AN EXPERIMENTAL STUDY ON THE SEISMIC INTERACTION OF FLEXIBLE CONDUCTORS WITH ELECTRICAL SUBSTATION EQUIPMENT

by

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We accept this thesis as conforming to the required standard

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Date Oct 12, 2001
ABSTRACT

Flexible conductors are usually employed to interconnect equipment items in electrical substations located on seismically active regions. They have sufficient slack, which allows the conductor to accommodate the relative displacement of the interconnected equipment under seismic loading. Generally, in the design process of the interconnected equipment and their connections to the flexible conductors, the seismic behavior of the conductors is not considered and the dynamic forces generated by them during an earthquake event are not taken into account. However, these forces could be significant and could overload the equipment and cause damage. This thesis presents an investigation on the seismic behavior of a class of high voltage flexible conductors by evaluating their interaction with and their effect on the equipment to which they are connected. This was done by performing various experimental tests on one of the most commonly used configurations of flexible conductors in substations throughout the province of British Columbia in Canada. The experiments included a quasi-static test on the full-scale flexible conductor and four series of shake table tests on the large scale models of the equipment in their stand-alone or interconnected set-up. The design of the equivalent models of the equipment was based on the stiffness and the natural frequencies of the actual equipment obtained from field tests. The input signals for the shake table were synthetic earthquakes. Three records from earthquakes in California were modified to fit the IEEE (the Institute of Electrical and Electronics Engineers) and BC Hydro prescribed design spectra. The specimens were instrumented throughout with acceleration and displacement transducers. Two multi-axial load cells were employed to measure the loads generated at the connections of the conductor to the equivalent equipment during the tests. The test results are summarized and presented in various forms. Various analyses including spectral analysis is performed on the test results and comparisons are made between the results of various tests and various analyses. This investigation showed that the dynamic effect of the flexible conductors should be considered while evaluating the seismic capacity of the interconnected equipment.
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CHAPTER 1

INTRODUCTION

1.1 Background

Substations are critical links in power distribution networks. They have several functions, such as changing the voltage and current level of the power for transmission and distribution purposes. Substations consist of various types of equipment including transformers, circuit breakers, surge arresters and disconnect switches which are considered to be some of the most vulnerable components of power systems to seismic loading. In many past earthquakes, damage to the electrical substation equipment caused power outages and blackouts. One of the most common types of failure in substations is the failure of the porcelain type elements of the equipment such as brittle ceramic insulators. High voltage equipment e.g. 500 and 230 kV equipment are more susceptible to earthquake damages.

Substation equipment items are interconnected by various types of electrical conductors one of which is flexible conductor. Flexible conductors have enough slack, which allows them to accommodate the relative displacement of the adjacent interconnected equipment under seismic loading without being excessively stretched or compressed. However, past earthquakes have demonstrated the vulnerability of these interconnected equipment and suggested that the dynamic interaction between the conductor and the equipment, and resulting amplified forces, can cause the equipment to overload and fail in the event of an earthquake.

Various research projects, experimental and numerical, have been carried out to investigate the behaviour of these flexible conductors and their interaction with the interconnected equipment. The results of these investigations have recommended that more comprehensive experimental studies were needed, due to the fact that flexible conductors are highly nonlinear structures with structural and dynamic properties that are not easily determined.
With regard to the safety and reliability of substations throughout British Columbia and in order to better understand the behaviour of flexible conductors and thus improve the seismic performance of substation electrical equipment, BC Hydro initiated and experimental study jointly with Powertech Labs. Inc. on the seismic behaviour of six most common configurations of equipment interconnected by flexible conductors. Table 1.1.1 shows the six configurations of the interconnected equipment and the connecting flexible conductors that are considered by BC Hydro. Configuration 2 is one of the most critical configurations and is the subject of this thesis. It consists of a 500 kV circuit breaker and a 500 kV current transformer interconnected by a twin 2303.5 kcmil aluminum stranded conductor. Two spacers are used between the two conductors. Figures 1.1.1 and 1.1.2 show the interconnected equipment and the flexible conductor configuration 2.

<table>
<thead>
<tr>
<th>Configuration No.</th>
<th>Equipment</th>
<th>Equipment</th>
<th>Natural Frequencies respectively (Hz)</th>
<th>Conductor Type (kcmil)</th>
<th>Approx. Span (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>500 kV Shunt Reactor</td>
<td>500 kV Surge Arrester</td>
<td>1.60, 10.66</td>
<td>2x2305.5</td>
<td>6.4</td>
</tr>
<tr>
<td>2</td>
<td>500 kV Circuit Breaker</td>
<td>500 kV Current Transformer</td>
<td>0.94, 3.4</td>
<td>2x2303.5</td>
<td>4.0</td>
</tr>
<tr>
<td>3</td>
<td>500 kV Pothead</td>
<td>500 kV Bus Support</td>
<td>2.86, 12.6</td>
<td>2x2303.5</td>
<td>3.0</td>
</tr>
<tr>
<td>4</td>
<td>230 kV Transformer</td>
<td>230 kV Surge Arrester</td>
<td>11.10, 3.16</td>
<td>1x1272</td>
<td>3.0</td>
</tr>
<tr>
<td>5</td>
<td>230 kV Circuit Breaker</td>
<td>230 kV Current Transformer</td>
<td>4.28, 1.56</td>
<td>2x1272</td>
<td>3.7</td>
</tr>
<tr>
<td>6</td>
<td>230 kV Circuit Breaker</td>
<td>230 kV Current Transformer</td>
<td>5.57, 1.55</td>
<td>2x2303.5</td>
<td>3.5</td>
</tr>
</tbody>
</table>
Figures 1.1.3 and 1.1.4 show examples of other configurations of the interconnected equipment by flexible conductors. Description of these configurations can be found in Table 1.1.1.

Figure 1.1.1 Geometry of the interconnected equipment and flexible conductor configuration 2
Figure 1.1.2 Interconnected equipment and flexible conductor configuration 2
Figure 1.1.3 Interconnected equipment and flexible conductor configuration 4

Figure 1.1.4 Interconnected equipment and flexible conductor configuration 1
1.2 Objectives of Research

The main goal of this study is to find out the effect of the conductor on the interconnected equipment and the forces that it induces on the equipment in an anticipated earthquake. The objectives of this research are as follows:

- To find out whether the flexible conductor changes the response of the interconnected equipment when compared with their stand-alone configuration under seismic loading.

- To find out the amount of forces generated at the connections of the conductor to the equipment under seismic loading and to estimate the amplification of forces due to dynamic behaviour of the conductor.

- To study the dynamic behaviour of the conductor under anticipated earthquake loading and to analyze its seismic interaction with the equipment.

1.3 Scope of Research

This research focuses on the interconnected equipment and flexible conductor configuration by performing various experimental tests and provides a methodology for studying other configurations. The experimental tests included cyclic quasi-static tests and various shake-table tests on the full scale flexible conductor and large-scale models of the equipment. The analytical study for this project included spectral analysis on the experimental test results.
CHAPTER 2
LITERATURE REVIEW

2.1 Introduction
In this chapter, flexible conductors, their geometry and their design concepts are described. Also a review on the experiences from past earthquakes and damage observed in the equipment is presented. Finally, a summary of the research carried out on the seismic interaction of the flexible conductors with the interconnected equipment is presented.

2.2 Flexible Conductors
Flexible conductors are electrical conductors used in substations as paths for high voltage electricity between different equipment. Figures 1.1.2 to 1.1.4 show some configurations of the substation equipment interconnected by flexible conductors.

In general, flexible conductors can be bare cables, braids or expansion joints, and can be connected to the equipment by bolted or welded connections. Two most common sizes of flexible conductors used in substations in British Columbia are 1272 kcmil and 2303.5 kcmil aluminum stranded conductors with minimum bending radii of 300 mm and 600 mm, respectively.\(^{(1)}\)

The geometry of flexible conductors is configured such that they accommodate the relative displacement of the interconnected equipment under seismic loading. They also meet the electrical design requirements. There are three basic geometry configurations which are most suitable for the commonly used 1272 and 2303.5 kcmil aluminum stranded conductors. These geometries provide the conductors with the necessary slack that enables the equipment to have differential movement without excessive stretch or
compression of the conductors. The three geometry configurations shown in Figure 2.2.1 are as follows: (1)

- Configuration 1 using two 90° connectors or special brackets, for short length connection at or near the minimum bending radius of the conductor.

- Configuration 2 using one 90° connector or special bracket and one straight connector, for intermediate length connections.

- Configuration 3 using two straight connectors, for long length connections.

Flexible conductors may consist of one stranded cable (single conductor) or two stranded cables (twin conductor). Spacers between the two cables are required for twin 1272 kcmil aluminum stranded conductors with length exceeding 1500 mm and for twin 2303.5 kcmil aluminum stranded conductors with length exceeding 2000 mm. (1)

The required conductor length is determined based on the deflections of the equipment at moderate seismic qualification level. The deflections of individual equipment items are different from each other depending on the type of the equipment. The typical values of
deflections are obtained from the results of past seismic studies and used for design purposes. The final conductor length however, is determined on site during installation to account for the diverse field conditions and assuring that the actual installed conductor does not display excessive flexibility.\(^{(1)}\)

### 2.3 What Happened in Past Earthquakes

Failure of the equipment interconnected by flexible conductors has been observed in past earthquakes even in the equipment that were designed to withstand the earthquake individually. Examples of these earthquakes are the 1978 Off-Miyagi earthquake of magnitude 7.4 which shook the northern part of Japan,\(^{(13)}\) the 1986 North Palm Spring earthquake of magnitude 5.9 in Southern California,\(^{(5,14)}\) and the 1988 Saguenay earthquake of magnitude 6.2 in Québec, Canada.\(^{(5)}\) The latter earthquake was to blame for serious damage to three Hydro-Québec substations. North Palm Springs earthquake caused damage to 500, 200 and 115 KV substations. Typical damage included broken insulators, conductor supports and bushings on lightning arresters, transformers and circuit breakers.\(^{(14)}\)

The study of the damage caused by past earthquakes to the equipment in substations led the investigators to conclude that connections with flexible conductors could be a significant cause of the failure. As a result of this conclusion it became necessary to investigate the seismic interaction of flexible conductors with the interconnected equipment.

### 2.4 Past Research on the Interaction of Flexible Conductors with Interconnected Equipment

After the 1978 Off-Miyagi earthquake, Japanese initiated a research program to study the influence of the flexible conductors on the equipment under seismic loadings.\(^{(13)}\) This study included both experimental and numerical analysis. Both types of analysis revealed that the additional pulling force caused by the stretch of the conductor on the porcelain
column of the equipment was the reason for failure of the equipment. The experimental investigation consisted of shake table testing of a full scale model of a selected pair of equipment interconnected with a flexible conductor. The numerical study included finite element analysis which was found to be too complicated to be used for studying the dynamic behaviour of the flexible conductor. The complexity was due to the equipment-conductor coupling system and the nonlinearity caused by the conductor and its large deflections. The final recommendation was to avoid the tension forces in the conductors by configuring them such that they are not stretched during an earthquake. A design procedure for the flexible conductors was also proposed.

Additional forces due to the stretch of the conductor, however, had not always been the reason for the failure of the interconnected equipment. Damage had also been observed in the equipment interconnected by flexible conductors with enough slack, which provided enough room for the displacements of the equipment without being excessively stretched. Further research has been carried out recently in order to explain the reason for failure through understanding the dynamic behaviour of the conductor and its interaction with the equipment.

In 1995, Dastous and Pierre (5) from Hydro-Québec published the results of their research on dynamic behaviour of flexible conductors. Their main goal was to find whether typical flexible conductors have natural frequencies that could be excited during an earthquake and to provide insight into the dynamic behaviour of those conductors. To achieve this, they ran cyclic static tests as well as sine sweep tests with a frequency band from 0.5 to 5 Hz at expected ground motion amplitudes. Figure 2.4.1 shows the frequency bands and the corresponding amplitudes for sine sweep tests. The excitation was either only at one end of the conductor with the other end fixed or at both ends oscillating out of phase with respect to each other. The test specimens, comprising of either one cable or two cables with spacers, were two of the most commonly used conductors in Hydro-Québec substations. Properties of these conductors are shown in Table 2.4.1. The forces at the ends of the conductor were measured using load cells.
The results showed that the flexible conductors are nonlinear dynamic systems which have variable natural frequencies when responding to an earthquake. These frequencies are variable due to the nonlinear behaviour of the conductor and vary according to its configuration and the amplitude of excitation and they are likely in the range of 0.5 to 5 Hz. The magnitude of forces measured at the ends of the conductors during their resonance, indicated that it is not sufficient to design these conductors on a static basis. Figure 2.4.2 shows three force response spectra obtained from a test in which resonance of the conductor did not happen, a test interrupted because of very large forces generated at the ends of the conductor due to resonance, and an uninterrupted test showing the resonance of the conductor.

Dastous and Pierre concluded that the resonance of the conductors must be avoided during an earthquake and they mentioned the importance of designing them such that the range of the natural frequencies at which they can be excited would be different than the natural frequencies of the equipment interconnected by them. They also concluded that a large sag/span ratio would improve the dynamic stability of the conductor and reduces the risk of its resonance and suggested that if a large sag/span ratio violates the required distance of electrical insulation, other geometries of the flexible conductors might be alternatives. They recommended that the severity of forces be verified for real earthquakes since the sinusoidal excitation could not completely simulate the effect of an earthquake.
Table 2.4.1 Properties of conductors used by Dastous and Pierre

<table>
<thead>
<tr>
<th>Property</th>
<th>1796-MCM</th>
<th>4000-MCM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter (mm)</td>
<td>39.2</td>
<td>58.6</td>
</tr>
<tr>
<td>Area (mm²)</td>
<td>910</td>
<td>2027</td>
</tr>
<tr>
<td>Linear mass (kg/m)</td>
<td>2.51</td>
<td>5.70</td>
</tr>
</tbody>
</table>

Figure 2.4.1 Frequency bands and amplitudes for sine sweep tests performed by Dastous and Pierre

<table>
<thead>
<tr>
<th>Amplitude (m)</th>
<th>Frequency band (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.02</td>
<td>no sweep, continuous sine test at 0.5 Hz</td>
</tr>
<tr>
<td>0.04</td>
<td>no sweep, continuous sine test at 0.5 Hz</td>
</tr>
<tr>
<td>0.08</td>
<td>no sweep, continuous sine test at 0.5 Hz</td>
</tr>
<tr>
<td>0.15</td>
<td>no sweep, continuous sine test at 0.5 Hz</td>
</tr>
<tr>
<td>0.30</td>
<td>no sweep, continuous sine test at 0.5 Hz</td>
</tr>
</tbody>
</table>
Figure 2.4.2 Force response spectra obtained by Dastous and Pierre
In another experimental research project carried out at the University of California at San Diego by Filiatrault et al.\(^7\) in order to evaluate the behaviour of substation equipment interconnected by both flexible and rigid conductors, quasi-static cyclic tests were performed on two different types of flexible conductors. The test specimens were 2300 MCM single conductor and 1113 MCM twin conductors. The results showed increasing tensile forces due to the stretch of the conductor and very low compressive forces. These tests demonstrated the insignificance of the flexural stiffness of the conductor in generating the resulting static forces.

At the University of California at Berkeley, Der Kiureghian et al.\(^6\) conducted a numerical investigation on the interaction between the flexible conductors and the electrical equipment under dynamic loading by performing finite element analyses. The equipment items were modeled as single degree of freedom systems that represented a linear system with distributed mass, damping and stiffness properties. The presence of response amplification was determined using a “response ratio”, defined as the ratio of the displacement of the top of the interconnected equipment relative to its base, to the relative displacement of the stand-alone equipment. The model was able to achieve a good qualitative agreement with the existing experimental results; however, quantitative agreement was not attained due to the complexity of defining the exact properties of the conductor and the lack of complete information about the experimental tests conditions. The results showed dynamic forces in the conductor ends at magnitudes much higher than forces at quasi-static conditions. An “interaction parameter” was proposed to study the interaction of the interconnected equipment. This parameter is defined as 

$$\beta = \Delta / (s - L)$$

where \(\Delta\) is the maximum relative displacement of the equipment with respect to each other, and \(s\) and \(L\) are the length and the span of the conductor respectively. It was shown for a pair of interconnected equipment with 1 and 5 Hz natural frequencies that if \(\beta \leq 1.0\), there will be no amplification in the response of the interconnected equipment. A minimum conductor length was suggested based on this finding. Figure 2.4.3 shows the finite element prediction for force response spectrum of the conductor subjected to an out of phase sinusoidal excitation at its supports. These results can be compared with the results of Dastous and Pierre.\(^5\)
Figure 2.4.3 Force response spectrum predicted by finite element analysis (after Der Kiureghian et al)
CHAPTER 3
AN OVERVIEW ON THE CONCEPTS OF FOURIER ANALYSIS AND DIGITAL SIGNAL PROCESSING

3.1 Introduction
This chapter first presents a general overview on the concepts of presenting signals and time domain sequences in frequency domain, and then explains the fundamentals of Fourier analysis, linear systems, digital signal processing, spectral analysis and system identification method used as computational and analytical tools throughout this study.

3.2 Representation of Signals in Frequency Domain by Fourier Series
A signal is a function or a set of data that represents a physical quantity such as the acceleration response of a single degree of freedom system to an arbitrary dynamic loading. Signals contain lots of information about the physical quantity they are representing. However, portions of this information are hidden when the signal is presented in the time domain, but would be revealed if the signal was presented in the frequency domain. Signals can be presented in the frequency domain in terms of the linear combination of sine and cosine functions. Time domain and frequency domain descriptions of a signal compliment each other and taken together they provide a better understanding of the signal.

In order to better understand the concept of frequency content, a function $f(t)$ satisfying the following conditions (sufficient but not necessary conditions) is considered:\(^{(17)}\):

1. $f$ is periodic with period $T_0$
2. $f$ is bounded
3. At any particular period, the function may have at most a finite number of discontinuities and a finite number of maxima and minima.

\( f(t) \) can be expressed in terms of Fourier series as follows:

\[
\begin{align*}
f(t) &= A_0 + \sum_{n=1}^{\infty} A_n \cos n\omega_0 t + B_n \cos n\omega_0 t \\
&= A_0 + \sum_{n=1}^{\infty} A_n \cos n\omega_0 t + B_n \cos n\omega_0 t
\end{align*}
\]  
(3.2.1)

where

\[
\omega_0 = \frac{2\pi}{T_0}
\]  
(3.2.2)

\[
A_0 = \frac{1}{T_0} \int_{-T_0/2}^{T_0/2} f(t) dt
\]  
(3.2.3)

\[
A_n = \frac{2}{T_0} \int_{-T_0/2}^{T_0/2} f(t) \cos n\omega_0 t dt \\
n = 1, 2, 3, \ldots
\]  
(3.2.4)

\[
B_n = \frac{2}{T_0} \int_{-T_0/2}^{T_0/2} f(t) \sin n\omega_0 t dt \\
n = 1, 2, 3, \ldots
\]  
(3.2.5)

Equation 3.2.1 can also be written in the compact trigonometric form of Fourier series as shown in Equation 3.2.6:

\[
f(t) = C_0 + \sum_{n=1}^{\infty} C_n \cos(n\omega_0 t + \theta_n)
\]  
(3.2.6)

in which

\[
C_0 = A_0
\]  
(3.2.7)
The compact trigonometric Fourier series in Equation 3.2.6 shows that a periodic signal $f(t)$ can be expressed as a sum of sinusoids with frequencies $0$, $\omega_0$, $2\omega_0$, ..., $n\omega_0$, ..., which have amplitudes of $C_0$, $C_1$, $C_2$, ..., $C_n$, ... and phases of $0$, $\theta_1$, $\theta_2$, ..., $\theta_n$, ... respectively. (11) A plot of $C_n$ vs. $\omega$ is called the amplitude spectrum and a plot of $\theta_n$ vs. $\omega$ is called the phase spectrum. These two plots together form the frequency spectra of $f(t)$. These spectra show the frequency composition of $f(t)$ and are in fact the frequency domain description of $f(t)$. The amplitude spectrum is a presentation of the amounts of various frequency components of $f(t)$.

The resulting Fourier series is a periodic function of period $T_0$, therefore for computing the series coefficients we may perform the integration over any interval of $T_0$ and not necessarily from $-T_0/2$ to $T_0/2$.

A more convenient and more compact form of the Fourier series is the exponential form

$$
f(t) = \sum_{n=-\infty}^{\infty} D_n e^{in\omega_0 t}
$$

(3.2.10)

where

$$
D_n = \frac{1}{T_0} \int_{-T_0/2}^{T_0/2} f(t)e^{-in\omega_0 t} dt
$$

(3.2.11)

It can be observed that coefficients $D_n$ are complex numbers. Their relation with trigonometric series coefficients are

$$
C_n = \sqrt{A_n^2 + B_n^2}
$$

(3.2.8)

$$
\theta_n = \tan^{-1}\left(\frac{B_n}{A_n}\right)
$$

(3.2.9)
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\[ D_n = \frac{1}{2} C_n e^{i\theta} \]

\[ D_{-n} = \frac{1}{2} C_n e^{-i\theta} \]  \hspace{1cm} (3.2.12)

\( D_n \) and \( D_{-n} \) are complex conjugates.\(^{(11)}\)

Next section describes how a function can be represented in the frequency domain if it is not a periodic function.

