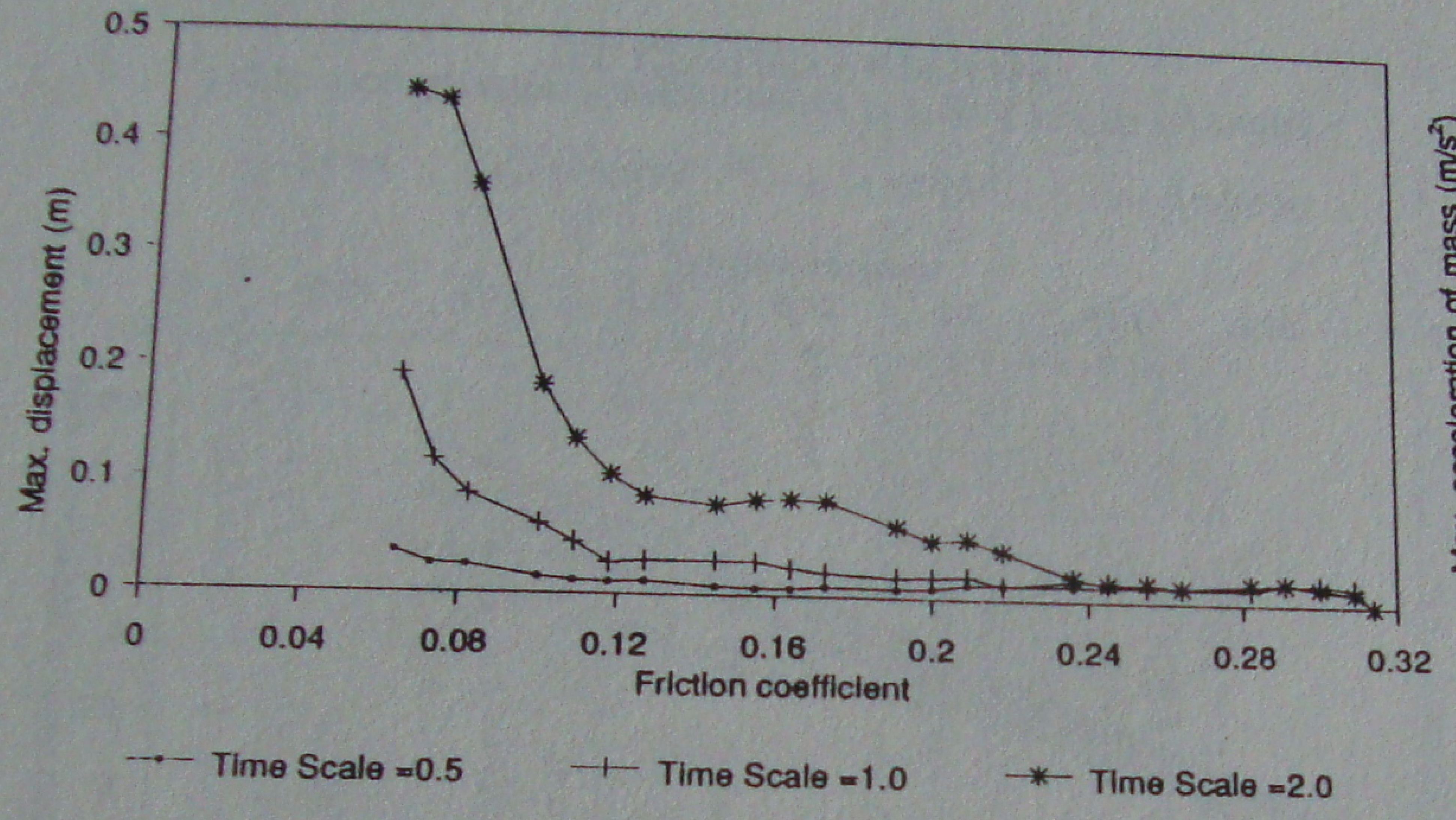

Fig.5 Displacement Responses for Different Frequency Contents (Pure-friction System for EL-CENTRO Record)