3.3 The Fourier Transform

In previous section it was assumed that the function \( f(t) \) was a periodic function of \( t \). If \( f(t) \) is not a periodic function then a new periodic signal \( f_{r0}(t) \) is constructed by repeating the signal \( f(t) \) at interval of \( T_0 \) seconds. The period \( T_0 \) is made long enough to avoid overlaps between the repeating pulses. The periodic signal \( f_{r0}(t) \) can then be represented by an exponential Fourier series. If \( T_0 \to \infty \), the pulses in the periodic signal repeat after an infinite interval and therefore

\[ \lim_{{T_0 \to \infty}} f_{r0}(t) = f(t) \]  \hspace{1cm} (3.2.13)

Thus the Fourier series representing \( f_{r0}(t) \) will also represent \( f(t) \) in the limit \( T_0 \to \infty \). The exponential Fourier series is given by

\[ f_{r0}(t) = \sum_{n=-\infty}^{\infty} D_n e^{i\omega_0 t} \]  \hspace{1cm} (3.2.14)

where \( \omega_0 \) is expressed by Equation 3.2.2 and

\[ D_n = \frac{1}{T_0} \int_{-T_0/2}^{T_0/2} f_{r0}(t) e^{-i\omega_0 t} \, dt = \frac{1}{T_0} \int_{-\infty}^{\infty} f_{r0}(t) e^{-i\omega_0 t} \, dt \]  \hspace{1cm} (3.2.15)
If $F(\omega)$ is defined as

$$F(\omega) = \int_{-\infty}^{\infty} f(t)e^{-j\omega t} dt$$  \hspace{1cm} (3.2.16)

then

$$D_n = \frac{1}{T_0} F(n\omega_0)$$  \hspace{1cm} (3.2.17)

And so in the limit $f(t) = \lim_{T_0 \to \omega} f_{T_0}(t)$, $f(t)$ becomes

$$f(t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} F(\omega)e^{-j\omega t} d\omega$$  \hspace{1cm} (3.2.18)

The integral on the right hand side of the Equation 3.2.18 is called the Fourier integral and represents the non-periodic signal $f(t)$ just as Fourier series represent periodic signals. The Fourier integral is basically a Fourier series in the limit with fundamental frequency $\Delta \omega \to 0$ and thus the function $F(\omega)$ given by Equation 3.2.16 acts as a frequency spectral function. $F(\omega)$ given by Equation 3.2.16 is called the direct Fourier transform of $f(t)$, and $f(t)$ given by Equation 3.2.18 is called the inverse Fourier transform of $F(\omega)$ and both of them together is called the Fourier transform pair.$^{11}$

Note that these integrals do not always exist. Discussion on the existence of these integrals is beyond the scope of this overview and it is assumed here that they both exist.
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3.4 The Discrete Fourier Transform of Signals

3.4.1 Introduction

As discussed before, Fourier series is an operation that takes a function \( f(t) \) and returns a sequence of coefficients \( D_n \), and the Fourier transform is an operation that maps a function \( f(t) \) to another function \( F(\omega) \).\(^{17}\) Doing either of these operations requires evaluating an integral. To determine these integrals, \( f(t) \) must be described analytically and must be rather uncomplicated which does not usually happen in the real world. However, there is a numerical way of doing the above-mentioned operations with digital computers. This is achieved by means of the Discrete Fourier Transform (DFT) which is an operation that takes the signal \( f(t) \) as a sequence of numbers and maps it to \( F(\omega) \) as another sequence of numbers.\(^{17}\) Obviously, the signal \( f(t) \) must be digitized before it can be processed by DFT.

3.4.2 The Discrete Fourier Transform Pair

The periodic function \( f_{\Delta}(t) \) was defined as

\[
f_{\Delta}(t) = \sum_{n=-\infty}^{\infty} D_n e^{j2\pi nt/T_0}
\]  

(3.2.14)

\( D_n \) can be computed numerically by using DFT. Before any computations, however, \( T_0 \) needs to be selected because it cannot be just an infinite number. Then \( f_{\Delta}(t) \) is sampled at a sampling interval of \( \Delta t \). Hence there are \( N_0 = T_0 / \Delta t \) number of samples in one period \( T_0 \):

\[
D_n = \frac{1}{T_0} \int_{-T_0/2}^{T_0/2} f(t) e^{-j2\pi nt/T_0} dt
\]

\[
= \lim_{\Delta t \to 0} \frac{1}{T_0} \sum_{k=0}^{N_0-1} f(k\Delta t) e^{-j2\pi nk\Delta t} \Delta t
\]  

(3.2.19)
Substitution of

\[ N_0 = \frac{T_0}{\Delta t}, \quad \omega_0 = \frac{2\pi}{T_0} \]  \hspace{1cm} (3.2.20)

yields

\[ D_n = \lim_{\Delta t \to 0} \frac{1}{N_0} \sum_{k=0}^{N_0-1} f(k\Delta t)e^{-2\pi i k N_0 \Delta t} \]  \hspace{1cm} (3.2.21)

Practically, it is impossible to make \( \Delta t \to 0 \) for computing the right hand side of Equation 3.2.21 and \( \Delta t \) can be small but not zero. So the limit on \( \Delta t \) in Equation 3.2.21 is ignored assuming that \( \Delta t \) is reasonably small. It should be noted however, that \( \Delta t \) cannot be too small as very small \( \Delta t \) will cause the data to increase without limit. \(^{(11)}\)

Therefore

\[ D_n = \frac{1}{N_0} \sum_{k=0}^{N_0-1} f(k\Delta t)e^{-2\pi i k N_0 \Delta t} \]  \hspace{1cm} (3.2.22)

Equation 3.2.22 is the discrete form of \( D_n \) which can be computed by a digital computer.

The discrete Fourier transform pair can be found in a similar way. Equations 3.2.22 and 3.2.23 show the DFT pair.

\[ F_r = \sum_{k=0}^{N_0-1} f_k e^{-2\pi i kN_0} \]  \hspace{1cm} (3.2.22)

\[ f_k = \frac{1}{N_0} \sum_{r=0}^{N_0-1} F_re^{2\pi i rN_0} \]  \hspace{1cm} (3.2.23)

where

\[ f_k = \Delta f(k\Delta t) \]  \hspace{1cm} (3.2.24)
$F_r$ is the direct discrete Fourier transform (DFT) of $f_k$ and $f_k$ is the inverse discrete Fourier transform (IDFT) of $F_r$.

Performing the DFT requires a very large amount of computations. The Fast Fourier Transform (FFT) algorithm developed by Tukey and Cooley (1965) is an algorithm that dramatically reduces the number of computations required for performing the DFT. FFT is actually the algorithm that is most commonly used to perform DFT on digital computers. There are however, more recent algorithms that are even faster than FFT.

### 3.4.3 Sampling

As mentioned in Section 3.4.2, numerical computation of Fourier transform of a function $f(t)$ requires sample values of $f(t)$ because digital computers can work only with discrete data. Moreover, a computer can compute $F(\omega)$ only at some discrete values of $\omega$ which are the samples of $F(\omega)$. It is very important to understand the relation between the samples of the $f(t)$ and the samples of $F(\omega)$.

Figure 3.4.1 shows signal $f(t)$ which is limited to $\tau$ seconds along with its Fourier transform $F(\omega)$ (the real part)

$$F(\omega) = \int_\infty^\infty f(t)e^{-j\omega t} dt = \int f(t)e^{-j\omega t} dt \quad (3.2.25)$$
Figure 3.4.1 Samples of the Fourier transform (adopted from Lathi)

The periodic signal \( f_{r_0}(t) \), which is formed by repeating the signal \( f(t) \) every \( T_0 \) seconds \( (T_0 > \tau) \) is also shown in Figure 3.4.1. \( D_n \) was defined in Equation 3.2.17 as

\[
D_n = \frac{1}{T_0} F(n\omega_0)
\]  
(3.2.17)

Equation 3.2.17 shows that the coefficients of the Fourier series for \( f_{r_0}(t) \) are \( 1/T_0 \) times the sample values of the spectrum \( F(\omega) \) taken at intervals \( \omega_0 \) which means that these samples are separated by the fundamental frequency \( \omega_0 \). In other words, if the frequency is expressed in terms of Hz, the samples of \( F(\omega) \) are separated by the fundamental frequency \( f_0 \) of the periodic signal \( f_{r_0}(t) \) (the spectral sampling theorem). \(^{(11)}\)

\[
f_0 = 1/T_0
\]  
(3.2.26)

When we sample \( f_{r_0}(t) \) and compute its discrete Fourier transform, one of the most important consequences of sampling is that the Fourier spectrum repeats itself after every \( N_0 \) samples. The reason is that \( F_r = F_{r+N_0} \) since \( e^{2\pi ikN_0/N_0} = e^{2\pi ik/N_0} \). As samples of...
$F(\omega)$ are spaced at $1/T_0$ and since $N_0 = T_0/\Delta t$, it can be concluded that the Fourier spectrum repeats itself with the frequency $f_s$ (sampling frequency)

$$f_s = 1/\Delta t$$  \hspace{1cm} (3.2.27)

One of the results of the periodicity of $F(\omega)$ is the spectral overlap due to repeating cycles as depicted in Figure 3.4.2. The overlap is at $N_0/2$ or $f_s/2$ or $\omega_0/2$. This effect is called \textit{spectral folding or aliasing} and $f_s/2$ is called \textit{folding frequency}.

![Figure 3.4.2 Spectral folding of aliasing (adopted from Lathi \textsuperscript{11})](image)

This overlap causes error in the reconstructed signal from the sampled signal because if the signal is to be reconstructed from the sampled signal, then its Fourier spectrum should be recovered from its sampled spectrum. For a signal band-limited to $B$ Hz, there would be no overlap if $f_s \geq 2B$. The minimum sampling rate $f_s = 2B$ required to prevent aliasing of a signal is called \textit{Nyquist rate} or \textit{Nyquist frequency} for that signal. In reality however, signals are time-limited and they are not band-limited and aliasing would be inevitable. Therefore it is important to first decide on $B$, the essential bandwidth of the signal in Hz and then select suitable values for $N_0$, $\Delta t$, $T_0$. Once $B$ is picked, the sampling frequency can be chosen to satisfy

$$f_s \geq 2B$$  \hspace{1cm} (3.2.28)
Then the sampling interval is given by

\[ \Delta t \leq \frac{1}{2B} \quad (3.2.29) \]

Also if \( f_0 \) is known, which is the frequency resolution or separation between samples of \( F(\omega) \), \( T_0 \) can be selected knowing that \( f_0 = 1/T_0 \), and eventually the number of samples, \( N_0 \), can be obtained by \( N_0 = T_0 / \Delta t \).

Another way of decreasing the effect of aliasing is using the anti-aliasing filter before the signal is sampled. Anti-aliasing filter eliminates the frequency components of the signal that are beyond \( f_s / 2 \) Hz.

For data acquisition in this study, a sampling rate of 200 Hz was chosen. So the Nyquist frequency of the data was 100 Hz. Since the maximum expected frequency response of the test specimen was no more than 30 Hz, a Nyquist frequency of 100 Hz safely prevented the aliasing error and thus the sampling rate was considered to be adequate.

### 3.5 Systems and Transfer Functions

A system is defined to be a mapping of a set of input functions to a set of output functions. In other words, a system is a mathematical model of a physical phenomenon which has an input function \( f(t) \), and output function \( y(t) \) and a cause-effect relationship between them.\(^{17}\) Systems are classified in various categories. One of these categories is the linearity of the system, i.e. the system is linear or nonlinear. A system is linear if its output is proportional to its input and if its response to several causes can be identified by summing up its response to each cause separately. Most practical systems are linear systems.\(^{11}\)

Transfer function of a system is a function that describes how the system operates on the input data sequence to produce the output sequence.\(^{17}\) It can be proved that for a linear
time-invariant system (a linear system whose parameters do not change with time) the transfer function $H(\omega)$ is

$$H(\omega) = \frac{\text{output signal}}{\text{input signal}}$$  \hspace{1cm} (3.2.30)

in which the input signal is

$$e(t) = e^{2\pi \text{i} \omega t}$$  \hspace{1cm} (3.2.31)

The function $e(t)$ is the characteristic function (or eigenfunction) of the system because it is the only function to which the response of the system has the same exponential form and in fact that is how Equation 3.2.30 is obtained.

It can furthermore be observed that if $f(t)$ is the input signal with the Fourier transform $F(\omega)$

$$f(t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} F(\omega) e^{i\omega t} \, d\omega$$  \hspace{1cm} (3.2.18)

then the output signal would be

$$y(t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} H(\omega) F(\omega) e^{-i\omega t} \, d\omega$$  \hspace{1cm} (3.2.32)

Comparing equation (3.2.32) with the Fourier transform formula shows that $Y(\omega)$, the Fourier transform of $y(t)$, is

$$Y(\omega) = H(\omega) F(\omega)$$  \hspace{1cm} (3.2.33)
Equation (3.2.33) shows that if the transfer function of a system is known, then the Fourier transform of the output signal can be easily obtained by using the simple equation of (3.2.33) and then the output signal itself can be found by operating inverse Fourier transform. Simplicity of calculations in the frequency domain is one the major advantages of frequency domain analysis over time domain analysis, in addition to providing more insight into the behaviour of the system.

Next section includes an example application of transfer functions which is used in this study.

3.6 Integration in Frequency Domain

All the numerical integrations in this study were performed in the frequency domain. To do the integration in frequency domain first the transfer function of the integral operation must be determined.

If an input of \( e(t) = e^{2\pi i \omega t} \) is assumed and the output \( y(t) \) of the integrating system is calculated as

\[
y(t) = \int e^{2\pi i \omega t} dt
\]

\[
y(t) = \frac{e^{2\pi i \omega t}}{2\pi i \omega} = \frac{1}{2\pi i \omega} e(t)
\]  

(3.2.34)

Comparing Equations 3.2.34 and 3.2.30 shows that:

\[
H(\omega) = \frac{1}{2\pi i \omega}
\]  

(3.2.35)

Thus to integrate a signal, first the Fourier transform of the signal is evaluated. Then the Fourier transform of the signal is multiplied by \( H(\omega) \) (Equation 3.2.35) to yield the
Fourier transform of the integrated signal. Finally, by using the inverse Fourier transform, the integrated signal in time domain can be obtained from its Fourier transform.\(^{(11)}\)

In order to check the accuracy of the results thus obtained, the displacement of the shake table in one of the shake table tests performed for this study (Chapter 5) was calculated by integrating its acceleration response and was compared to its displacement directly measured by displacement transducers. Figure 3.6.1 shows both calculated and measured displacements. It shows that they are almost identical. Therefore the numerical integration scheme used for this project is considered reliable.

![Figure 3.6.1 Comparison of measured and calculated displacement of the shake table - Test 29](image)

**3.7 Data Truncation and Window Functions**

It is often necessary to truncate data for various reasons. This could be needed for shortening the length of the signal such as for choosing a finite length of an infinite signal, or for breaking the data sequence into segments of equal length while estimating the power spectrum of the signal by taking “averaged periodograms”, \(^{(16)}\) or while designing FIR filters. \(^{(16)}\)
Data truncation is carried out by multiplying the signal by a window function of smaller width. Table 3.8.1 shows some window functions and their characteristics. To describe the definitions of mainlobe and sidelobe of window functions shown in Table 3.7.1, mainlobe and sidelobes of a rectangular window are shown in Figure 3.7.1. Rolloff rate is the decay rate of sidelobes which is also shown in Figure 3.7.1. In Figure 3.7.1, $w_R(t)$ is the rectangular window function and $W_R(\omega)$ is its Fourier transform.

Table 3.7.1 Some window functions and their characteristics (adopted from Lathi (11))

<table>
<thead>
<tr>
<th>Window $w(t)$</th>
<th>Mainlobe Width</th>
<th>Rolloff Rate dB/oct</th>
<th>Peak Sidelobe Level in dB</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Rectangular: $\text{rect}(\frac{t}{T})$</td>
<td>$\frac{4\pi}{T}$</td>
<td>-6</td>
<td>-13.3</td>
</tr>
<tr>
<td>2. Bartlett: $\Delta(\frac{t}{T})$</td>
<td>$\frac{8\pi}{T}$</td>
<td>-12</td>
<td>-26.5</td>
</tr>
<tr>
<td>3. Hanning: $0.5 \left[1+\cos(\frac{2\pi t}{T})\right]$</td>
<td>$\frac{8\pi}{T}$</td>
<td>-18</td>
<td>-31.5</td>
</tr>
<tr>
<td>4. Hamming: $0.54 + 0.46 \cos(\frac{2\pi t}{T})$</td>
<td>$\frac{8\pi}{T}$</td>
<td>-6</td>
<td>-42.7</td>
</tr>
<tr>
<td>5. Blackman: $0.42 + 0.5 \cos(\frac{2\pi t}{T}) + 0.08 \cos(\frac{4\pi t}{T})$</td>
<td>$\frac{12\pi}{T}$</td>
<td>-18</td>
<td>-58.1</td>
</tr>
<tr>
<td>6. Kaiser: $\frac{t_0}{t_0(\alpha)} \left[\alpha \sqrt{1 - \left(\frac{\pi}{\alpha}\right)^2}\right] 1 \leq \alpha \leq 10$</td>
<td>$\frac{11\pi/2}{T}$</td>
<td>-6</td>
<td>-59.9 ($\alpha = 8.168$)</td>
</tr>
</tbody>
</table>

Figure 3.7.1 Rectangular window and its characteristics (adopted from Lathi (11))
Chapter 3

If \( f(t) \) is a signal to be windowed and \( w(t) \) is the window function, and if \( F(\omega) \) and \( W(\omega) \) are the Fourier transform of \( f(t) \) and \( w(t) \) respectively, then the windowed signal is

\[
\hat{f}(t) = f(t)w(t)
\]  

(3.2.36)

The Fourier transform of \( \hat{f}(t) \) would be the convolution of \( f(t) \) and \( w(t) \) [give ref. lathi] (page 302)

\[
\hat{F}(\omega) = \frac{1}{2\pi} F(\omega) * W(\omega)
\]

(3.2.27)

in which * is the convolution operator.

Truncation of a signal causes spectral spreading and leakage in the truncated signal. These are described as follows:

According to the width property of convolution, the width of \( \hat{F}(\omega) \) is equal to the sum of the widths of \( F(\omega) \) and \( W(\omega) \). Thus the truncated signal has larger bandwidth by the amount of bandwidth of \( w(t) \). So truncation spreads the spectrum of a signal by the amount of the bandwidth of \( w(t) \). This is called spectral spreading. Since the signal bandwidth is inversely proportional to its duration, a wider window would cause less spectral spreading. In other words, wider window means more samples of data and better approximation of the signal.

On the other hand, \( W(\omega) \) is not bandlimited and its amplitude approaches zero as \( \omega \) increases. So even if \( F(\omega) \) is bandlimited, \( \hat{F}(t) \) is not bandlimited and its amplitude approaches zero at the same rate as that of \( W(\omega) \). This is the other effect of data truncation which is called leakage.
Choosing a suitable window would minimize the side effects of truncation. A wide window would reduce the spectral spread and a smooth window would improve the leakage of the truncated signal. The two effects cannot always both be improved. For example, for a given width, the rectangular window has the smallest spectral spread but it has the worst leakage behavior with high sidelobe magnitudes. Hamming window has the smallest sidelobe magnitude for a given mainlobe width. Hanning is a window widely used for spectral analysis because it has faster rolloff rate compared to the other windows (-18 dB/oct compared to -6db/oct for hamming and rectangular). To achieve the best results, the application of the truncated data should be taken into account while selecting a window function to truncate the data sequence.

3.8 Digital Filtering

Digital filters are systems that are intended to change the frequency content of the input signal by keeping the desired frequencies and suppressing the rest. Filters also change the phase content of the input signal. In other words, the primary purpose of digital filtering is enhancing the output signal by changing the spectral content of the input signal.¹⁶

There are four types of filters based on their frequency response characteristics:

- **Low-pass filters** pass low frequency components of the input signal to the output signal and attenuate the high frequency components.
- **High-pass filters** allow the high frequency components to pass to the output signal while suppressing the low frequency components.
- **Band-pass filters** pass a range of frequencies while eliminating both high-frequency and low-frequency components of the input signal.
- **Band-stop filters** reject a range of frequencies and pass high-frequency and low-frequency components.

Filters are also categorized in terms of their impulse response:
• **Infinite impulse response (IIR) filters**, also called recursive filters, are systems of which the output is determined iteratively or recursively from its past values in addition to the values of the input signal.

• **Finite impulse response (FIR) filters**, also called non-recursive filters, are systems of which the output is computed from the present and past values of the input signal.

Compared to FIR filters, IIR filters can have sharp frequency cutoff characteristics with lower order structure which means they are faster and require less memory. However, IIR filters have nonlinear phase characteristics whereas FIR filters can be designed to have exactly linear phase response which is desirable in many applications where a linear phase response is important. So in selecting a digital filter, if computation time is not critical, an FIR filter would be a good choice.

In this study, in order to clean up the test results from noise, a bandpass FIR filter was designed and employed. To design this filter, a Hanning window was chosen because of its faster rolloff rate compared to other alternative windows (Section 3.7). To reduce the spectral spread of the filter, a very large width was chosen for the window. This filter was mainly used as a lowpass filter by setting the highpass frequency equal to zero. The filter lowpass frequency was set to 25 Hz for measured accelerations and displacements, and 20 Hz for measured forces (Chapter 5). Figure 3.8.1 shows both amplitude gain and power gain of the filters.\(^{(16)}\)

Figure 3.8.2 shows a comparison of filtered and not-filtered time-histories of a force response obtained from one of the shake table tests (Chapter 5). The peak values are also indicated.
Figure 3.8.1 Gain of the designed FIR filters
3.9 **Estimation of Power Spectrum**

The power spectra in this study were estimated by using averaged periodograms.\(^{(16)}\) Estimation of power spectra using averaged periodograms gives better results for long time series of random data compared to simply using the Fourier transform of the whole data sequence.

The periodogram of a signal or a sequence of data is defined as the squared magnitude of the Discrete Fourier Transform (DFT) of the signal divided by the number of samples,
The periodogram is a measure of power density of the signal. Recalling from Section 3.4.2, the DFT of the signal $f(t)$ is

$$F_r = \sum_{k=0}^{N_0-1} f_k e^{-2\pi i k / N_0}$$  \hspace{1cm} (6.2.1)

in which

$$f_k = Atf(kAt)$$  \hspace{1cm} (6.2.2)

The periodogram of $F_r$ at each point is defined as

$$P_r = \frac{1}{N_0} |F_r|^2 \hspace{1cm} r = 0,1,\ldots, N_0-1$$  \hspace{1cm} (6.2.3)

In the average periodogram method, the signal is broken up into segments with equal length which could be overlapped. Then a data window is applied to each segment to smoothen or shape the periodogram of each segment. Finally the periodogram of each windowed segment is calculated and the power spectrum is obtained by averaging the periodograms of the segments.\(^{(16)}\)

In this study, to calculate the power spectra, signals were broken up into four segments. A Hanning window was applied to each segment (Section 3.7) and the overlap of the segments was chosen at 25%. Note that it was observed that there was no significant difference between the results obtained with 25% overlap and 50% overlap, therefore, to avoid unnecessary computations, 25% overlap was chosen.

### 3.10 System Identification

System identification in this study involves finding the natural frequencies of the system and the mode shapes associated with those natural frequencies. For a system subjected to an input signal, this task is achieved by using the power spectra of the measured outputs...
of the system, and the cross spectrum and coherence between the selected output channels.

The resonance frequencies of the system are the frequencies at which the power spectrum of the system response peaks. For lightly damped systems, these frequencies could be good estimates of the natural frequencies of the system.

The cross spectrum is used to investigate the similarities of two selected output signals, and determine whether they follow each other or not. In fact, cross spectrum of two signals represents their cross correlation. The phase of the cross spectrum represents the phase angle between the two signals and is helpful in identifying the mode shapes of structures.

The coherence function is used to determine the linear dependence of two selected output signals. The coherence function is defined as the ratio of the squared magnitude of the cross spectrum to the power spectra of both signals. The coherence function has a value between 0 and 1. While a value of 1 for a certain frequency band shows a very good linear dependence between the two signals and indicates that they both are free of noise in that frequency band, a value of 0 indicates the existence of significant level of noise in the measurements. A low value of coherence could indicate either the existence of noise in the measurements, or resolution bias error in the estimation of the spectrum, or nonlinear relation between the two signals or any combination of them.

The problem with identifying the natural frequencies of a system is that any peak in the power spectrum does not necessarily represent a normal mode of vibration for that system. A peak could also represent a coupled mode or a source of noise. That means significant level of noise in the output measurements or coupling between the normal modes will distort the results \(^{(2)}\) which could be misleading in identifying the natural frequencies. Cross spectrum phase and coherence function are useful in distinguishing normal modes from coupled modes and noise. As mentioned earlier, the existence of noise in a measured signal causes the coherence function between that signal and any
other measured signal to be less than one. On the other hand, if the system is lightly
damped, the phase angle between two measured signals related to a normal mode will be
either 0° or 180°. So if the mode is a coupled mode, then the phase angle between the two
output signals will be other than 0° or 180°. In general, a peak in two power spectra with
coherence close to 1 and phase angle close to either 0 or 180°, indicates with confidence
the existence of a normal mode. Any other combination of values indicates either a
coupled mode or a frequency content contaminated by noise. (2)
CHAPTER 4

QUASI-STATIC TEST

4.1 Introduction

A quasi-static test was performed on the full scale flexible conductor configuration 2 (Table 1.1.1). In this test, one end of the conductor was subjected to cyclic displacements with increasing amplitudes, and the other end of the conductor was fixed. The purpose of this test was to study the behaviour of the conductor subjected to differential displacements at its ends caused by the deflections of the interconnected equipment. This test investigated the behaviour of the conductor statically and did not consider its dynamic behaviour.

4.2 Test Set-up

Figure 4.2.1 shows the test set-up for the quasi-static test which was performed in the Structural Laboratory at the University of British Columbia in January 2001. The test specimen was the high voltage flexible conductor configuration 2 as described in chapter 1. The lower end of the conductor, the end which would be connected to the circuit breaker in the substation, was connected to a steel pedestal. The other end, the end which would be connected to the current transformer in the substation, was attached to the frame of a linear shake table. The geometry of the conductor was according to the drawing shown in Figure 4.2.2. The conductor was connected to its supports by using aluminium u-shape plates called “angle adapters” and “terminal connectors” as shown in Figure 4.2.2. The displacements were applied to the conductor by moving the shake table back and forth.
Figure 4.2.1 Set-up for the quasi-static test
Figure 4.2.2 Geometry and connection details of the flexible conductor configuration 2
4.3 Instrumentation

A 10 kip load cell was used to measure the forces at the moving end of the conductor during the test. It was inserted between the terminal connector of the conductor and the steel frame of the shake table (Figure 4.3.1). This load cell measured the horizontal forces at the connection of the conductor to the shake table. The applied horizontal displacements at the same end of the conductor were obtained directly from the transducers of the shake table actuator. Details on the specifications of the transducers are included in Appendix A.

![Connection of the conductor to the load cell and to the frame of the shake table](image)

Figure 4.3.1 Connection of the conductor to the load cell and to the frame of the shake table

4.4 Test Protocol

A loading protocol was specifically developed to perform this quasi-static test. The Institute of Electrical and Electronics Engineers (IEEE) Recommended Practice for Seismic Design of Substations \(^9\) was used as a guide. According to this document (sec. 6.9.2), typical displacements at conductor attachment point to medium-frequency (2.5-8 Hz) 500 KV equipment subjected to 0.3g peak ground acceleration, is 200-600 mm. This protocol is designed to have a maximum displacement of 200 mm when pulling the
conductor and a maximum of 600 mm when pushing it. It was decided not to pull the conductor for more than 200 mm as this could generate excessive tension in the conductor and consequently cause damage to it. Damage to the conductor was prevented since the same conductor was to be used for the shake table tests.

Figure 4.4.1 shows the test protocol which consists of displacement cycles with increasing amplitudes. There are three cycles at each level of displacement amplitude. The displacements were applied at a rate of 4 mm/sec.

![Cyclic displacement sequence for quasi-static test](image)

Figure 4.4.1 Cyclic displacement sequence for quasi-static test

### 4.5 Test Results

Figure 4.5.1 shows the results of various cycles at different displacement amplitudes and Figure 4.5.2 shows the results for cycles 31 to 33 which correspond to maximum displacements. They show that a very small force, less than 180 N (40 lb), is required to push the conductor, even for a displacement as large as 600 mm. The pulling forces are higher and increase quickly as the conductor straightens up and goes into tension. Using a 10 kip load cell for measuring such low forces resulted low precision measurements;
however, the attained accuracy was acceptable for the purpose of this test. It was observed that:

- The differential displacement of the equipment, when considered statically, caused very low forces in the conductor and at the conductor attachment points. The conductor has almost no resistance against pushing forces. The very low flexural stiffness of the conductor is what provides some resistance against deflection when pushing the conductor.

- The nonlinearity due to yielding of the conductor material within the displacement range used for this test is negligible since it was observed that the load-displacement curves for all the cycles lie reasonably on each other (Figure 4.5.1). Thus it is possible to find an approximate curve which represents an equivalent stiffness for the conductor. This equivalent stiffness could be helpful for numerical studies on the conductor. The result is shown in Figure 4.5.3. The curve shown in Figure 4.5.3 is obtained by fitting a 6th order polynomial to the results of cycles 31 to 33 shown in Figure 4.5.2.
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Figure 4.5.1 Load-displacement curves at various amplitudes

Figure 4.5.2 Load-displacement curves for cycles 31 to 33
Figure 4.5.3  Equivalent stiffness of the 500 kV flexible conductor configuration 2
CHAPTER 5

SHAKE TABLE TESTS

5.1 Introduction

This chapter describes the shake table tests performed on the flexible conductor configuration 2. In order to study the interaction of the conductor and the interconnected equipment, a full scale model of the conductor and a large scale equivalent model (East Tower and West Towers as described in Section 5.4) of the equipment were used. The two equivalent equipment items were mounted on two sets of cantilever beams which were specially designed and used for extending the shake table to accommodate the large span of the specimen. In order to study the effect of the conductor on the behaviour of the equipment, first the stand-alone towers were tested. Then three different set-ups of the towers with the connecting conductor were tested. Uni-axial and bidirectional synthetic earthquakes were used as input signals of the shake table. These synthetic records were obtained by modifying three records from past earthquakes to fit BC Hydro and IEEE 693-1997 design spectra at 2% damping, with a target peak ground acceleration of 0.5g. The result was six different synthetic ground motion records that were used at different amplitudes for the purposes of the study.

5.2 Description of the Shake Table Facility

The shake table of the earthquake engineering research laboratory at the University of British Columbia is a 3 m by 3 m (10 ft by 10 ft) aluminum cellular structure with a payload capacity of 156 kN (35000 lbs). The motions are produced by hydraulic actuators, which have a maximum displacement of ±7.6 cm (±3 inches). The actuator used to produce the horizontal longitudinal (South-West) motions can generate up to 156 kN (35000 lbs) of force. The remaining four actuators are used to produce either vertical or horizontal motions and can generate each up to 67 kN (15000 lbs) of force. The actuators are mounted on an isolated concrete pit foundation. Clearance above the table is 4.3 m (14 ft).
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Shake Table Tests

The shake table motions are controlled by a specialized state-of-the-art Multi Exciter Vibration Control Software. This software performs a closed-loop control of the shakers and is capable of reproducing recorded earthquake motions with high accuracy. Since test set-up parameters are stored in digital form, accurate replication of shake table motions can be easily achieved.

A 32 channel data acquisition system is generally used for instrumentation of specimens tested on the shake table. All channels are conditioned by variable gain buffers and variable cut-off filters to provide optimal control over signal levels and noise reduction.

5.3 Extension Cantilever Beams

Since the dimensions of the shake table were not large enough to accommodate the specimen, it was necessary to design two sets of cantilever beams that project out of the shake table and provide bases for mounting the towers. These beams were designed to be versatile such that they would be useful for testing all the flexible conductor configurations mentioned in Chapter 1.

The projected lengths of the cantilever beams were chosen based on the span of the conductor and the mass of the towers associated with each set of beams so that both sets of beams had the same fundamental natural frequency. Enough stiffness was provided for these beams so that each had a first mode natural frequency of more than 50 Hz. This was to ensure that they would not pick up significant vibration during the tests and thus they would not introduce significant noise into the results of the tests.

It was impossible to design rigid beams with no deflection during the tests. However, the effect of their deflections was mainly changing the overall stiffness of the equivalent equipment as discussed in section 5.6.4.4. The details of these beams are included in Appendix B.
5.4 Equivalent Equipment

Two structures were designed to represent the equipment interconnected by the flexible conductor. The goal in designing these two structures was to achieve the stiffness and the first mode natural frequency of the equipment. However, due to limitations such as height limitation above the shake table, it was impossible to achieve all of the above mentioned goals. So it was decided to design structures which are reasonably acceptable as equivalent equipment and then interpret the results based on these structures.

As is illustrated in Appendix B the equivalent equipment were steel towers consisting of four 70 mm diameter solid round bars and stacks of steel plates attached to the top of the bars with fixed connections. The bars and the stack of plates provided the stiffness and required mass of the equivalent equipment. It was possible to add or remove plates in order to increase or decrease the mass of the towers for decreasing or increasing their natural frequencies. The heights of these towers were selected to provide the right geometry of the conductor (Figure 4.2.2).

The 500 kV Current Transformer (5CT) is the shorter equipment which was represented by the shorter tower (West Tower). The West Tower was located on the west side of the shake table. The 500 kV Circuit Breaker (5CB) is the taller equipment which was represented by the taller tower (East Tower). The East Tower was located on the east side of the shake table (Figure 5.6.1).

Reasonable agreement was achieved between the stiffness and the first mode natural frequency of the current transformer with those of the West Tower. It was not feasible however, to achieve a good agreement between the fundamental frequency of the circuit breaker and the fundamental frequency of the East Tower. That was because the fundamental frequency of the circuit breaker was as low as 1 Hz. So it was decided to design the East Tower for a fundamental frequency equal to the second mode natural frequency of the actual equipment.
As mentioned earlier, the deflection and rotation of the extension cantilever beams affected the overall stiffness of the towers and consequently their natural frequencies. The actual natural frequencies and equivalent stiffness of the towers are obtained from the results of the tests as described in Section 5.6.

5.5 Input Signals

In order to verify the equipment design criteria, it was decided to use earthquakes that had response spectra matching BC Hydro’s and IEEE’s design spectra. The target spectra were at moderate seismic performance level with 2% damping. These spectra are illustrated in Figure 5.5.1.

![Figure 5.5.1. Target Spectra for 2% Damping](image)

In order to study the possibility of different behaviour of the conductor under different seismic loadings with different time domain characteristics, three different input signals with different time domain characteristics were generated for each target spectrum. To
do so, three records from the 1984 Northridge, the 1979 El Centro and the 1992 Landers earthquakes in California were used to generate synthetic ground motions (Figure 5.5.2).

SYNTH, a program developed by Naumoski (1985), was used to generate the synthetic earthquake records. This program uses an initial earthquake record and generates another record that matches a prescribed target spectrum. In order to match the computed spectrum with the target spectrum, the program raises and suppresses the computed spectrum iteratively by modifying the corresponding Fourier coefficients. The program was run enough times until very good agreement was achieved between the target and computed spectra. Figures 5.5.3 and 5.5.4 show the results.

To prepare the final input signals for the shake table, the acceleration records generated by SYNTH program were cut off at appropriate times and conditioned with ramps and post pulses by using Mathcad (12) worksheets developed for this project. The cut off times, ramps and post pulses were chosen such that the acceleration records and their corresponding velocities and displacements had reasonably smooth ramp-ups and ring-downs. Corresponding velocities and displacements were obtained by integrating the acceleration records. Integration was done numerically in the frequency domain (Section 3.6) with the help of a custom-developed Mathcad worksheet. Resulting velocities and displacements were checked to assure that they were within the limits of the shake table. Since the peak displacements of all the records were beyond the limits of the shake table, they were filtered by high-pass filters. The cut off frequencies were chosen for each record individually and were variable from 0.5 to 0.8 Hz.

In preparing the input records, IEEE 693-1997 requirement for the time history shake table tests (9) was also taken into account. According to this requirement, “The input duration of the time history tests shall be at least 20 s of strong motion. Ring down time or acceleration ramp-up time shall not be included in the 20 s of strong motion. The duration of strong motion shall be defined as the time range between when the plot of the time history first reaches 25% of the maximum value to the time when it falls for the last time to 25% of the maximum value”. The signal generated from Northridge record
conformed to this requirement. The signal generated from El Centro record had a shorter duration of strong motion and was used in order to observe different effects that might be caused by a different type of record. The record generated from Landers record had a very long duration of strong motion which obviously satisfied the IEEE requirements. Figures 5.5.3 to 5.5.5 show the resulting input records. Since the records whose response spectra match BC Hydro spectrum were less severe than the ones whose response spectra match IEEE spectrum, only the later records were used in this investigation. However, additional tests were carried out by using the less severe records to assure that the response to them is always less severe.

The performance of the shake table was verified by running the shake table with the specimen on it. The synthetic generated records were used as the input signals. The actual acceleration of the shake table was measured. The peak accelerations were checked to have the desired value and the response spectra of these recorded accelerations were verified to have a good match with the target spectra. It was found that the best match would be obtained by using these records at 90% amplitude. However, it was decided to use the signal generated from the Landers record at 75% of its amplitude since it was a very long duration record and a 90% scale simulation could cause irreparable damage to the specimens. Figures 5.5.6 and 5.5.7 show the target spectra and the spectra of the generated records. Figure 5.5.8 shows the response spectra from the actual acceleration response of the shake table with the specimen attached to it. It shows a very good match between these spectra and the target spectrum.
Figure 5.5.2 Earthquake records used to generate synthetic ground motions
Figure 5.5.3 Comparison of the BC Hydro target spectrum for 2% damping and the spectra of the generated records
Figure 5.5.4 Comparison of the IEEE 693-1997 target spectrum for 2% damping and the spectra of the generated records
IEEE-Northridge at 90% Amplitude

IEEE-El Centro at 90% Amplitude

IEEE-Landers at 75% Amplitude

Figure 5.5.5 Comparison of the IEEE 693-1997 target spectrum and the shake table acceleration response spectra
Figure 5.5.6. Input signal generated from Northridge record; IEEE target spectrum
Figure 5.5.7. Input signal generated from El Centro record; IEEE target spectrum
Figure 5.5.8. Input signal generated from Landers record; IEEE target spectrum
5.6 Stand-Alone Towers

In order to study the effect of the conductor on the behaviour of the equipment, and to identify the characteristics of the equivalent equipment, first the stand-alone towers were tested before the conductor was mounted. This section discusses these tests and presents the test results. To find out the effect of the conductor on the response of the towers, these results are compared with the results from the other test set-ups (Chapter 7). In addition to the analyses carried out in this chapter, a comprehensive spectral analysis is performed on the results of these tests in Chapter 6 with the purpose of studying the interaction between the conductor and the towers.

5.6.1 Description of the Test Set-Up

This set-up consisted of the two towers connected to the shake table through the extension cantilever beams. They were not interconnected by the flexible conductor. Figure 5.6.1 shows a picture of the test set-up. East Tower, the taller tower, was located on the east side of the shake table and West Tower, the shorter tower, was located on the west side of the shake table. Uni-axial earthquake motions in E-W direction were used for these tests.
5.6.2 Instrumentation

The towers and the extension cantilever beams were instrumented as illustrated in Figure 5.6.2. East Tower was instrumented with two accelerometers attached to the sides of its plates. One accelerometer measured the East-West (E-W) horizontal acceleration response of the tower and the other one measured its North-South (N-S) horizontal acceleration response. West Tower was instrumented with three accelerometers attached to the sides of its plates. Two accelerometers measured the E-W horizontal acceleration response of the tower and the third one measured it along the N-S direction. The N-S acceleration was measured for examining the possible noise introduced by vibration of the towers in that direction. The E-W acceleration of West Tower was measured at two locations on its plates in order to study its torsional modes. This was done because the mass of the West Tower could not be considered as a concentrated mass since it was
provided by large plates. Both Towers were instrumented with cable extension transducers (Section 5.7.2) which measured their displacements in the E-W direction.

The extension cantilever beams were also instrumented for investigating their effect on the response of the Towers and the noise introduced by them. One accelerometer on each set of cantilever beams measured N-S acceleration at the cantilevers tip and one Linear Variable Differential Transformer (LVDT) (Section 5.7.2) on each of them measured vertical displacements of the tip.

The shake table itself was instrumented with three accelerometers, one measuring the acceleration of the table in E-W direction, and the other two measuring the N-S accelerations of the table at its east and west sides. The displacement of the table is measured by transducers built into the actuators.