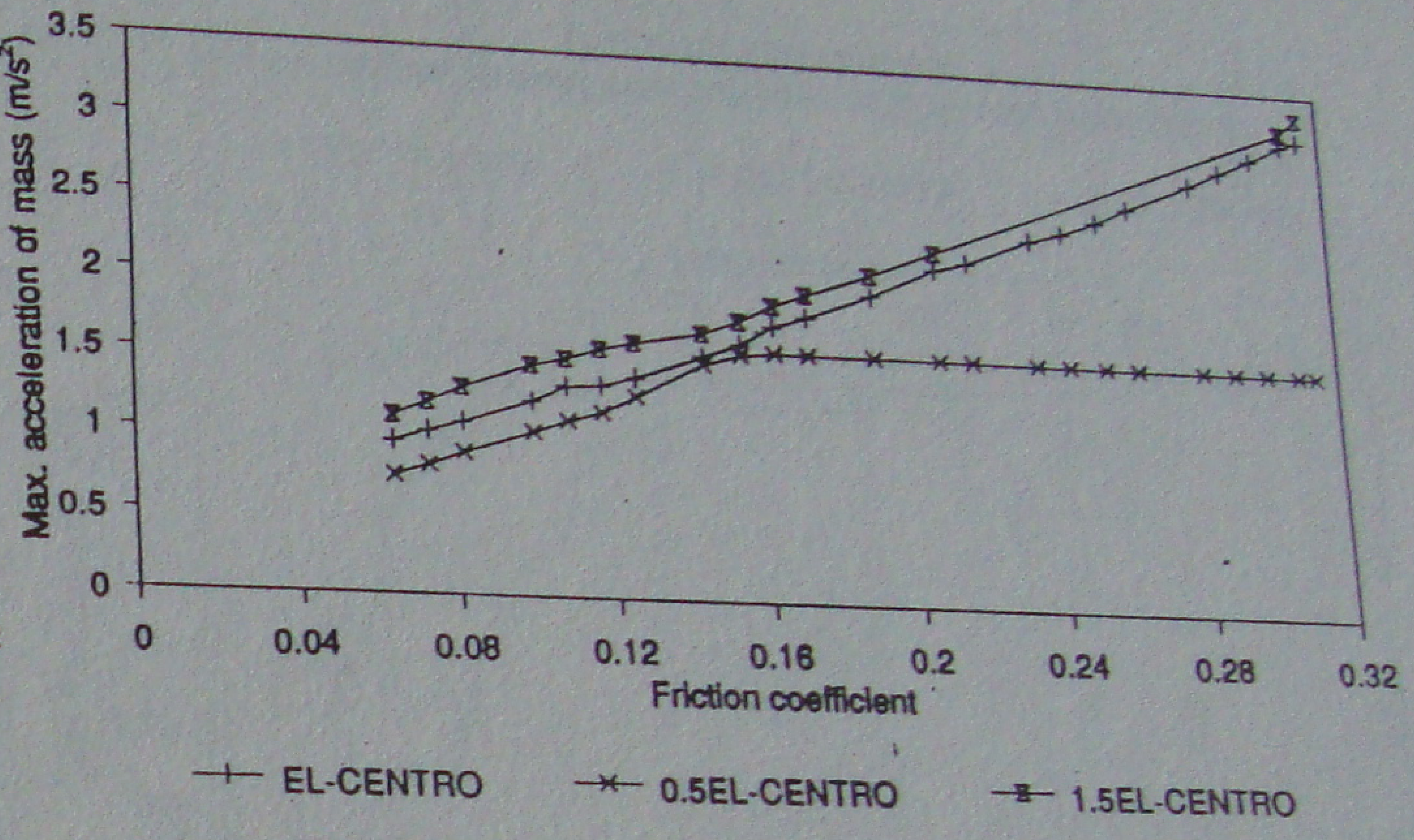

Fig.6 Acceleration Responses of R-FBI System (Natural Frequency = 0.4 Hz)