Table 5.6.1 shows a list of measured responses for this test set-up. In this table, “Col No.” indicates which column of numbers in the data file that contains the measurements, is the corresponding “Type of Response” shown in the table. “Ch No.” is the channel number of the data acquisition system. Further details about transducers are included in Appendix A.
Figure 5.6.2 Instrumentation plan for stand-alone towers set-up
Table 5.6.1 Measured responses for the stand-alone towers tests

<table>
<thead>
<tr>
<th>Col No.</th>
<th>Ch No.</th>
<th>Type of Response</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>Table E-W Displacement</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>Table N-S Displacement/West Side</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td>Table N-S Displacement/East Side</td>
</tr>
<tr>
<td>4</td>
<td>3</td>
<td>East Side Extension Cantilever Beams Tip Vertical Displacement</td>
</tr>
<tr>
<td>5</td>
<td>4</td>
<td>West Side Extension Cantilever Beams Tip Vertical Displacement</td>
</tr>
<tr>
<td>6</td>
<td>5</td>
<td>East Side Extension Cantilever Beams Tip Horizontal N-S Acceleration</td>
</tr>
<tr>
<td>7</td>
<td>6</td>
<td>West Side Extension Cantilever Beams Tip Horizontal N-S Acceleration</td>
</tr>
<tr>
<td>8</td>
<td>7</td>
<td>West Tower N-S Acceleration</td>
</tr>
<tr>
<td>9</td>
<td>8</td>
<td>West Tower E-W Acceleration/South Side</td>
</tr>
<tr>
<td>10</td>
<td>9</td>
<td>West Tower E-W Acceleration/North Side</td>
</tr>
<tr>
<td>11</td>
<td>16</td>
<td>East Tower E-W Displacement</td>
</tr>
<tr>
<td>12</td>
<td>19</td>
<td>East Tower N-S Acceleration</td>
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<td>20</td>
<td>East Tower E-W Acceleration</td>
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<td>21</td>
<td>West Tower E-W Displacement</td>
</tr>
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<td>15</td>
<td>29</td>
<td>Table N-S Acceleration/East Side</td>
</tr>
<tr>
<td>16</td>
<td>30</td>
<td>Table N-S Acceleration/West Side</td>
</tr>
<tr>
<td>17</td>
<td>31</td>
<td>Table E-W Acceleration</td>
</tr>
</tbody>
</table>

5.6.3 Test Sequence

Table 5.7.1 shows the test sequence for stand-alone towers tests. These tests can be categorized in three groups as follows:

- **Sine sweep tests**: The purpose of these tests was to find the natural frequencies of the towers. The input of the shake table was a sinusoidal wave with frequencies sweeping from 0 to 25 Hz at a constant acceleration of 0.2g. One sine sweep test was performed before all the other tests and one was performed after running all the tests. This was done to see whether the characteristics of the specimen were changed due to any possible yielding in the structure.
- **Step Force tests**: The purpose of these tests was to put the towers in the state of free vibration by applying a step force to the system through the shake table. The results of these tests were used to measure the damping ratios of the towers by using the logarithmic decrement method. Since damping ratio is amplitude dependent, the step force was applied at two different amplitudes.

- **Seismic loading tests**: These tests involved subjecting the towers to the generated synthetic earthquakes. All six records were used and they were used at various amplitudes. In Table 5.6.2, the acronym before each input signal name indicates the target spectrum and the second part of the name indicates which earthquake record the input signal was generated from.

Table 5.6.2 Stand-alone towers shake table tests sequence

<table>
<thead>
<tr>
<th>Test No.</th>
<th>Description of the Test</th>
<th>Input Signal</th>
<th>Amplitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Frequencies of Stand-Alone Towers</td>
<td>Sinusoidal</td>
<td>0.2g</td>
</tr>
<tr>
<td>2</td>
<td>Damping of Stand-Alone Towers</td>
<td>Step Force</td>
<td>N/A</td>
</tr>
<tr>
<td>3</td>
<td>Damping of Stand-Alone Towers</td>
<td>Step Force</td>
<td>N/A</td>
</tr>
<tr>
<td>4</td>
<td>Seismic Loading - Stand-Alone Towers</td>
<td>BCH - Northridge</td>
<td>50%</td>
</tr>
<tr>
<td>5</td>
<td>Seismic Loading - Stand-Alone Towers</td>
<td>BCH - Northridge</td>
<td>100%</td>
</tr>
<tr>
<td>6</td>
<td>Seismic Loading - Stand-Alone Towers</td>
<td>BCH - El Centro</td>
<td>50%</td>
</tr>
<tr>
<td>7</td>
<td>Seismic Loading - Stand-Alone Towers</td>
<td>BCH - El Centro</td>
<td>100%</td>
</tr>
<tr>
<td>8</td>
<td>Seismic Loading - Stand-Alone Towers</td>
<td>BCH - Landers</td>
<td>50%</td>
</tr>
<tr>
<td>9</td>
<td>Seismic Loading - Stand-Alone Towers</td>
<td>BCH - Landers</td>
<td>100%</td>
</tr>
<tr>
<td>10</td>
<td>Seismic Loading - Stand-Alone Towers</td>
<td>IEEE - Northridge</td>
<td>50%</td>
</tr>
<tr>
<td>11</td>
<td>Seismic Loading - Stand-Alone Towers</td>
<td>IEEE - Northridge</td>
<td>90%</td>
</tr>
<tr>
<td>12</td>
<td>Seismic Loading - Stand-Alone Towers</td>
<td>IEEE - El Centro</td>
<td>50%</td>
</tr>
<tr>
<td>13</td>
<td>Seismic Loading - Stand-Alone Towers</td>
<td>IEEE - El Centro</td>
<td>90%</td>
</tr>
<tr>
<td>14</td>
<td>Seismic Loading - Stand-Alone Towers</td>
<td>IEEE - Landers</td>
<td>50%</td>
</tr>
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<td>15</td>
<td>Seismic Loading - Stand-Alone Towers</td>
<td>IEEE - Landers</td>
<td>75%</td>
</tr>
<tr>
<td>16</td>
<td>Frequencies of Stand-Alone Towers</td>
<td>Sinusoidal</td>
<td>0.2g</td>
</tr>
<tr>
<td>17</td>
<td>Damping of Stand-Alone Towers</td>
<td>Step Force</td>
<td>N/A</td>
</tr>
<tr>
<td>18</td>
<td>Damping of Stand-Alone Towers</td>
<td>Step Force</td>
<td>N/A</td>
</tr>
</tbody>
</table>
5.6.4 Tests Results and Analysis

5.6.4.1 Natural Frequencies

Natural frequencies were obtained by analyzing the results of sine sweep tests with the help of a MathCAD worksheet. In this worksheet, the measured response signals were read and their Fourier amplitudes were calculated by using the Fast Fourier Transform (FFT) algorithm. The trends of the signal, if existed, were removed. Then, normalized Fourier amplitudes were calculated by dividing the Fourier amplitudes by their maximum absolute value. The resulting normalized Fourier amplitudes were plotted versus the frequency. The natural frequencies are identified as the frequencies at which there is a peak. Figure 5.6.3 shows the results for the towers.

![East Tower E-W Acceleration](chart1)

![West Tower E-W Acceleration/South Side](chart2)

Figure 5.6.3 Sine sweep test results for the towers
The natural frequencies of the towers obtained from sine sweep tests are given in Table 5.6.3. Results of the sine sweep tests also showed no difference in the natural frequencies of the towers before and after applying seismic loadings. This indicated that there was no yielding or damage in any part of the structures and they remained elastic during the tests.

<table>
<thead>
<tr>
<th>First Mode Natural Frequencies of the Towers (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>East Tower</td>
</tr>
<tr>
<td>3.53</td>
</tr>
<tr>
<td>West Tower</td>
</tr>
<tr>
<td>2.88</td>
</tr>
</tbody>
</table>

The natural frequencies shown in Table 5.6.3 are the fundamental frequencies of the towers. Towers also have other modes of vibration with different natural frequencies. Other modes of vibration were especially noticeable in the behaviour of the West Tower, which experienced torsional effects because of its large plates. Evidence of this is shown in Figure 5.6.4 which plots the FFT of the subtraction of the two acceleration responses at two opposite sides of the plates. Three peaks at 5.76, 6.80 and 7.80 Hz in Figure 5.6.4 indicate the presence of other modes. The presence of these modes could also be caused by the deflection and rotation of the extension cantilever beams. The identification of these secondary modes and their effect on the response of the system is discussed in more detail in Chapter 6.
5.6.4.2 Damping Ratios

Damping ratios of the towers were obtained by using the logarithmic decrement method.\(^3\) Damping ratio is amplitude dependent. That means the damping ratio calculated by choosing two peaks from the high-amplitude portion of the free vibration response would be different than the damping ratio obtained by choosing the peaks from the low-amplitude portion of the record.\(^4\) Therefore, in order to get better results, both acceleration and displacement response of the towers obtained from the first two step load tests (Test 2 and Test 3) are used to calculate the damping ratios. Thus four values of damping ratios are obtained for each tower which are then averaged to give the final damping ratio for the corresponding tower. The first and second peaks are chosen respectively from high-amplitude and low-amplitude portions of the chosen records. Tables 5.6.4 and 5.6.5 show the calculation of the damping ratios.
Table 5.6.4 Calculation of damping ratio for East Tower

<table>
<thead>
<tr>
<th>Test 2 (Step Force I)</th>
<th>Number of Cycles $j$</th>
<th>Amplitude of the First Chosen Peak $P_1$</th>
<th>Amplitude of the $j^{th}$ Peak from the First Peak $P_{1+j}$</th>
<th>Damping Ratio $\zeta = \frac{1}{\ln \frac{P_1}{P_{1+j}}} \frac{1}{2\pi j}$</th>
<th>Average ($%$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Displacement (mm)</td>
<td>38</td>
<td>1.504</td>
<td>0.355</td>
<td>0.0060</td>
<td>0.54</td>
</tr>
<tr>
<td>Acceleration (g)</td>
<td>43</td>
<td>0.081</td>
<td>0.022</td>
<td>0.0048</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Test 3 (Step Force II)</th>
<th>Number of Cycles $j$</th>
<th>Amplitude of the First Chosen Peak $P_1$</th>
<th>Amplitude of the $j^{th}$ Peak from the First Peak $P_{1+j}$</th>
<th>Damping Ratio $\zeta = \frac{1}{\ln \frac{P_1}{P_{1+j}}} \frac{1}{2\pi j}$</th>
<th>Average ($%$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Displacement (mm)</td>
<td>34</td>
<td>1.332</td>
<td>0.325</td>
<td>0.0066</td>
<td>0.58</td>
</tr>
<tr>
<td>Acceleration (g)</td>
<td>37</td>
<td>0.075</td>
<td>0.023</td>
<td>0.0051</td>
<td></td>
</tr>
</tbody>
</table>

Damping Ratio $\zeta$ ($\%$) 0.56
Table 5.6.5 Calculation of damping ratio for West Tower

<table>
<thead>
<tr>
<th>West Tower</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Test 2 (Step Force I)</strong></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Number of Cycles</td>
</tr>
<tr>
<td>---------------------</td>
</tr>
<tr>
<td>Displacement (mm)</td>
</tr>
<tr>
<td>Acceleration (g)</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td><strong>Test 3 (Step Force II)</strong></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Number of Cycles</td>
</tr>
<tr>
<td>---------------------</td>
</tr>
<tr>
<td>Displacement (mm)</td>
</tr>
<tr>
<td>Acceleration (g)</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td><strong>Damping Ratio $\zeta$ (%)</strong></td>
</tr>
</tbody>
</table>
5.6.4.3 Seismic Response

In this section, a summary of the test results from the seismic tests is presented, including acceleration and displacement responses at the top of the towers. As mentioned earlier, the results of the tests with input signals having the IEEE target spectra were used in the analyses. Figures 5.6.5 and 5.6.6 show sample time histories of the results. Tables 5.6.6 to 5.6.8 present a summary of the results and include the amplification factors for the acceleration responses. Note that the displacements of the towers are relative to the shake table.
Table 5.6.6 East Tower acceleration response

<table>
<thead>
<tr>
<th>Maximum Absolute Response</th>
<th>Input Signal</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>IEEE-Northridge 90%</td>
</tr>
<tr>
<td>Acceleration (g)</td>
<td></td>
</tr>
<tr>
<td>East Tower</td>
<td>2.61</td>
</tr>
<tr>
<td>Shake Table</td>
<td>0.53</td>
</tr>
<tr>
<td>Amplification Factor</td>
<td>4.92</td>
</tr>
</tbody>
</table>

Table 5.6.7 West Tower acceleration response

<table>
<thead>
<tr>
<th>Maximum Absolute Response</th>
<th>Input Signal</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>IEEE-Northridge 90%</td>
</tr>
<tr>
<td>Acceleration (g)</td>
<td></td>
</tr>
<tr>
<td>West Tower</td>
<td>2.33</td>
</tr>
<tr>
<td>Shake Table</td>
<td>0.53</td>
</tr>
<tr>
<td>Amplification Factor</td>
<td>4.40</td>
</tr>
</tbody>
</table>

Table 5.6.8 Towers Displacement Response

<table>
<thead>
<tr>
<th>Maximum Absolute Displacement (mm)</th>
<th>Input Signal</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>IEEE-Northridge 90%</td>
</tr>
<tr>
<td>East Tower</td>
<td>52</td>
</tr>
<tr>
<td>West Tower</td>
<td>66</td>
</tr>
<tr>
<td>Towers Relative Displacement</td>
<td>90</td>
</tr>
<tr>
<td></td>
<td>-87</td>
</tr>
</tbody>
</table>
Figure 5.6.5 Shake table and towers accelerations - Test 11

Shake Table

max = 0.53 g  min = -0.49 g

East Tower

max = 2.61 g  min = -2.61 g

West Tower

max = 2.33 g  min = -2.31 g
Figure 5.6.6 Shake table and towers displacement - Test 11
5.6.4.4 Effect of the Extension Cantilever Beams

Results showed that the deflection response at the tips of the extension cantilever beams were at the rates of the deflection of the towers (Figure 5.6.7). This is because they deflected under the loads caused by overturning moments of the towers. Flexibility of the beams affected the overall stiffness of the towers. An equivalent stiffness can be calculated for the equivalent equipment by knowing their masses and natural frequencies and considering them as single degree of freedom systems. Table 5.6.9 presents the results. Analysis of the results also showed no significant N-S acceleration response at the tip of the cantilever beams.

<table>
<thead>
<tr>
<th>Equivalent Equipment</th>
<th>Modal Mass (kg)</th>
<th>Natural Frequency (Hz)</th>
<th>Equivalent Stiffness (N/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>East Tower</td>
<td>650</td>
<td>3.53</td>
<td>3.20E+05</td>
</tr>
<tr>
<td>West Tower</td>
<td>2360</td>
<td>2.88</td>
<td>7.73E+05</td>
</tr>
</tbody>
</table>
Figure 5.6.7 Frequency response of vertical displacement at the tips of cantilever beams during sine sweep tests

5.7 Flexible Conductor Test Set-up 1

After testing the stand-alone towers, the flexible conductor was mounted and connected to the towers such that its geometry was as depicted in Figure 4.2.2. This was the first set-up of the towers interconnected by the flexible conductor.

5.7.1 Description of the Test Set-Up

This test set-up is similar to the stand-alone towers set-up with the addition of the conductor interconnecting the towers (Figure 5.7.1). The conductor was connected to the towers by using u-shaped aluminum connectors or "angle adapters" (Figure 4.2.2) and triangular-shaped mounting brackets. The load cells were inserted between the angle adapters and mounting brackets. Figures 5.7.2 and 5.7.3 show the connection of the conductor to the towers.
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Figure 5.7.1 Interconnected equipment test set-up 1

Figure 5.7.2 Connection of the conductor to the East Tower
Figure 5.7.3 Connection of the conductor to the West Tower
5.7.2 Instrumentation

Various types of transducers were employed for the dynamic data acquisition. A description of the instruments used in these tests is as follows:

- **Accelerometers**: Two types of accelerometers, piezoelectric and piezoresistive, were used in these tests. Piezoelectric accelerometers are transducers that use piezoelectric crystals or ceramics to sense the accelerations applied to their base.\(^{(10)}\) These accelerometers are not sensitive to the angle between the axis of the accelerometer and the direction of motion. They always measure the acceleration along their sensitive axis. This type of accelerometer was used for the instrumentation of the flexible conductor (Figure 5.7.7). Piezoresistive accelerometers use “strain-sensitive materials”.\(^{(10)}\) “A strain-sensitive material changes its electrical resistance in proportion to the instantaneous spatial-average strain applied over the surface area of the material”.\(^{(10)}\) These accelerometers are sensitive to the angle between the axis of the accelerometer and the direction of motion. This type of accelerometer was used where the direction of motion did not change its angle, i.e. it always remained horizontal or vertical. For instrumentation of the towers, piezoresistive accelerometers were used.

- **Displacement Transducers**: Two types of transducers were used to measure displacement responses. The first type was Linear Variable Differential Transformer also known as LVDT. The LVDT is a series of inductors in a hollow cylindrical shaft and a solid cylindrical core. It produces electrical output proportional to the position of the core. The LVDT may be used in many different types of measuring devices that need to convert changes in physical position to an electrical output (www.flw.com/lvdt_2.htm). In these tests, LVDTs were used to measure the tip deflection of the extension cantilever beams (Figure 5.7.4). The second type of displacement transducer used in these tests was cable extension transducers or string pots. These transducers use a stainless steel cable wound around a spring-powered precision machined drum. The bearing-mounted drum is
mated to a precision potentiometric element that translates linear position information to an electrical signal (www.spaceagecontrol.com/170176.htm). These transducers are installed by mounting their base to a fixed surface and attach their cable to the movable object. Figure 5.7.5 shows a cable extension transducer used for measuring the displacement of the towers.

Figure 5.7.4 LVDT used for measuring the vertical displacement at the tip of the extension cantilever beams
Figure 5.7.5 Cable extension transducers used for measuring towers displacement

- **Force Transducers**: Two similar multi-component load cells were used to measure the forces at the connection of the flexible conductor to the towers in both horizontal and vertical directions. These force/torque load cells have six outputs corresponding to the three force and the three torque components. These transducers have a 12.57 cm (4.95 in) diameter top and bottom mounting surfaces equipped with mounting holes and threaded inserts. The standard capacities of these load cells are 10680 N (2500 lb) in the direction normal to mounting surfaces (z direction) and half of that rating for the forces on the plane of the mounting surface (x and y directions) [ref]. Figure 5.7.2 shows one of the load cells mounted on top of the West Tower.

Figure 5.7.6 shows the instrumentation plan and Table 5.7.1 has a list of measured responses for this test set-up. The towers and cantilever beams were instrumented with acceleration and displacement transducers similar to those of stand-alone towers. The conductor was instrumented with three pairs of piezoelectric accelerometers. Lightweight custom-made aluminum clamps were employed for attaching the accelerometers to the
conductor (Figure 5.7.7). The load cells were used to measure the forces at the connection points of the conductor to the towers. They measured the vertical force (Fy) and horizontal force in E-W direction (Fz) at both connections. Figures 5.7.2 and 5.7.3 show how the load cells were installed. More details on the specifications of the transducers are included in Appendix A.
Figure 5.7.6 Instrumentation plan for test set-up 1
Table 5.7.1 Measured responses in test set-up 1

<table>
<thead>
<tr>
<th>Col No</th>
<th>Ch No</th>
<th>Type of Response</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>Table E-W Displacement</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>Table N-S Displacement/West Side</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td>Table N-S Displacement/East Side</td>
</tr>
<tr>
<td>4</td>
<td>3</td>
<td>East Side Extension Cantilever Beams Tip Vertical Displacement</td>
</tr>
<tr>
<td>5</td>
<td>4</td>
<td>West Side Extension Cantilever Beams Tip Vertical Displacement</td>
</tr>
<tr>
<td>6</td>
<td>5</td>
<td>East Side Extension Cantilever Beams Tip Horizontal N-S Acceleration</td>
</tr>
<tr>
<td>7</td>
<td>6</td>
<td>West Side Extension Cantilever Beams Tip Horizontal N-S Acceleration</td>
</tr>
<tr>
<td>8</td>
<td>7</td>
<td>West Tower N-S Acceleration</td>
</tr>
<tr>
<td>9</td>
<td>8</td>
<td>West Tower E-W Acceleration/South Side</td>
</tr>
<tr>
<td>10</td>
<td>9</td>
<td>West Tower E-W Acceleration/North Side</td>
</tr>
<tr>
<td>11</td>
<td>10</td>
<td>Conductor Acceleration Normal to the Conductor/West South Side</td>
</tr>
<tr>
<td>12</td>
<td>11</td>
<td>Conductor Acceleration Normal to the Conductor/East South Side</td>
</tr>
<tr>
<td>13</td>
<td>12</td>
<td>Conductor Acceleration Normal to the Conductor/East North Side</td>
</tr>
<tr>
<td>14</td>
<td>13</td>
<td>Conductor Acceleration Normal to the Conductor/West North Side</td>
</tr>
<tr>
<td>15</td>
<td>14</td>
<td>Conductor Acceleration Normal to the Conductor/Centre</td>
</tr>
<tr>
<td>16</td>
<td>15</td>
<td>Conductor Acceleration Along the Conductor/Centre</td>
</tr>
<tr>
<td>17</td>
<td>16</td>
<td>East Tower E-W Displacement</td>
</tr>
<tr>
<td>18</td>
<td>17</td>
<td>Vertical Force Fy - Conductor Connection to East Tower</td>
</tr>
<tr>
<td>19</td>
<td>18</td>
<td>Horizontal Force Fz - Conductor Connection to East Tower</td>
</tr>
<tr>
<td>20</td>
<td>19</td>
<td>East Tower N-S Acceleration</td>
</tr>
<tr>
<td>21</td>
<td>20</td>
<td>East Tower E-W Acceleration</td>
</tr>
<tr>
<td>22</td>
<td>21</td>
<td>West Tower E-W Displacement</td>
</tr>
<tr>
<td>23</td>
<td>22</td>
<td>Vertical Force Fy - Conductor Connection to West Tower</td>
</tr>
<tr>
<td>24</td>
<td>23</td>
<td>Horizontal Force Fz - Conductor Connection to West Tower</td>
</tr>
<tr>
<td>25</td>
<td>29</td>
<td>Table N-S Acceleration/East Side</td>
</tr>
<tr>
<td>26</td>
<td>30</td>
<td>Table N-S Acceleration/West Side</td>
</tr>
<tr>
<td>27</td>
<td>31</td>
<td>Table E-W Acceleration</td>
</tr>
</tbody>
</table>
Figure 5.7.7 Instrumentation of the flexible conductor; accelerometers
5.7.3 Test Sequence

The test sequence for set-up 1 of the interconnected towers was similar to that of the stand-alone towers and included sine sweep tests, step force tests and seismic loading tests. Input signals were also the same as the ones used for the stand-alone towers, at the same amplitudes. The test numbers followed the test numbers of the stand-alone towers tests. Table 5.7.2 shows the test sequence.

Table 5.7.2 Test sequence for set-up 1

<table>
<thead>
<tr>
<th>Test No.</th>
<th>Test Description</th>
<th>Input Signal</th>
<th>Amplitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>19</td>
<td>Frequencies of Interconnected Towers</td>
<td>Sinusoidal</td>
<td>0.2g</td>
</tr>
<tr>
<td>20</td>
<td>Damping of Interconnected Towers</td>
<td>Step Force</td>
<td>N/A</td>
</tr>
<tr>
<td>21</td>
<td>Damping of Interconnected Towers</td>
<td>Step Force</td>
<td>N/A</td>
</tr>
<tr>
<td>22</td>
<td>Seismic Loading</td>
<td>BCH - Northridge</td>
<td>0.5</td>
</tr>
<tr>
<td>23</td>
<td>Seismic Loading</td>
<td>BCH - Northridge</td>
<td>100%</td>
</tr>
<tr>
<td>24</td>
<td>Seismic Loading</td>
<td>BCH - El Centro</td>
<td>50%</td>
</tr>
<tr>
<td>25</td>
<td>Seismic Loading</td>
<td>BCH - El Centro</td>
<td>100%</td>
</tr>
<tr>
<td>26</td>
<td>Seismic Loading</td>
<td>BCH - Landers</td>
<td>50%</td>
</tr>
<tr>
<td>27</td>
<td>Seismic Loading</td>
<td>BCH - Landers</td>
<td>100%</td>
</tr>
<tr>
<td>28</td>
<td>Seismic Loading</td>
<td>IEEE - Northridge</td>
<td>50%</td>
</tr>
<tr>
<td>29</td>
<td>Seismic Loading</td>
<td>IEEE - Northridge</td>
<td>90%</td>
</tr>
<tr>
<td>30</td>
<td>Seismic Loading</td>
<td>IEEE - El Centro</td>
<td>50%</td>
</tr>
<tr>
<td>31</td>
<td>Seismic Loading</td>
<td>IEEE - El Centro</td>
<td>90%</td>
</tr>
<tr>
<td>32</td>
<td>Seismic Loading</td>
<td>IEEE - Landers</td>
<td>50%</td>
</tr>
<tr>
<td>33</td>
<td>Seismic Loading</td>
<td>IEEE - Landers</td>
<td>75%</td>
</tr>
<tr>
<td>34</td>
<td>Frequencies of Interconnected Towers</td>
<td>Sinusoidal</td>
<td>0.2g</td>
</tr>
<tr>
<td>35</td>
<td>Damping of Interconnected Towers</td>
<td>Step Force</td>
<td>N/A</td>
</tr>
<tr>
<td>36</td>
<td>Damping of Interconnected Towers</td>
<td>Step Force</td>
<td>N/A</td>
</tr>
</tbody>
</table>

5.7.4 Test Results and Analysis

In this section, tests results are summarized and presented in various forms. MathCAD worksheets were developed for the analysis and presentation of the results.
5.7.4.1 Resonance Frequencies

Resonance frequencies of the towers are evaluated and compared to their natural frequencies (Table 5.7.3). This comparison is to see whether the conductor stiffness has a considerable effect on the characteristics of the interconnected towers.

<table>
<thead>
<tr>
<th></th>
<th>Resonance Frequencies of the Interconnected Towers (Hz)</th>
<th>Fundamental Frequencies of the Stand-Alone Towers (Hz)</th>
<th>% Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>East Tower</td>
<td>3.45</td>
<td>3.53</td>
<td>2</td>
</tr>
<tr>
<td>West Tower</td>
<td>2.85</td>
<td>2.88</td>
<td>1</td>
</tr>
</tbody>
</table>

The results show that the conductor reduced the resonance frequencies of the towers by no more than 2%.

Strong shaking of the conductor indicated that its natural frequencies are within the range of the towers natural frequencies. However, no specific values for these frequencies could be detected due to the nonlinearity of the conductor and the fact that its natural frequencies continuously change as its geometry changes. Detailed spectral analysis on the results is performed in Chapter 6.

5.7.4.2 Acceleration Response

In this section, the time histories of the acceleration response at selected locations of the specimen from selected tests are shown. Also, a summary of the peak accelerations and amplification factors is presented. Sample results are presented in Figures 5.7.8 and 5.7.9. All presented data were digitally filtered as described in Chapter 3. More test results can be found in Appendix C.
Figure 5.7.8 Shake table and towers accelerations - Test 29
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Shake Table Tests

Figure 5.7.9 Conductor acceleration - Test 29
Tables 5.7.4 and 5.7.5 present peak acceleration responses and amplification factors of the towers. Peak accelerations of the shake table are also presented.

<table>
<thead>
<tr>
<th>Maximum Absolute Response</th>
<th>Input Signal</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>IEEE-Northridge 90%</td>
</tr>
<tr>
<td>Acceleration (g) East Tower</td>
<td>1.97</td>
</tr>
<tr>
<td>Acceleration (g) Shake Table</td>
<td>0.53</td>
</tr>
<tr>
<td>Amplification Factor</td>
<td>3.72</td>
</tr>
</tbody>
</table>

Table 5.7.5 West Tower Acceleration Response

<table>
<thead>
<tr>
<th>Maximum Absolute Response</th>
<th>Input Signal</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>IEEE-Northridge 90%</td>
</tr>
<tr>
<td>Acceleration (g) West Tower</td>
<td>1.88</td>
</tr>
<tr>
<td>Acceleration (g) Shake Table</td>
<td>0.53</td>
</tr>
<tr>
<td>Amplification Factor</td>
<td>3.55</td>
</tr>
</tbody>
</table>

Tables 5.7.6 to 5.7.8 show the peak acceleration responses of the conductor at its instrumented locations (Figure 5.7.6). At each location along the conductor, considerable difference between the two normal accelerations measured on each of the cables was observed. This is ascribed to the initial out-of-plane deformation of the conductor after it was mounted (Figure 5.7.10). As a result of this irregularity in the conductor geometry, one cable of the twin conductor picked up more acceleration compared with the adjacent one. In order to estimate one value for the peak accelerations, the two values at each
location were averaged. These average numbers represent reasonable values for the peak accelerations since the two cables of the twin conductor vibrated reasonably in phase (see Chapter 6 for a discussion on this).

Figure 5.7.10 Out-of-plane initial deformation of the conductor

Table 5.7.6 Conductor acceleration response to IEEE-Northridge 90%

<table>
<thead>
<tr>
<th>Location of the Transducer</th>
<th>Peak Acceleration Response (g)</th>
<th>Normal to the Axes of the Conductor</th>
<th>Along the Axes of the Conductor</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>East (Location 1)</td>
<td>Centre (Location 2)</td>
</tr>
<tr>
<td>North Side</td>
<td></td>
<td>6.90</td>
<td>3.91</td>
</tr>
<tr>
<td>South Side</td>
<td></td>
<td>4.08</td>
<td>N/A</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td>5.49</td>
<td>3.91</td>
</tr>
<tr>
<td>Amplification Factor</td>
<td></td>
<td>10.36</td>
<td>7.38</td>
</tr>
</tbody>
</table>
**Chapter 5**

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Table 5.7.7 Conductor acceleration response to IEEE-El Centro 90%

<table>
<thead>
<tr>
<th>Location of the Transducer</th>
<th>Peak Acceleration Response (g)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Normal to the Axes of the Conductor</td>
<td>Along the Axes of the Conductor</td>
</tr>
<tr>
<td></td>
<td>East (Location 1)</td>
<td>Centre (Location 2)</td>
</tr>
<tr>
<td>North Side</td>
<td>7.84</td>
<td>4.05</td>
</tr>
<tr>
<td>South Side</td>
<td>4.62</td>
<td>N/A</td>
</tr>
<tr>
<td>Average</td>
<td>6.23</td>
<td>4.05</td>
</tr>
<tr>
<td>Amplification Factor</td>
<td>11.13</td>
<td>7.23</td>
</tr>
</tbody>
</table>

Table 5.7.8 Conductor acceleration response to IEEE-Landers 75%

<table>
<thead>
<tr>
<th>Location of the Transducer</th>
<th>Peak Acceleration Response (g)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Normal to the Axes of the Conductor</td>
<td>Along the Axes of the Conductor</td>
</tr>
<tr>
<td></td>
<td>East (Location 1)</td>
<td>Centre (Location 2)</td>
</tr>
<tr>
<td>North Side</td>
<td>5.45</td>
<td>3.40</td>
</tr>
<tr>
<td>South Side</td>
<td>3.47</td>
<td>N/A</td>
</tr>
<tr>
<td>Average</td>
<td>4.46</td>
<td>3.40</td>
</tr>
<tr>
<td>Amplification Factor</td>
<td>10.37</td>
<td>7.91</td>
</tr>
</tbody>
</table>
5.7.4.3 Displacement Response

In this section, the displacement response at selected locations of the specimen is presented. Displacements of the towers were directly measured by using displacement transducers. The conductor, however, did not have displacement transducers and its displacement responses were obtained by integrating its acceleration responses. The integration was done numerically in the frequency domain as explained in Chapter 3.

Figures 5.7.11 and 5.7.12 show sample displacement time-histories obtained from Test 29. More test results are included in Appendix C.
Figure 5.7.11 Shake table and towers displacement - Test 29
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East North Side - Normal to Conductor

max = 133 mm  min = -166 mm

West North Side - Normal to Conductor

max = 90 mm  min = -90 mm

Centre North Side - Normal to Conductor

max = 43 mm  min = -52 mm

Centre North Side - Along the Conductor

max = 99 mm  min = -96 mm

Figure 5.7.12 Conductor absolute displacements - Test 29
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Table 5.7.9 summarizes the peak values of the displacement response of the towers relative to the shake table. Table 5.7.9 also includes the peak values of the towers displacement relative to each other. These values indicate the maximum stretch or compression that the conductor experienced during the tests. Positive number means that the conductor was compressed and negative number means the conductor was stretched.

<table>
<thead>
<tr>
<th>Location and Type of Response</th>
<th>Input Signal</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>IEEE-Northridge 90%</td>
<td>IEEE-El Centro 90%</td>
<td>IEEE-Landers 75%</td>
<td></td>
</tr>
<tr>
<td>East Tower; Relative to Shake Table</td>
<td>40</td>
<td>35</td>
<td>42</td>
<td></td>
</tr>
<tr>
<td>West Tower; Relative to Shake Table</td>
<td>52</td>
<td>62</td>
<td>55</td>
<td></td>
</tr>
<tr>
<td>Towers; Relative to Each Other</td>
<td>65</td>
<td>72</td>
<td>64</td>
<td></td>
</tr>
<tr>
<td></td>
<td>-66</td>
<td>-75</td>
<td>-59</td>
<td></td>
</tr>
</tbody>
</table>

Table 5.7.10 summarizes the peak displacement response of the conductor at the locations of the accelerometers (Figure 5.7.6). Similar to the acceleration response of the conductor, these values are obtained by averaging the displacements of the two cables at each location.
Table 5.7.10 Displacement response of the conductor

<table>
<thead>
<tr>
<th>Input Signal</th>
<th>Location of the Transducer</th>
<th>Peak Displacement Response (mm)</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Normal to the Conductor</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>East (Location 1)</td>
<td>Centre (Location 2)</td>
<td>West (Location 3)</td>
<td>Centre (Location 2)</td>
</tr>
<tr>
<td>IEEE-Northridge 90%</td>
<td>North Side</td>
<td>166</td>
<td>52</td>
<td>91</td>
<td>99</td>
</tr>
<tr>
<td></td>
<td>South Side</td>
<td>89</td>
<td>N/A</td>
<td>38</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td>Average</td>
<td>127</td>
<td>52</td>
<td>64</td>
<td>99</td>
</tr>
<tr>
<td>IEEE-El Centro 90%</td>
<td>North Side</td>
<td>173</td>
<td>64</td>
<td>75</td>
<td>92</td>
</tr>
<tr>
<td></td>
<td>South Side</td>
<td>88</td>
<td>N/A</td>
<td>44</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td>Average</td>
<td>130</td>
<td>64</td>
<td>59</td>
<td>92</td>
</tr>
<tr>
<td>IEEE-Landers 75%</td>
<td>North Side</td>
<td>148</td>
<td>56</td>
<td>83</td>
<td>80</td>
</tr>
<tr>
<td></td>
<td>South Side</td>
<td>86</td>
<td>N/A</td>
<td>32</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td>Average</td>
<td>117</td>
<td>56</td>
<td>57</td>
<td>80</td>
</tr>
</tbody>
</table>

To better understand the behaviour of the conductor, its deflected shapes were obtained from the calculated displacement time-histories. An interpolation scheme was used to reconstruct the deflected shape. The initial geometry of the conductor was obtained by measuring its coordinates at 16 locations along its length (Appendix B). Figure 5.7.13 shows the deflected shape of the conductor at various positions obtained from Test 29. Figure 5.7.14 shows pictures of the deflection of the conductor during one of the tests.
Figure 5.7.13  Deflected shape of the conductor at various positions

Figure 5.7.14  Deflected shapes of the conductor
5.7.4.4 Force Response

In this section, the forces measured by the load cells are presented. As mentioned earlier, two force components were measured at each conductor attachment point. They are the vertical force, Fy, and the E-W horizontal force, Fz.

Table 5.7.11 shows the static forces in the connections of the conductor. They were obtained by measuring forces before applying the seismic loadings. These forces are the amount of baseline shift in the measured force time-histories and can be obtained from the force response signals.

<table>
<thead>
<tr>
<th>Absolute Static Force (N)</th>
<th>East Tower</th>
<th>West Tower</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fz</td>
<td>Fy</td>
<td>Fz</td>
</tr>
<tr>
<td>306</td>
<td>112</td>
<td>262</td>
</tr>
</tbody>
</table>

The maximum absolute dynamic forces generated in the connections of the flexible conductor due to seismic loadings are summarized in Table 5.7.12. A force parameter, denoted as Force Amplification Factor (FAF), is used here to compare dynamic and static forces. This parameter provides a scale for comparing the severity of dynamic forces. FAF is defined as:

\[
FAF = \frac{\text{Peak Dynamic Force}}{\text{Static Force}} \tag{5.7.1}
\]

Table 5.7.13 presents the FAF of the measured forces obtained from the seismic loading tests. For easier comparison, these results are also presented by bar charts (Figure 5.7.15).
Table 5.7.12 Peak dynamic forces in the connections of the conductor

<table>
<thead>
<tr>
<th>Input Signal</th>
<th>Peak Dynamic Force (N)</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>East Tower</td>
<td>West Tower</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fz</td>
<td>Fy</td>
<td>Fz</td>
<td>Fy</td>
<td></td>
</tr>
<tr>
<td>IEEE-Northridge 50%</td>
<td>629</td>
<td>445</td>
<td>863</td>
<td>179</td>
<td></td>
</tr>
<tr>
<td>IEEE-Northridge 90%</td>
<td>1137</td>
<td>1061</td>
<td>1385</td>
<td>440</td>
<td></td>
</tr>
<tr>
<td>IEEE-El Centro 50%</td>
<td>705</td>
<td>541</td>
<td>904</td>
<td>208</td>
<td></td>
</tr>
<tr>
<td>IEEE-El Centro 90%</td>
<td>1230</td>
<td>1273</td>
<td>1459</td>
<td>456</td>
<td></td>
</tr>
<tr>
<td>IEEE-Landers 50%</td>
<td>648</td>
<td>415</td>
<td>905</td>
<td>167</td>
<td></td>
</tr>
<tr>
<td>IEEE-Landers 75%</td>
<td>1055</td>
<td>730</td>
<td>1422</td>
<td>351</td>
<td></td>
</tr>
</tbody>
</table>

Table 5.7.13 Force Amplification Factors (FAF)

<table>
<thead>
<tr>
<th>Input Signal</th>
<th>Force Amplification Factor (FAF)</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>East Tower</td>
<td>West Tower</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fz</td>
<td>Fy</td>
<td>Fz</td>
<td>Fy</td>
<td></td>
</tr>
<tr>
<td>IEEE-Northridge 50%</td>
<td>1.99</td>
<td>3.98</td>
<td>3.30</td>
<td>0.63</td>
<td></td>
</tr>
<tr>
<td>IEEE-Northridge 90%</td>
<td>3.57</td>
<td>9.44</td>
<td>5.30</td>
<td>1.55</td>
<td></td>
</tr>
<tr>
<td>IEEE-El Centro 50%</td>
<td>2.33</td>
<td>4.89</td>
<td>3.43</td>
<td>0.75</td>
<td></td>
</tr>
<tr>
<td>IEEE-El Centro 90%</td>
<td>4.11</td>
<td>11.56</td>
<td>5.59</td>
<td>1.62</td>
<td></td>
</tr>
<tr>
<td>IEEE-Landers 50%</td>
<td>2.16</td>
<td>3.67</td>
<td>3.46</td>
<td>0.61</td>
<td></td>
</tr>
<tr>
<td>IEEE-Landers 75%</td>
<td>3.51</td>
<td>6.45</td>
<td>5.44</td>
<td>1.27</td>
<td></td>
</tr>
</tbody>
</table>
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Figure 5.7.15 Comparison of Force Amplification Factors from different tests
These results show that the force response of the east tower to IEEE-El Centro record at both magnitude scales is consistently higher than the response to the other input records. This difference is more obvious between the East Tower Fy responses for which the FAF obtained from IEEE-El Centro seismic loading is 23% higher than that obtained from IEEE-Northridge seismic loading. This considerable difference is an important observation since the records used for these tests have all similar response spectra and hence similar frequency content, and elucidates the sensitivity of the system to other characteristics of the ground motion not clearly identified in the response and frequency spectra. This indicates that the time domain characteristic of the seismic loading could play an important role in the force response of the conductor. These results also show that the Fz response to IEEE-Landers at 75% is very close to its response to IEEE-Northridge at 90%. This is despite the fact that the amplitude of the latter record is about 20% higher than that of the former one. This again indicates the importance of the time domain characteristics of the seismic loading in the response of the system.

To find out a relation between the generated forces and the response of the towers, dynamic force-displacement hysteresis loops were plotted (Figures 5.7.16 and 5.7.17). These diagrams show that Fz at each tower peaks when the displacement of the same tower reaches its maximum value (Figure 5.7.16). However it does not necessarily peak when the towers reach their maximum displacement relative to each other. This indicates that the horizontal force response at each tower is highly dependent on the displacement response of the same tower, and that this force could reach its maximum value even if the conductor is not experiencing its maximum stretch or compression. Results also show no specific pattern in the Fy force-displacement response of the towers (Figure 5.7.17). This indicates that the Fy response at each tower is dependent on the response of both towers. In other words the vertical force response at each tower is affected by the response of the adjacent tower.

To investigate critical load combinations at each tower, Fz is plotted against Fy (Figure 5.7.18). The results show that Fz and Fy could reach their maximum value at the same time. This indicates that the maximum horizontal and vertical forces could affect the
equipment simultaneously. Detailed spectral analysis on the measured forces is included in Chapter 6.
Figure 5.7.16  Fz - displacement hysteresis loops - Test 29
Figure 5.7.17  Fy - displacement hysteresis loops - Test 29
Figure 5.7.18  Fz vs. Fy for East and West Towers - Test 29
5.8 Flexible Conductor Test Set-up 2

The purpose of flexible conductor test set-up 2 was to observe the behaviour of the conductor under bidirectional seismic loadings. The input signals used for this set-up were the generated earthquake records applied at low amplitude in both the E-W and N-S directions.

5.8.1 Description of the set-up

This test set-up is a modification of set-up 1. The modification to the specimen consisted of removing the bracing of the west tower.