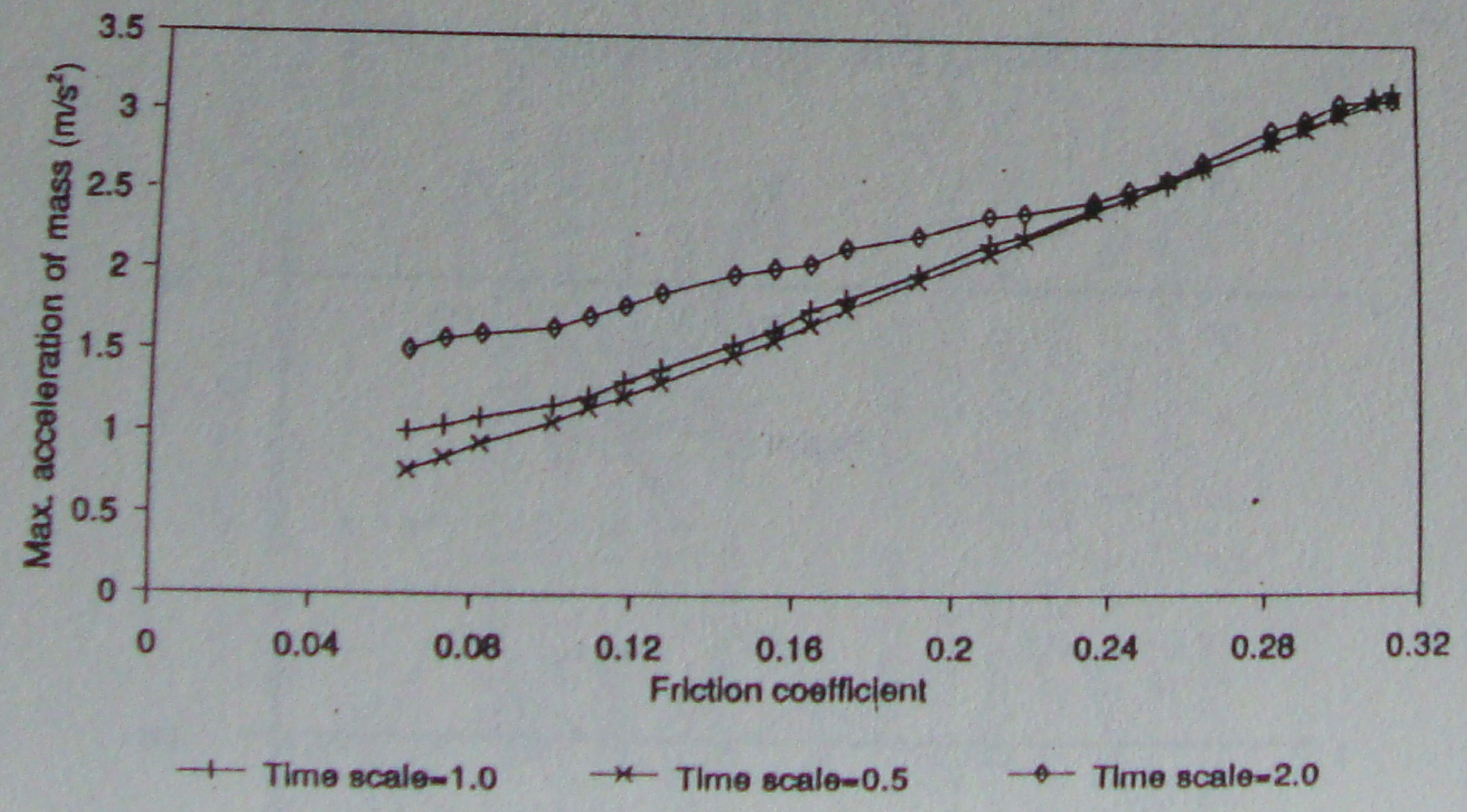

Fig.7 Acceleration Responses (EL-CENTRO Earthquake) (Natural Frequency = 0.4 Hz)