5.8.2 Instrumentation

The responses measured in this test set-up were similar to those of set-up 1. Only the arrangement of the accelerometers on the conductor was modified in order to measure the acceleration of the conductor along the N-S direction. The N-S horizontal forces in the conductor connections (Fx) were also measured by using the same load cells that measured other force components. Figure 5.8.1 shows the instrumentation plan for this test set-up and Table 5.8.1 shows the measured responses.
Table 5.8.1 Measured responses in test set-up 2

<table>
<thead>
<tr>
<th>Col No</th>
<th>Ch No.</th>
<th>Type of Response</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>Table E-W Displacement</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>Table N-S Displacement/West Side</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td>Table N-S Displacement/East Side</td>
</tr>
<tr>
<td>4</td>
<td>3</td>
<td>East Side Extension Cantilever Beams Tip Vertical Displacement</td>
</tr>
<tr>
<td>5</td>
<td>4</td>
<td>West Side Extension Cantilever Beams Tip Vertical Displacement</td>
</tr>
<tr>
<td>6</td>
<td>5</td>
<td>East Side Extension Cantilever Beams Tip Horizontal N-S Acceleration</td>
</tr>
<tr>
<td>7</td>
<td>6</td>
<td>West Side Extension Cantilever Beams Tip Horizontal N-S Acceleration</td>
</tr>
<tr>
<td>8</td>
<td>7</td>
<td>West Tower N-S Acceleration</td>
</tr>
<tr>
<td>9</td>
<td>8</td>
<td>West Tower E-W Acceleration/South Side</td>
</tr>
<tr>
<td>10</td>
<td>9</td>
<td>West Tower E-W Acceleration/North Side</td>
</tr>
<tr>
<td>11</td>
<td>10</td>
<td>Conductor Acceleration Normal to Conductor/Centre South Side</td>
</tr>
<tr>
<td>12</td>
<td>11</td>
<td>Conductor Acceleration N-S/East North Side</td>
</tr>
<tr>
<td>13</td>
<td>12</td>
<td>Conductor Acceleration Normal to Conductor/East North Side</td>
</tr>
<tr>
<td>14</td>
<td>13</td>
<td>Conductor Acceleration N-S/Centre North Side</td>
</tr>
<tr>
<td>15</td>
<td>14</td>
<td>Conductor Acceleration Normal to Conductor/Centre North Side</td>
</tr>
<tr>
<td>16</td>
<td>15</td>
<td>Conductor Acceleration Along the Conductor/Centre North Side</td>
</tr>
<tr>
<td>17</td>
<td>16</td>
<td>East Tower E-W Displacement</td>
</tr>
<tr>
<td>18</td>
<td>17</td>
<td>Vertical Force Fy - Conductor Connection to East Tower</td>
</tr>
<tr>
<td>19</td>
<td>18</td>
<td>Horizontal Force Fz - Conductor Connection to East Tower</td>
</tr>
<tr>
<td>20</td>
<td>19</td>
<td>East Tower N-S Acceleration</td>
</tr>
<tr>
<td>21</td>
<td>20</td>
<td>East Tower E-W Acceleration</td>
</tr>
<tr>
<td>22</td>
<td>21</td>
<td>West Tower E-W Displacement</td>
</tr>
<tr>
<td>23</td>
<td>22</td>
<td>Vertical Force Fy - Conductor Connection to West Tower</td>
</tr>
<tr>
<td>24</td>
<td>23</td>
<td>Horizontal Force Fz - Conductor Connection to West Tower</td>
</tr>
<tr>
<td>25</td>
<td>24</td>
<td>Conductor Acceleration N-S/West North Side</td>
</tr>
<tr>
<td>26</td>
<td>25</td>
<td>East Tower E-W Acceleration/North Side</td>
</tr>
<tr>
<td>27</td>
<td>26</td>
<td>Horizontal Force Fx - Conductor Connection to East Tower</td>
</tr>
<tr>
<td>28</td>
<td>27</td>
<td>Horizontal Force Fx - Conductor Connection to West Tower</td>
</tr>
<tr>
<td>29</td>
<td>28</td>
<td>Table N-S Acceleration/East Side</td>
</tr>
<tr>
<td>30</td>
<td>29</td>
<td>Table N-S Acceleration/West Side</td>
</tr>
<tr>
<td>31</td>
<td>30</td>
<td>Table E-W Acceleration</td>
</tr>
</tbody>
</table>
Figure 5.8.1 Instrumentation Plan for Set-up 2
5.8.3 Test Sequence

For test set-up 2 only the input records which were generated from Northridge and El Centro records were used. The input signals were used in both E-W and N-S directions simultaneously. They were applied at low amplitudes since the extension cantilever beams were not originally designed to take large transverse forces. The maximum amplitude was chosen at 35% in each direction and there was no phase lag between the two signals. This is equivalent to the same record being applied at 50% magnitude with 45° degree angle from the E-W direction. Before each bidirectional test, one uni-axial test for each direction was carried out. Test sequence for the set-up 2 is shown in Table 5.8.2.
Table 5.8.2 Test Sequence for Set-up 2

<table>
<thead>
<tr>
<th>Test No.</th>
<th>Test Description</th>
<th>Input Signal</th>
<th>Amplitude</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Frequencies of Interconnected Towers E/W</td>
<td>Sinusoidal E/W</td>
<td>0.2g</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>Damping of Interconnected Towers E/W</td>
<td>Step Force I E/W</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>3</td>
<td>Damping of Interconnected Towers E/W</td>
<td>Step Force II E/W</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>4</td>
<td>Frequencies of Interconnected Towers N/S</td>
<td>Sinusoidal N/S</td>
<td>0</td>
<td>0.2g</td>
</tr>
<tr>
<td>5</td>
<td>Damping of Interconnected Towers N/S</td>
<td>Step Force I N/S</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>6</td>
<td>Damping of Interconnected Towers N/S</td>
<td>Step Force II N/S</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>7</td>
<td>Seismic Loading</td>
<td>IEEE-Northridge</td>
<td>18%</td>
<td>0%</td>
</tr>
<tr>
<td>8</td>
<td>Seismic Loading</td>
<td>IEEE-Northridge</td>
<td>0%</td>
<td>18%</td>
</tr>
<tr>
<td>9</td>
<td>Seismic Loading</td>
<td>IEEE-Northridge</td>
<td>18%</td>
<td>18%</td>
</tr>
<tr>
<td>10</td>
<td>Seismic Loading</td>
<td>IEEE-Northridge</td>
<td>35%</td>
<td>0%</td>
</tr>
<tr>
<td>11</td>
<td>Seismic Loading</td>
<td>IEEE-Northridge</td>
<td>0%</td>
<td>35%</td>
</tr>
<tr>
<td>12</td>
<td>Seismic Loading</td>
<td>IEEE-Northridge</td>
<td>35%</td>
<td>35%</td>
</tr>
<tr>
<td>13</td>
<td>Seismic Loading</td>
<td>IEEE-El Centro</td>
<td>18%</td>
<td>0%</td>
</tr>
<tr>
<td>14</td>
<td>Seismic Loading</td>
<td>IEEE-El Centro</td>
<td>0%</td>
<td>18%</td>
</tr>
<tr>
<td>15</td>
<td>Seismic Loading</td>
<td>IEEE-El Centro</td>
<td>18%</td>
<td>18%</td>
</tr>
<tr>
<td>16</td>
<td>Seismic Loading</td>
<td>IEEE-El Centro</td>
<td>35%</td>
<td>0%</td>
</tr>
<tr>
<td>17</td>
<td>Seismic Loading</td>
<td>IEEE-El Centro</td>
<td>0%</td>
<td>35%</td>
</tr>
<tr>
<td>18</td>
<td>Seismic Loading</td>
<td>IEEE-El Centro</td>
<td>35%</td>
<td>35%</td>
</tr>
<tr>
<td>19</td>
<td>Frequencies of Interconnected Towers E/W</td>
<td>Sinusoidal E/W</td>
<td>0.2g</td>
<td>0</td>
</tr>
<tr>
<td>20</td>
<td>Damping of Interconnected Towers E/W</td>
<td>Step Force I E/W</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>21</td>
<td>Damping of Interconnected Towers E/W</td>
<td>Step Force II E/W</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>22</td>
<td>Frequencies of Interconnected Towers N/S</td>
<td>Sinusoidal N/S</td>
<td>0</td>
<td>0.2g</td>
</tr>
<tr>
<td>23</td>
<td>Damping of Interconnected Towers N/S</td>
<td>Step Force I N/S</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>24</td>
<td>Damping of Interconnected Towers N/S</td>
<td>Step Force II N/S</td>
<td>N/A</td>
<td>N/A</td>
</tr>
</tbody>
</table>

5.8.4 Test Results

Since the main objective of performing tests on the set-up 2 was to investigate the magnitude of forces generated when the actual ground motion is not only in the direction of the conductor, only a summary of the force responses is presented here. The comparison of these forces with the forces obtained from set-up 1 is included in Chapter 7. Table 5.8.3 shows the maximum absolute force response at the conductor connections obtained from this test set-up. Table 5.8.4 presents the resultant of the horizontal forces.
(Fz and Fx) calculated by using the Square Root of Sum of the Squares (SRSS) rule of combination.

**Table 5.8.3 Maximum absolute force response**

<table>
<thead>
<tr>
<th>Bidirectional Input Signal</th>
<th>Maximum Absolute Dynamic Force (N)</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>East Tower</td>
<td>Fz</td>
<td>Fx</td>
<td>Fy</td>
<td></td>
</tr>
<tr>
<td>IEEE-Northridge 35%</td>
<td>397</td>
<td>204</td>
<td>271</td>
<td></td>
<td></td>
</tr>
<tr>
<td>IEEE-El Centro 35%</td>
<td>273</td>
<td>215</td>
<td>145</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Table 5.8.4 Resultant horizontal forces**

<table>
<thead>
<tr>
<th>Bidirectional Input Signal</th>
<th>Maximum Absolute Dynamic Force (N)</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>East Tower</td>
<td>Fy</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>West Tower</td>
<td>SRSS of Fz and Fx</td>
<td>Fy</td>
<td></td>
<td></td>
</tr>
<tr>
<td>IEEE-Northridge 35%</td>
<td>447</td>
<td>271</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IEEE-El Centro 35%</td>
<td>348</td>
<td>145</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
5.9 Flexible Conductor Test Set-up 3

The first mode natural frequencies of the interconnected equipment configuration 2 are 1.1 and 3.4 Hz. So there is 2.3 Hz difference between their first mode natural frequencies. However, the first mode natural frequencies of the towers used as equivalent equipment in set-up 1 were 3.4 and 2.85 Hz which were 0.55 Hz different. So the towers were modified so that their natural frequencies would be more different. This was to study the effect of frequency difference between the towers on the results. Comparing the results of these tests with the results of set-up 1 would provide a better insight into the interaction between the conductor and the equipment.

5.9.1 Description of the set-up

To achieve the above mentioned goal, the first mode natural frequency of the East Tower was increased. This was achieved by removing 5 of the 8 plates of the East Tower which decreased its mass and therefore increased its natural frequency. Everything else was similar to test set-up 1 and the bracings of the West Tower which were removed for test set-up 2 were connected again for this set-up.

5.9.2 Instrumentation

Instrumentation for this set-up was similar to that of set-up 1 with a few differences. A list of responses measured in this set-up is presented in Table 5.9.1. Figure 5.9.1 shows the instrumentation plan.
Figure 5.9.1 Instrumentation plan for test set-up 3
Table 5.9.1 Responses measured from the set-up 3

<table>
<thead>
<tr>
<th>Col No</th>
<th>Ch No</th>
<th>Type of Response</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>Table E-W Displacement</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>Table N-S Displacement/West Side</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td>Table N-S Displacement/East Side</td>
</tr>
<tr>
<td>4</td>
<td>3</td>
<td>East Side Extension Cantilever Beams Tip Vertical Displacement</td>
</tr>
<tr>
<td>5</td>
<td>4</td>
<td>West Side Extension Cantilever Beams Tip Vertical Displacement</td>
</tr>
<tr>
<td>6</td>
<td>5</td>
<td>East Side Extension Cantilever Beams Tip Horizontal N-S Acceleration</td>
</tr>
<tr>
<td>7</td>
<td>6</td>
<td>West Side Extension Cantilever Beams Tip Horizontal N-S Acceleration</td>
</tr>
<tr>
<td>8</td>
<td>7</td>
<td>West Tower N-S Acceleration</td>
</tr>
<tr>
<td>9</td>
<td>8</td>
<td>West Tower E-W Acceleration/South Side</td>
</tr>
<tr>
<td>10</td>
<td>9</td>
<td>West Tower E-W Acceleration/North Side</td>
</tr>
<tr>
<td>11</td>
<td>10</td>
<td>Conductor Acceleration Normal to the Conductor Axes/West South Side</td>
</tr>
<tr>
<td>12</td>
<td>11</td>
<td>Conductor Acceleration Normal to the Conductor Axes/East South Side</td>
</tr>
<tr>
<td>13</td>
<td>12</td>
<td>Conductor Acceleration Normal to the Conductor Axes/East North Side</td>
</tr>
<tr>
<td>14</td>
<td>13</td>
<td>Conductor Acceleration Normal to the Conductor Axes/N-S Direction/Centre</td>
</tr>
<tr>
<td>15</td>
<td>14</td>
<td>Conductor Acceleration Normal to the Conductor Axes/Centre</td>
</tr>
<tr>
<td>16</td>
<td>15</td>
<td>Conductor Acceleration Along the Conductor Axes/Centre</td>
</tr>
<tr>
<td>17</td>
<td>16</td>
<td>East Tower E-W Displacement</td>
</tr>
<tr>
<td>18</td>
<td>17</td>
<td>Vertical Force Fy - Conductor Connection to East Tower</td>
</tr>
<tr>
<td>19</td>
<td>18</td>
<td>Horizontal Force Fz - Conductor Connection to East Tower</td>
</tr>
<tr>
<td>20</td>
<td>19</td>
<td>East Tower N-S Acceleration</td>
</tr>
<tr>
<td>21</td>
<td>20</td>
<td>East Tower E-W Acceleration/South Side</td>
</tr>
<tr>
<td>22</td>
<td>21</td>
<td>West Tower E-W Displacement</td>
</tr>
<tr>
<td>23</td>
<td>22</td>
<td>Vertical Force Fy - Conductor Connection to West Tower</td>
</tr>
<tr>
<td>24</td>
<td>23</td>
<td>Horizontal Force Fz - Conductor Connection to West Tower</td>
</tr>
<tr>
<td>25</td>
<td>24</td>
<td>Conductor Acceleration Normal to the Conductor Axes/West North Side</td>
</tr>
<tr>
<td>26</td>
<td>25</td>
<td>East Tower E-W Acceleration/North Side</td>
</tr>
<tr>
<td>27</td>
<td>26</td>
<td>Horizontal Force Fx - Conductor Connection to East Tower</td>
</tr>
<tr>
<td>28</td>
<td>27</td>
<td>Horizontal Force Fx - Conductor Connection to West Tower</td>
</tr>
<tr>
<td>29</td>
<td>28</td>
<td>Table N-S Acceleration/East Side</td>
</tr>
<tr>
<td>30</td>
<td>29</td>
<td>Table N-S Acceleration/West Side</td>
</tr>
<tr>
<td>31</td>
<td>30</td>
<td>Table E-W Acceleration</td>
</tr>
</tbody>
</table>
5.9.3 Test Sequence

The same test sequence as for test set-up 1 was used for this set-up too. However the less severe records with BC Hydro target spectrum were not used. The test sequence is shown in Table 5.9.2.

<table>
<thead>
<tr>
<th>Test No.</th>
<th>Test Description</th>
<th>Input Signal</th>
<th>Amplitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Frequencies of Interconnected Towers</td>
<td>Sinusoidal</td>
<td>0.2g</td>
</tr>
<tr>
<td>2</td>
<td>Damping of Interconnected Towers</td>
<td>Step Force</td>
<td>N/A</td>
</tr>
<tr>
<td>3</td>
<td>Damping of Interconnected Towers</td>
<td>Step Force</td>
<td>N/A</td>
</tr>
<tr>
<td>4</td>
<td>Seismic Loading</td>
<td>IEEE-Northridge</td>
<td>50%</td>
</tr>
<tr>
<td>5</td>
<td>Seismic Loading</td>
<td>IEEE-Northridge</td>
<td>90%</td>
</tr>
<tr>
<td>6</td>
<td>Seismic Loading</td>
<td>IEEE-El Centro</td>
<td>50%</td>
</tr>
<tr>
<td>7</td>
<td>Seismic Loading</td>
<td>IEEE-El Centro</td>
<td>90%</td>
</tr>
<tr>
<td>8</td>
<td>Seismic Loading</td>
<td>IEEE-Landers</td>
<td>50%</td>
</tr>
<tr>
<td>9</td>
<td>Seismic Loading</td>
<td>IEEE-Landers</td>
<td>75%</td>
</tr>
<tr>
<td>10</td>
<td>Frequencies of Interconnected Towers</td>
<td>Sinusoidal</td>
<td>0.2g</td>
</tr>
<tr>
<td>11</td>
<td>Damping of Interconnected Towers</td>
<td>Step Force</td>
<td>N/A</td>
</tr>
<tr>
<td>12</td>
<td>Damping of Interconnected Towers</td>
<td>Step Force</td>
<td>N/A</td>
</tr>
</tbody>
</table>

5.9.4 Test Results

Test results from test set-up 3 are presented in a similar fashion to that of set-up 1. A comparison between the results from these two set-ups is done in chapter 7.

5.9.4.1 Resonance Frequencies

The resonance frequencies of the interconnected towers are presented in Table 5.9.3. As shown in Section 5.7.4.1, the resonance frequencies of the interconnected towers can be considered as their natural frequencies. So the natural frequency of the new East Tower was obtained by identifying its resonance frequency from this test set-up. Table 5.9.3
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shows that a difference of 1.74 Hz was achieved between the natural frequencies of the towers.

<table>
<thead>
<tr>
<th>Equivalent Equipment</th>
<th>Resonance Frequencies of the Interconnected Towers (Hz)</th>
<th>First Mode Natural Frequencies of the Stand-Alone Towers (Hz)</th>
<th>% Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>East Tower</td>
<td>4.59</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>West Tower</td>
<td>2.85</td>
<td>2.88</td>
<td>1</td>
</tr>
</tbody>
</table>

5.9.4.2 Acceleration Response

The presentation of acceleration response for set-up 3 is similar to that of set-up 1. Figures 5.9.2 and 5.9.3 present sample acceleration time-histories obtained from Test 5. Tables 5.9.4 and 5.9.5 present peak acceleration responses and amplification factors of the towers. Tables 5.9.6 to 5.9.8 show the peak acceleration responses of the conductor at its instrumented locations (Figure 5.9.1).
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Figure 5.9.2 Shake table and towers accelerations - Test 5
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Figure 5.9.3 Conductor acceleration - Test 5

East North Side - Normal to Conductor

max = 6.69 g  min = -4.47 g

West North Side - Normal to Conductor

max = 4.89 g  min = -6.56 g

Centre North Side - Normal to Conductor

max = 4.39 g  min = -3.86 g

Centre North Side - Along the Conductor

max = 3.83 g  min = -3.44 g
Table 5.9.4 East Tower acceleration response

<table>
<thead>
<tr>
<th>Maximum Absolute Response</th>
<th>Input Signal</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>IEEE-Northridge 90%</td>
</tr>
<tr>
<td></td>
<td>IEEE-El Centro 90%</td>
</tr>
<tr>
<td></td>
<td>IEEE-Landers 75%</td>
</tr>
<tr>
<td>Acceleration (g)</td>
<td>East Tower</td>
</tr>
<tr>
<td></td>
<td>2.79</td>
</tr>
<tr>
<td></td>
<td>2.29</td>
</tr>
<tr>
<td></td>
<td>2.50</td>
</tr>
<tr>
<td></td>
<td>Shake Table</td>
</tr>
<tr>
<td></td>
<td>0.54</td>
</tr>
<tr>
<td></td>
<td>0.54</td>
</tr>
<tr>
<td></td>
<td>0.44</td>
</tr>
<tr>
<td>Amplification Factor</td>
<td>5.17</td>
</tr>
<tr>
<td></td>
<td>4.24</td>
</tr>
<tr>
<td></td>
<td>5.68</td>
</tr>
</tbody>
</table>

Table 5.9.5 West Tower acceleration response

<table>
<thead>
<tr>
<th>Maximum Absolute Response</th>
<th>Input Signal</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>IEEE-Northridge 90%</td>
</tr>
<tr>
<td></td>
<td>IEEE-El Centro 90%</td>
</tr>
<tr>
<td></td>
<td>IEEE-Landers 75%</td>
</tr>
<tr>
<td>Acceleration (g)</td>
<td>West Tower</td>
</tr>
<tr>
<td></td>
<td>1.86</td>
</tr>
<tr>
<td></td>
<td>2.19</td>
</tr>
<tr>
<td></td>
<td>1.92</td>
</tr>
<tr>
<td></td>
<td>Shake Table</td>
</tr>
<tr>
<td></td>
<td>0.54</td>
</tr>
<tr>
<td></td>
<td>0.54</td>
</tr>
<tr>
<td></td>
<td>0.44</td>
</tr>
<tr>
<td>Amplification Factor</td>
<td>3.44</td>
</tr>
<tr>
<td></td>
<td>4.06</td>
</tr>
<tr>
<td></td>
<td>4.36</td>
</tr>
</tbody>
</table>

Table 5.9.6 Conductor acceleration response to IEEE-Northridge 90%

<table>
<thead>
<tr>
<th>Location of the Transducer</th>
<th>Peak Acceleration Response (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Normal to the Conductor</td>
</tr>
<tr>
<td></td>
<td>East (Location 1)</td>
</tr>
<tr>
<td>North Side</td>
<td>6.70</td>
</tr>
<tr>
<td>South Side</td>
<td>4.06</td>
</tr>
<tr>
<td>Average</td>
<td>5.38</td>
</tr>
<tr>
<td>Amplification Factor</td>
<td>9.96</td>
</tr>
</tbody>
</table>
Table 5.9.7 Conductor acceleration response to IEEE-El Centro 90%

<table>
<thead>
<tr>
<th>Location of the Transducer</th>
<th>Peak Acceleration Response (g)</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Normal to the Conductor</td>
<td>East (Location 1)</td>
<td>Centre (Location 2)</td>
<td>West (Location 3)</td>
</tr>
<tr>
<td>North Side</td>
<td>7.21</td>
<td>4.10</td>
<td>6.7</td>
<td>3.74</td>
</tr>
<tr>
<td>South Side</td>
<td>3.54</td>
<td>N/A</td>
<td>3.57</td>
<td>N/A</td>
</tr>
<tr>
<td>Average</td>
<td>5.38</td>
<td>4.10</td>
<td>5.14</td>
<td>3.74</td>
</tr>
<tr>
<td>Amplification Factor</td>
<td>9.95</td>
<td>7.59</td>
<td>9.51</td>
<td>6.68</td>
</tr>
</tbody>
</table>

Table 5.9.8 Conductor acceleration response to IEEE-Landers 75%

<table>
<thead>
<tr>
<th>Location of the Transducer</th>
<th>Peak Acceleration Response (g)</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Normal to the Conductor</td>
<td>East (Location 1)</td>
<td>Centre (Location 2)</td>
<td>West (Location 3)</td>
</tr>
<tr>
<td>North Side</td>
<td>7.17</td>
<td>4.52</td>
<td>6.8</td>
<td>3.60</td>
</tr>
<tr>
<td>South Side</td>
<td>3.63</td>
<td>N/A</td>
<td>3.64</td>
<td>N/A</td>
</tr>
<tr>
<td>Average</td>
<td>5.40</td>
<td>4.52</td>
<td>5.22</td>
<td>3.60</td>
</tr>
<tr>
<td>Amplification Factor</td>
<td>12.27</td>
<td>10.27</td>
<td>11.86</td>
<td>8.37</td>
</tr>
</tbody>
</table>
5.9.4.3 Displacement Response

Presentation of displacement response for set-up 3 is similar to the presentation of the results from set-up 1. Figures 5.9.4 and 5.9.5 show sample results. Table 5.9.9 summarizes the peak values of the displacement response of the towers. Displacements are relative to the shake table. Towers displacements relative to each other is also included. Table 5.9.10 summarizes the peak absolute displacement response of the conductor at the locations of the accelerometers (Figure 5.9.1).
Figure 5.9.4 Shake table and towers displacement - Test 5
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East North Side - Normal to Conductor

max = 139 mm  min = -179 mm

West North Side - Normal to Conductor

max = 188 mm  min = -159 mm

Centre North Side - Normal to Conductor

max = 42 mm  min = -52 mm

Centre North Side - Along the Conductor

max = 103 mm  min = -87 mm

Figure 5.9.5 Displacements of the conductor - Test 5
Table 5.9.9 Towers peak displacement response (mm)

<table>
<thead>
<tr>
<th>Location and Type of Response</th>
<th>Input Signal</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>IEEE-Northridge 90%</td>
</tr>
<tr>
<td>East Tower; Relative to Shake Table</td>
<td>31</td>
</tr>
<tr>
<td>West Tower; Relative to Shake Table</td>
<td>54</td>
</tr>
<tr>
<td>Towers; Relative to Each Other</td>
<td>70</td>
</tr>
</tbody>
</table>

Table 5.9.10 Conductor displacement response

<table>
<thead>
<tr>
<th>Input Signal</th>
<th>Location of the Transducer</th>
<th>Peak Displacement Response (mm)</th>
<th>Along the Axes of the Conductor</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Normal to the Conductor</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>East (Location 1)</td>
<td>Centre (Location 2)</td>
</tr>
<tr>
<td>IEEE-Northridge 90%</td>
<td>North Side</td>
<td>179</td>
<td>52</td>
</tr>
<tr>
<td></td>
<td>South Side</td>
<td>44</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td>Average</td>
<td>111</td>
<td>52</td>
</tr>
<tr>
<td>IEEE-El Centro 90%</td>
<td>North Side</td>
<td>160</td>
<td>57</td>
</tr>
<tr>
<td></td>
<td>South Side</td>
<td>45</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td>Average</td>
<td>103</td>
<td>57</td>
</tr>
<tr>
<td>IEEE-Landers 75%</td>
<td>North Side</td>
<td>148</td>
<td>60</td>
</tr>
<tr>
<td></td>
<td>South Side</td>
<td>36</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td>Average</td>
<td>92</td>
<td>60</td>
</tr>
</tbody>
</table>
5.9.4.4 Force Response

Results from the force response of the system are summarized similar to that of set-up 1. Comparison between the results from different set-ups is made in Chapter 7.

Table 5.9.11 Peak dynamic forces in the connections of the conductor

<table>
<thead>
<tr>
<th>Input Signal</th>
<th>East Tower</th>
<th></th>
<th>West Tower</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Fz</td>
<td>Fy</td>
<td>Fz</td>
<td>Fy</td>
</tr>
<tr>
<td>IEEE-Northridge 50%</td>
<td>738</td>
<td>404</td>
<td>820</td>
<td>160</td>
</tr>
<tr>
<td>IEEE-Northridge 90%</td>
<td>1327</td>
<td>1006</td>
<td>1491</td>
<td>437</td>
</tr>
<tr>
<td>IEEE-El Centro 50%</td>
<td>564</td>
<td>433</td>
<td>858</td>
<td>176</td>
</tr>
<tr>
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Table 5.9.12 Force Amplification Factors

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<td>Fy</td>
<td>Fz</td>
<td>Fy</td>
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Figure 5.9.6 Comparison of Force Amplification Factors from different tests
Chapter 5

Shake Table Tests

These results show the tendency of the system for higher response to IEEE-Landers record, even though its magnitude is lower than the other records. It can also be observed that in contrast to set-up 1, the response to IEEE-El Centro is not more severe than the response to the other records. Since all these records have similar response spectra, the difference indicates that the time domain characteristics of the ground motion could be important. A detailed comparison between these results and results obtained from set-up 1 is included in chapter 7.

Similar to set-up 1, to find out a relation between the generated forces and the response of the towers, dynamic force-displacement hysteresis loops were plotted (Figures 5.9.7 and 5.9.8). These diagrams are similar to those of set-up 1 (Figures 5.7.16 and 5.6.17) and thus the observations and comments on them are also consistent to those of set-up 1 (Section 5.7.5.4).

Also similar to set-up 1, in order to investigate critical load combinations at each tower, Fz is plotted against Fy (Figure 5.9.9). Similar to set-up 1, results show that Fz and Fy could reach their maximum value at the same time. This indicates that the maximum horizontal and vertical forces could affect the equipment simultaneously. Detailed spectral analysis on the measured forces is included in Chapter 6.
Figure 5.9.7 Fz - displacement hysteresis loops - Test 5
Figure 5.9.8 Fy - displacement hysteresis loops - Test 5
Figure 5.9.9 Towers Fz vs. Fy - Test 5
6.1 Introduction

This chapter provides further insight into the behaviour of the conductor and its interaction with the towers under seismic loading. The main goal is the identification of frequencies at which the force responses at the conductor connections are maximum and relate them to the modal characteristics of the system. This requires modal identification of the towers and the conductor and it is accomplished by performing spectral analysis, which is interpretation of data by using correlation and spectral density functions. The basic concepts of frequency domain analysis, which are the basis for spectral analysis, are described in Chapter 3.

6.2 Frequency Content of the Force Response

The first step towards finding the force response frequencies is to plot the power spectra of the force output signals. The preliminary results showed that there is no significant power for frequencies above 20 Hz, therefore the signal is conditioned with a lowpass filter at 20 Hz in order to clean it up from high frequency noise. The power spectra were estimated by using averaged periodograms with the help of Mathcad sheets developed for calculating and plotting the spectra as well as finding and sorting their peaks.

Figures 6.2.1 to 6.2.4 show the power spectra of the four force responses to all three input signals as well as the sinusoidal loading of the sine sweep test for the test set-up 1. The force responses are East Tower Fz and Fy and West Tower Fz and Fy. Figures 6.2.5 to 6.2.8 show the same results for set-up 3.
Figure 6.2.1 Force response power spectra, set-up 1, sinusoidal loading
Figure 6.2.2 Force response power spectra, set-up 1, IEEE-Northridge at 90%
Figure 6.2.3 Force response power spectra, set-up 1, IEEE-El Centro at 90%
Figure 6.2.4 Force response power spectra, set-up 1, Landers at 75%
Figure 6.2.5 Force response power spectra, set-up 3, sinusoidal
Figure 6.2.6 Force response power spectra, set-up 3, IEEE-Northridge at 90%
Figure 6.2.7 Force response power spectra, set-up 3, IEEE-El Centro at 90%
Figure 6.2.8 Force response power spectra, set-up 3, Landers at 75%
The peaks of the spectra in figures 6.2.1 to 6.2.8 show the frequencies at which the forces mainly respond to the excitation of the system. These frequencies are basically the resonance frequencies at which either the towers or the conductor respond. By examining the magnitude of the spectra at the mentioned frequencies, it is possible to find out what characteristic of the system is most influential in the amount of forces generated at the conductor connection points.

To make this examination, the magnitude and the corresponding frequency of the first four peaks from the presented spectra, excluding the ones obtained from sine sweep tests, are summarized and presented in Tables 6.2.1 and 6.2.2. To make more sense out of the tabulated numbers and in order to summarize the results of the power spectra, a normalized parameter is used. This parameter is introduced as the ratio of the magnitude of the spectrum at each frequency to the sum of the four magnitudes of the peaks. This ratio is called Participation Index (PI):

\[
PI = \frac{\text{power spectrum magnitude of a significant peak}}{\text{sum of the power spectrum magnitudes of all the significant peaks}} \tag{6.2.4}
\]

The contribution of the system response at each frequency in generating forces would easily be compared to each other by calculating PI at each of those frequencies. A value closer to 1.0 for PI indicates higher contribution of the corresponding system response in generating the corresponding forces. The values of PI are also shown in Tables 6.2.1 and 6.2.2. For easier comparison of PI for different force responses, the results are illustrated in Figures 6.2.9 and 6.2.10.
Table 6.2.1 PI for forces at the conductor connection to East Tower; set-up 1

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<th>Input Signal</th>
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<th>Power Spectrum Amplitude (g²/Hz)</th>
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Table 6.2.2 PI for forces at the conductor connection to West Tower; set-up 1

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<th>Power Spectrum Amplitude (g²/Hz)</th>
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Figure 6.2.9 PI for forces at conductor connection to East Tower; set-up 1
Figure 6.2.10 PI for forces at conductor connection to West Tower; set-up 1
As can be seen in the results, the $F_z$ responses, which are the horizontal forces at the connections of the conductor, are predominantly at the fundamental frequencies of the towers. The $F_z$ response at West Tower is at the fundamental frequency of the West Tower and the responses at other frequencies are negligible. Similarly, the $F_z$ response at East Tower is at the fundamental frequency of the tower and the responses at other frequencies are negligible. There is however one exception. That is the $F_z$ response at East Tower to IEEE-El Centro which has considerable magnitude at 5.78 Hz. As it is explained in section 6.3, this frequency is one of the other resonance frequencies of the West Tower. This result indicates that the horizontal forces measured at one tower could be affected by the response of the adjacent tower.

The $F_y$ responses however, do not respond only at the fundamental frequencies of the towers and have higher magnitudes at other frequencies. As it will be shown in Section 6.3, all the first four frequencies at which the force responses peak, are one of the resonance frequencies of the towers related to either a normal mode or a coupled mode of vibration. This shows that the behaviour of the conductor and the interaction of the conductor with the towers are such that the vibration of the towers mainly affect the forces induced in the connections of the conductor. It can also be observed that $F_y$ at each tower primarily responds at the fundamental frequency of the tower except for the $F_y$ response of the East Tower to IEEE-El Centro which is primarily affected by the vibration of the West Tower as can be seen in Figure 6.2.12. This indicates that the time domain characteristic of the ground motion could play a role in the interaction of the conductor with the equipment.

In order to further investigate the force and conductor acceleration response frequency contents, a similar analysis was carried out on the test results from test set-up 3, in which the natural frequency of the East Tower is higher than its corresponding value in test set-up 1. The results from both test set-ups reveal similar characteristics for the interaction between the conductor and the towers with minor differences. The results from set-up 3 are shown in Tables 6.2.3 and 6.2.4 and in Figures 6.2.12 and 6.2.13.
Table 6.2.3 PI for forces at the conductor connection to East Tower; set-up 3

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Table 6.2.4 PI for forces at the conductor connection to West Tower; set-up 3

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<td>26242</td>
<td>0.59</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4.59</td>
<td>9424</td>
<td>0.21</td>
</tr>
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<td></td>
<td></td>
<td>5.81</td>
<td>7394</td>
<td>0.17</td>
</tr>
<tr>
<td></td>
<td></td>
<td>7.48</td>
<td>1422</td>
<td>0.03</td>
</tr>
<tr>
<td></td>
<td><strong>Fz</strong></td>
<td>2.93</td>
<td>1896394</td>
<td>0.98</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4.59</td>
<td>32977</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5.81</td>
<td>3586</td>
<td>0.00</td>
</tr>
<tr>
<td></td>
<td></td>
<td>7.48</td>
<td>1599</td>
<td>0.00</td>
</tr>
</tbody>
</table>
East Tower $F_y$

- IEEE-Northridge 90%
- IEEE-El Centro 90%
- IEEE-Landers 75%

East Tower $F_z$

- IEEE-Northridge 90%
- IEEE-El Centro 90%
- IEEE-Landers 75%

Figure 6.2.11 PI for forces at conductor connection to East Tower; set up 3
Figure 6.2.12 PI for forces at conductor connection to West Tower; set-up 3
6.3 Frequency Content of the Acceleration Response of the Conductor

To further understand the relation between the responses of the towers, the response of the conductor and the generated forces at the conductor connections, the acceleration responses of the conductor are investigated. Examples of the power spectra obtained from acceleration response of the conductor at three locations on the conductor are shown in Figure 6.3.1. As can be seen, these results show that the significant peaks are at the same frequencies as the force responses are.

Next section discusses system identification, which involves identification of the resonance frequencies of the system in detail and deals with finding out why there is a peak at a particular frequency in the power spectra obtained from force and acceleration responses. More specifically, it is necessary to identify the system response at 5.78 an 6.34 Hz to determine whether each of these frequencies is a resonance frequency of one of the towers or a resonance frequency of the conductor or noise or numerical error.
Figure 6.3.1 Conductor acceleration power spectra – Test 29
It was mentioned in Chapter 5 that due to initial out-of-plane deformation of the conductor, considerable difference between the two normal accelerations measured on each location of the conductor was observed and therefore in order to estimate one value for the peak accelerations along the conductor, these two values at each location were averaged. In order to justify using the averaged number, this section presents the cross spectrum and coherence between the normal accelerations at East North and East South sides of the conductor, obtained from test 29 of set-up 1 (Figure 6.3.2). Results show that within the frequency range of interest, these two measurements are reasonably in phase (reasonable low phase angle between them). Thus it is reasonable to take their average as a single value representing the acceleration of the conductor at that location. Similar results were obtained for the accelerations at the other location of the conductor.
Figure 6.3.2 East North and West North accelerations of the conductor – Test 29
6.4 Resonance Frequency and Vibration Mode Identification

The method explained in Chapter 3, is used to identify the vibration modes of the test specimen. West tower was instrumented with two accelerometers on its top, which measured the horizontal absolute accelerations at the sides of the top plates. The responses measured by these two transducers were used to identify the modes associated to the peaks observed in the power spectra of the results. East tower was instrumented with one accelerometer for test set-up 1 and stand alone set-up. Another accelerometer was added to the tower of the test set-up 3 to obtain more information on the coupled modes of the East tower.

Figures 6.4.1 to 6.4.6 show the power spectra, the cross spectrum magnitude, the cross spectrum phase and the coherence function for the acceleration outputs of the towers which were obtained from various test set-ups subjected to sinusoidal loading. The power spectra of the two signals are plotted together. For stand alone set-up and set-up 1 only one power spectrum is estimated for the East Tower since it had only one accelerometer measuring its response.

A summary of the analysis is given in Tables 6.4.1 to 6.4.3. These tables show the resonance frequencies which are the frequencies at which both the power spectra and the cross spectrum magnitude peak. They also show the values of the phase and coherence corresponding to each of the resonance frequencies.

For example in Figure 6.4.3 which shows the spectra of the two acceleration response of the West Tower from the set-up 3, a very strong peak at 2.85 Hz can be identified with corresponding phase of 0° and coherence of 1. This frequency in fact is the fundamental natural frequency of the tower in its first transversal mode. The second peak is at 5.70 Hz with 136 degree phase between the two measurements and has a coherence value of 0.56. The values of the phase and coherence indicate that there is no clean normal mode at this frequency and there may be a coupled mode with coupling between transversal and torsional modes. The low value of coherence is most likely due to the nonlinearity in the relation between the measurements and not because of the existence of significant noise.
in them. This nonlinearity could be explained by the effect of the extension cantilever beams and the complex modes that they could introduce in the response of the towers. The third peak is at 6.34 Hz and has a relative phase angle of about 10 degrees and a coherence value of 0.85. This mode is reasonably acceptable as a clean normal mode. The fourth resonance frequency is 8.55 Hz. The phase angle between the two output signals is 175 degrees and their coherence is 0.98. This mode is an example of a torsional mode for the West Tower. Generally, what can be seen in Figure 6.4.3 is a clean response of the tower in its normal longitudinal mode to frequencies from 0.5 to 5.5 Hz, and not-so-clean response in coupled modes to frequencies from 5.5 to 10 Hz. There is no significant response to frequencies above 10 Hz. The results of the analysis performed on the East Tower for the same test set-up, as illustrated in Figure 6.4.4, show a better behaviour of the tower in its normal mode as a single degree of freedom system. This is because the tower has less of a tendency to respond in its torsional mode due to its concentrated mass. Note that there is a low amplitude peak at 5.7 Hz, which is the effect of the excitation of the West Tower carried to the East Tower through the conductor.

The results of the spectral analysis of the stand alone towers are given in table 6.4.3. These results identify the vibration modes of the towers without any influence of conductor on them and they show the natural frequencies of the towers. Figure 6.4.5 shows six peaks in the power spectrum of acceleration response of the West Tower, four of which match the resonance frequencies identified for other set-ups. The reason for too many peaks for the west tower in stand alone set-up is the existence of coupled modes with frequencies close to each other. Since these peaks have very low power, they might not show up when the towers are interconnected with the conductor.