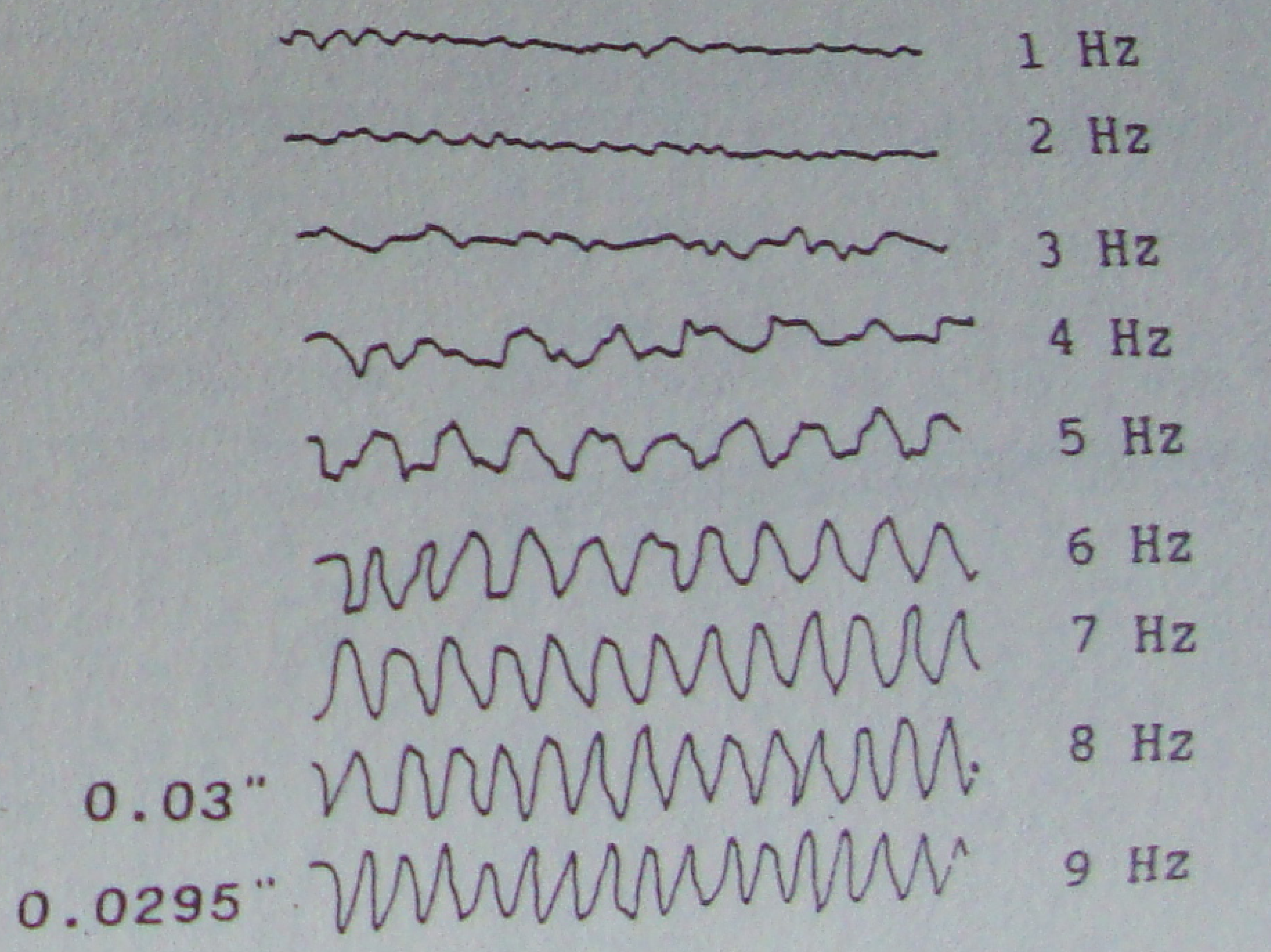

Fig.8 Displacement Time Histories of the Block
For Different Frequencies of the sine signal
(Natural Frequency = 0.4 Hz)