Finally, there is a peak at 20 Hz in all the spectra. This peak presents nothing but noise since it is in the spectra of all the measured signals. The source of the noise is in the acquisition system used for recording data.
Figure 6.4.1 Modal identification of West Tower; set-up 1; sinusoidal loading
Figure 6.4.2 Modal identification of East Tower; set-up 1; sinusoidal loading
Figure 6.4.3 Modal identification of West Tower; set-up 3; sinusoidal loading
Figure 6.4.4 Modal identification of East Tower; set-up 3; sinusoidal loading
Figure 6.4.5 Modal identification of West Tower; stand alone; sinusoidal loading
Figure 6.4.6 Modal identification of East Tower; stand alone; sinusoidal loading

Table 6.4.1 Towers response mode identification; set-up 1

<table>
<thead>
<tr>
<th>Equivalent Equipment</th>
<th>Resonance Frequencies (Hz)</th>
<th>Relative Phase (deg)</th>
<th>Coherence</th>
<th>Description of the Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>West Tower</td>
<td>2.85</td>
<td>0</td>
<td>1.00</td>
<td>Normal Mode - Longitudinal</td>
</tr>
<tr>
<td></td>
<td>5.70</td>
<td>164</td>
<td>0.84</td>
<td>Coupled Mode</td>
</tr>
<tr>
<td></td>
<td>6.34</td>
<td>10</td>
<td>0.86</td>
<td>Normal Mode - Longitudinal</td>
</tr>
<tr>
<td></td>
<td>7.70</td>
<td>143</td>
<td>0.20</td>
<td>Coupled Mode</td>
</tr>
<tr>
<td>East Tower</td>
<td>3.45</td>
<td>0</td>
<td>1.00</td>
<td>Normal Mode - Longitudinal</td>
</tr>
<tr>
<td></td>
<td>5.71</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
</tbody>
</table>
### Table 6.4.2 Towers response mode identification; set-up 3

<table>
<thead>
<tr>
<th>Equivalent Equipment</th>
<th>Resonance Frequencies (Hz)</th>
<th>Relative Phase (deg)</th>
<th>Coherence</th>
<th>Description of the Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>West Tower</td>
<td>2.85</td>
<td>0</td>
<td>1.00</td>
<td>Normal Mode - Longitudinal</td>
</tr>
<tr>
<td>West Tower</td>
<td>5.70</td>
<td>136</td>
<td>0.56</td>
<td>Coupled Mode</td>
</tr>
<tr>
<td>West Tower</td>
<td>6.34</td>
<td>10</td>
<td>0.85</td>
<td>Normal Mode - Longitudinal</td>
</tr>
<tr>
<td>West Tower</td>
<td>8.55</td>
<td>175</td>
<td>0.98</td>
<td>Normal Mode - Torsional</td>
</tr>
<tr>
<td>East Tower</td>
<td>4.60</td>
<td>0</td>
<td>1.00</td>
<td>Normal Mode - Longitudinal</td>
</tr>
<tr>
<td>East Tower</td>
<td>5.70</td>
<td>0</td>
<td>1.00</td>
<td>N/A</td>
</tr>
</tbody>
</table>

### Table 6.4.3 Stand alone towers response mode identification

<table>
<thead>
<tr>
<th>Equivalent Equipment</th>
<th>Resonance Frequencies (Hz)</th>
<th>Relative Phase (deg)</th>
<th>Coherence</th>
<th>Description of the Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>West Tower</td>
<td>2.88</td>
<td>0</td>
<td>1.00</td>
<td>Normal Mode - Longitudinal</td>
</tr>
<tr>
<td>West Tower</td>
<td>5.76</td>
<td>65</td>
<td>0.63</td>
<td>Coupled Mode</td>
</tr>
<tr>
<td>West Tower</td>
<td>6.20</td>
<td>10</td>
<td>0.90</td>
<td>Normal Mode - Longitudinal</td>
</tr>
<tr>
<td>West Tower</td>
<td>6.80</td>
<td>167</td>
<td>0.80</td>
<td>Normal Mode - Torsional</td>
</tr>
<tr>
<td>West Tower</td>
<td>7.80</td>
<td>60</td>
<td>0.80</td>
<td>Coupled Mode</td>
</tr>
<tr>
<td>West Tower</td>
<td>8.63</td>
<td>82</td>
<td>0.40</td>
<td>Coupled Mode</td>
</tr>
<tr>
<td>East Tower</td>
<td>3.53</td>
<td>0</td>
<td>1.00</td>
<td>Normal Mode - Longitudinal</td>
</tr>
</tbody>
</table>

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6.5 Equipment-Conductor Interaction

The analysis of the stand alone towers revealed whether any of the resonance frequencies identified for the towers in set-ups 1 and 3 was caused by the response of the conductor at its resonance frequencies. This was especially the case for the west tower which showed numerous peaks in its power spectrum. Distinguishing the resonance frequencies of the towers from those of the conductor provides a better insight into the behaviour of the conductor and its interaction with the towers. The comparison of the identified resonance frequencies of the stand alone towers with those of the interconnected towers from other set-ups and with those of the conductor, reveals that all the identified resonance frequencies of the conductor coincide with the natural frequencies of the towers. Hence the resonance frequencies identified for the conductor are not independent from the vibration modes of the towers. The comparison of the resonance frequencies of the towers and the conductor with the frequency contents of the force responses shows that the response of the conductor at fundamental frequencies of the towers is mainly responsible for the horizontal dynamic forces (Fz) generated at its attachment points. However, the response of the conductor at frequencies corresponding to the coupled modes has a considerable effect in producing vertical forces (Fy) at its connections.

Although the performed analysis did not identify a specific natural frequency for the conductor due to the fact that the conductor does not have a well-determined natural frequency, it indicated the possibility of significant excitation of the conductor in the frequency range of interest due to its interaction with the equipment.
Chapter 7

Comparison of Results and Discussion

7.1 Introduction

In this chapter the results from various tests are compared, including comparison of forces obtained from quasi-static and dynamic tests, comparison of the response of the towers from stand-alone set up and the interconnected set-ups.

7.2 Comparison of Static and Dynamic Forces

As can be seen in Section 5.9.4.4, for test set-up 3 the horizontal forces in the connections of the conductor (Fz) reached a peak value of 1327 N at East Tower (Table 5.9.11). This force corresponds to a displacement of less than 30 mm for East Tower. The horizontal force at the same connection point of the conductor for the same level of displacement obtained from the quasi-static test (Chapter 4), is no more than 55 N which is 24 times less than the dynamic force of 1327 N. Similarly for test set-up 1, the comparison would be between a dynamic force of 1230 N (Section 5.7.5.4) and a static force of 75 N corresponding to a displacement of 40 mm, which shows that the dynamic force obtained from seismic tests is about 16 times more than the same force obtained from the quasi-static test. These are substantial differences and show that the magnitude of forces generated in the connections of the conductor due to dynamic behaviour of the conductor are much higher than the forces obtained by just considering its static behaviour. This finding indicates that it is not sufficient to determine the forces in the connections of the conductor statically by just considering the differential displacements of the equipment. Rather, the dynamic behaviour of the conductor must be taken into account in order to reach to a reasonable estimate of the forces induced on the equipment during an earthquake event.
Chapter 7  
Comparison of Results and Discussion

7.3 Effect of Conductor on the Response of the Towers

To find the effect of the conductor on the response of the towers, the acceleration and displacement response of the towers obtained from stand-alone towers set-up and set-up 1 are compared. Since the peak acceleration of the shake table were not exactly identical for the two set-ups, instead of the absolute accelerations themselves, the acceleration amplification factors (Tables 5.6.6, 5.6.7, 5.7.4 and 5.7.5) are used to compare the acceleration responses. Acceleration Response Ratio is defined as the ratio of the acceleration amplification factor of the towers obtained from set-up 1 to that of obtained from the stand-alone set-up. Displacement Response Ratio for each tower is defined as the peak relative displacement of the tower from set-up 1 to that of stand-alone towers set-up. Tables 7.3.1 to 7.3.4 show the results. These results show that in most cases, the conductor reduces the response of the towers. However, in one case, the response of the East Tower to IEEE-Landers record, the conductor amplified the response of the tower. This indicates that there is a possibility that interconnected equipment would have a more severe response compared to its stand-alone response. It also indicates the effect of the time domain characteristics of the record on the response of the system.

<table>
<thead>
<tr>
<th>Test Set-up</th>
<th>Acceleration Amplification Factor of East Tower</th>
<th>Input Signal</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>IEEE-Northridge 90%</td>
</tr>
<tr>
<td>Stand-Alone Towers</td>
<td>4.92</td>
<td>4.48</td>
</tr>
<tr>
<td>Set-up 1</td>
<td>3.72</td>
<td>3.13</td>
</tr>
<tr>
<td>Acceleration Response Ratio</td>
<td>0.76</td>
<td>0.70</td>
</tr>
</tbody>
</table>
Table 7.3.2 Acceleration Response Ratio for West Tower

<table>
<thead>
<tr>
<th>Test Set-up</th>
<th>Acceleration Amplification Factor of West Tower</th>
<th>Input Signal</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>IEEE-Northridge</td>
</tr>
<tr>
<td></td>
<td></td>
<td>90%</td>
</tr>
<tr>
<td>Stand-Alone Towers</td>
<td>4.40</td>
<td>4.35</td>
</tr>
<tr>
<td>Set-up 1</td>
<td>3.55</td>
<td>4.02</td>
</tr>
<tr>
<td>Acceleration Response Ratio</td>
<td>0.81</td>
<td>0.92</td>
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</table>

Table 7.3.3 Displacement Response Ratio for East Tower

<table>
<thead>
<tr>
<th>Test Set-up</th>
<th>Displacement of East Tower (mm)</th>
<th>Input Signal</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>IEEE-Northridge</td>
</tr>
<tr>
<td></td>
<td></td>
<td>90%</td>
</tr>
<tr>
<td>Atand-Alone Towers</td>
<td>52.00</td>
<td>48.00</td>
</tr>
<tr>
<td>Set-up 1</td>
<td>40.00</td>
<td>35.00</td>
</tr>
<tr>
<td>Displacement Response Ratio</td>
<td>0.77</td>
<td>0.73</td>
</tr>
</tbody>
</table>

Table 7.3.4 Displacement Response Ratio for West Tower

<table>
<thead>
<tr>
<th>Test Set-up</th>
<th>Displacement of West Tower (mm)</th>
<th>Input Signal</th>
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</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>IEEE-Northridge</td>
</tr>
<tr>
<td></td>
<td></td>
<td>90%</td>
</tr>
<tr>
<td>Stand-Alone Towers</td>
<td>66.00</td>
<td>63.00</td>
</tr>
<tr>
<td>Set-up 1</td>
<td>52.00</td>
<td>62.00</td>
</tr>
<tr>
<td>Displacement Response Ratio</td>
<td>0.79</td>
<td>0.98</td>
</tr>
</tbody>
</table>
7.4 Comparison of Forces Obtained from Set-ups 1 and 3

To study the effect of the frequency difference between the two towers on the magnitude of forces, tests on set-up 3 were carried out. In this section, a comparison is made between the results obtained from test set-ups 1 and 3 for different levels of the same input records. Table 7.4.1 shows the results, where the Force Amplification Factors (FAF) from the two set-ups are compared. The “% Change” indicates increase or decrease of FAF obtained from set-up 3 with respect to that obtained from set-up 1. The table shows that:

For East Tower:

- $F_z$ increased up to 38% when the input record was IEEE-Northridge or IEEE-Landers. It decreased down to 13% when the input record was IEEE-El Centro.
- $F_y$ increased up to 30% when the input record was IEEE-Landers and decreased down to 37% when the input record was IEEE-Northridge or IEEE-El Centro.

For West Tower:

- $F_z$ decreased down to 13%. However, the percentage of decrease is no more that 4% in most cases which indicates no significant change for $F_z$ at this tower. It never increased.
- $F_y$ increased up to 20% when the input record was IEEE-Landers and decreased down to 28% when the input record was IEEE-Northridge or IEEE-El Centro.

This comparison shows no specific trend towards increasing or decreasing of $F_z$ at the East Tower or $F_y$ at any one of the towers, although the East Tower in set-up 3 had higher natural frequency and less mass compared to the East Tower in set-up 1. This indicates that the frequency domain characteristics of the input records are not sufficient to predict the response of the system and indicates the importance of the time-domain characteristics of the input in the force response of the conductor at its connection points.
Table 7.4.1 does not show a very significant change in the Fz at the West Tower. This finding was expected since it was found that the response of West Tower has the major participation in the Fz response at the tower (Chapter 6).

Table 7.4.1 Comparison of forces obtained from test set-ups 1 and 3

<table>
<thead>
<tr>
<th>Input Signal</th>
<th>Set-up</th>
<th>Force Amplification Factor (FAF)</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>East Tower</td>
<td>West Tower</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Fz</td>
<td>Fy</td>
</tr>
<tr>
<td>IEEE-Northridge 50%</td>
<td>Set-up 1</td>
<td>1.99</td>
<td>3.30</td>
<td>0.63</td>
</tr>
<tr>
<td></td>
<td>Set-up 3</td>
<td>2.64</td>
<td>2.87</td>
<td>0.50</td>
</tr>
<tr>
<td></td>
<td>% Difference</td>
<td>32.7</td>
<td>-13.0</td>
<td>-20.6</td>
</tr>
<tr>
<td>IEEE-Northridge 90%</td>
<td>Set-up 1</td>
<td>3.57</td>
<td>5.30</td>
<td>1.55</td>
</tr>
<tr>
<td></td>
<td>Set-up 3</td>
<td>4.76</td>
<td>5.22</td>
<td>1.38</td>
</tr>
<tr>
<td></td>
<td>% Difference</td>
<td>33.3</td>
<td>-1.5</td>
<td>-11.0</td>
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<tr>
<td>IEEE-El Centro 50%</td>
<td>Set-up 1</td>
<td>2.33</td>
<td>3.43</td>
<td>0.75</td>
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<tr>
<td></td>
<td>Set-up 3</td>
<td>2.03</td>
<td>2.97</td>
<td>0.54</td>
</tr>
<tr>
<td></td>
<td>% Difference</td>
<td>-12.9</td>
<td>-13.4</td>
<td>-28.0</td>
</tr>
<tr>
<td>IEEE-El Centro 90%</td>
<td>Set-up 1</td>
<td>4.11</td>
<td>5.59</td>
<td>1.62</td>
</tr>
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<td></td>
<td>Set-up 3</td>
<td>3.75</td>
<td>5.37</td>
<td>1.37</td>
</tr>
<tr>
<td></td>
<td>% Difference</td>
<td>-8.8</td>
<td>-3.9</td>
<td>-15.4</td>
</tr>
<tr>
<td>IEEE-Landers 50%</td>
<td>Set-up 1</td>
<td>2.16</td>
<td>3.46</td>
<td>0.61</td>
</tr>
<tr>
<td></td>
<td>Set-up 3</td>
<td>2.99</td>
<td>3.45</td>
<td>0.73</td>
</tr>
<tr>
<td></td>
<td>% Difference</td>
<td>38.4</td>
<td>-0.3</td>
<td>19.7</td>
</tr>
<tr>
<td>IEEE-Landers 90%</td>
<td>Set-up 1</td>
<td>3.51</td>
<td>5.44</td>
<td>1.27</td>
</tr>
<tr>
<td></td>
<td>Set-up 3</td>
<td>4.69</td>
<td>5.39</td>
<td>1.39</td>
</tr>
<tr>
<td></td>
<td>% Difference</td>
<td>33.6</td>
<td>-0.9</td>
<td>9.4</td>
</tr>
</tbody>
</table>
7.5 Comparison of Forces Obtained from Set-ups 1 and 2

Set-up 2 was tested to include the transverse vibration of the conductor in this investigation and in order to study the magnitude of forces when the input motion is bidirectional. To compare the results of these tests with those obtained from set-up 1, resultant horizontal forces were calculated for the cases when input signals were at 35% amplitude in both E-W and N-S directions (Section 5.8.4). These input signals were equivalent to the same records being applied at 50% magnitude at an angle of 45° with the E-W direction. A comparison the resultant horizontal forces from these tests with the horizontal forces obtained from test set-up 1 subjected to the same input signals at 50% in E-W direction, shows whether it is necessary to consider bidirectional horizontal ground motions. A summary of this comparison is shown in Table 7.5.1. which shows that both horizontal and vertical forces obtained from bidirectional tests are significantly lower than those obtained from set-up 1. This observation indicates that for the given earthquake records at the given magnitude, the highest magnitude of forces generated at the connections of the conductor to the equipment were obtained when the direction of motion was along the direction of the conductor. Thus it is not necessary to consider further the bidirectional horizontal ground motions as far as critical loading conditions are concerned.
Table 7.5.1 Comparison of forces obtained from test set-ups 1 and 2

<table>
<thead>
<tr>
<th>Input Signal</th>
<th>Set-up</th>
<th>Peak Dynamic Force [N]</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>East Tower</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Horizontal Force</td>
<td></td>
<td>Vertical Force</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>IEEE-El Centro 35%</td>
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<tr>
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CHAPTER 8
CONCLUSIONS AND RECOMMENDATIONS

8.1 Summary
In past earthquakes it has been observed that electrical substation equipment interconnected by flexible conductors are susceptible to damage under seismic loading. They have shown to be vulnerable despite the fact that the flexible conductors have enough slack which allows the equipment to experience displacement without facing any significant resistance from the conductor. The flexible conductors do not apply significant load on the equipment if the behaviour of the system is analysed statically. However, it has been observed that the conductor applies much larger forces on the equipment due to its significant dynamic response under seismic loadings. Since these forces could be one of the reasons for the failure of the equipment, it became necessary to investigate the dynamic behaviour of the flexible conductors and their interaction with the equipment and estimate the magnitude forces induced by the conductor on the equipment under anticipated earthquakes. This research also investigated the possibility of the amplification of the response of the equipment due to presence of the conductor because if the interconnected equipment itself responds at higher amplitude compared to its stand-alone response, it experiences higher inertia forces compared to what it is designed for.

In this study, the mentioned investigation was carried out through a series of experimental tests including a quasi-static test on one of the commonly used configuration of conductors and four series of shake table tests on large-scale equivalent models of the equipment and the full-scale flexible conductor. The input records used for the shake table tests were synthetic records generated from three different earthquake records to fit prescribed response spectra. The quasi-static test provided information on the static behaviour of the conductor. The dynamic tests included uni-axial (horizontal) shake table tests on the stand-alone equivalent equipment as well as uni-axial tests on two set-ups for the interconnected ones. A series of bidirectional tests was also included. The
comparison of the results obtained from stand-alone set-up with those obtained from interconnected set-ups provided information on the effect of the conductor on the response of the equipment. Testing of various interconnected set-ups provided insight into the magnitude of forces generated at the connections of the conductor to the equipment under seismic loading. The results of dynamic tests provided insight into the dynamic behaviour of the conductor and its interaction with the equipment either directly or by performing spectral analysis.

8.2 Conclusions

The main conclusions of this study are:

- The presence of the conductor could decrease or amplify the response of the equipment subjected to strong ground motion, depending on characteristics of the record. This means that the interconnected equipment can experience higher inertia forces compared to its stand-alone state. It should also be realized that characteristics other than frequency content and peak acceleration of the ground motion can play an important role in the response of the equipment.

- The dynamic forces generated at the connections of the conductor to the equipment have much higher magnitude compared to those ones obtained statically. Thus the dynamic interaction of the conductor with the equipment should be considered in evaluating the earthquake-induced forces on the equipment and it is not adequate to estimate it only from static principles.

- The horizontal dynamic force response at the connection of the conductor to any one of the interconnected equipment items is primarily affected by the response of the same equipment item, while the vertical force response is dependent on the response of both interconnected equipment items.
Chapter 8

Conclusions and Recommendations

- It has been shown that it is not necessary to conduct bidirectional horizontal seismic tests because horizontal and vertical forces generated in the connections of the conductor under bidirectional seismic loadings did not exceed the forces obtained when the uni-axial loadings with the same magnitude were used.

- The study on the interaction of the conductor with the towers showed that the conductor responded at the natural frequencies of the towers. These results, although did not show any obvious natural frequency for the conductor at which it would respond to the seismic excitation, indicated the importance of the interaction between the conductor and the equipment and the dependence of the response of the conductor to the natural frequencies and response of the equipment.

- The methodology used in this study can be used as a guideline for studying the flexible conductors with other configurations explained in Chapter 1.

8.3 Recommendations

- To study the effect of vertical seismic loading on the behaviour of the conductor and its interaction with the equipment, it is recommended that a similar investigation be carried out by performing bidirectional shake table tests comprising of vertical table motion combined with the horizontal one in the direction of the conductor.

- An in-depth analytical study on the seismic behaviour of the conductor as a system with two inputs and multiple outputs could give more information about its vibration characteristics and its interaction with the equipment.
• Due to variety of flexible conductors, numerical studies on the behaviour of the conductor and its interaction with the equipment are recommended. The experimental data of this study can be used for calibrating the numerical models.

• If more precise estimation of forces is desired, testing of the full scale interconnected equipment and flexible conductor could be considered as an option. It is recommended however, that first, the sensitivity of forces to vertical seismic loading be investigated to find the most critical combination of input motions that would be used for the tests.
REFERENCES


APPENDIX A

INSTRUMENTATION DETAILS
Transducer Type: Accelerometer
Brand Name: FC Sensor Model 3140-005
Serial Number: 3B 12743
Sensitivity: 400 mV/g
Location Used: West Tower; E-W Direction

Transducer Type: Piezoelectric Accelerometer
Brand Name: PCB Model 320B41
Serial Number: PCB 23539
Sensitivity: 100 mV/g
Location Used: Conductor

Transducer Type: Piezoelectric Accelerometer
Brand Name: PCB Model 320B41
Serial Number: PCB 23360
Sensitivity: 100 mV/g
Location Used: Conductor

Transducer Type: Piezoelectric Accelerometer
Brand Name: Kistler Model 8628A5
Serial Number: C85648
Sensitivity: 1 V/g
Location Used: Conductor

Transducer Type: Piezoelectric Accelerometer
Brand Name: Kistler Model 8628A5
Serial Number: C85552
Sensitivity: 1 V/g
Location Used: Conductor

Transducer Type: Piezoelectric Accelerometer
Brand Name: Kistler Model 8628A5
Serial Number: C85647
Sensitivity: 1 V/g
Location Used: Conductor

Transducer Type: Piezoelectric Accelerometer
Brand Name: Kistler Model 8628A5
Serial Number: C85661
Sensitivity: 1 V/g
Location Used: Conductor
Transducer Type: Displacement - String Pot
Brand Name: Celsco Model PT101-10
Serial Number: A09267
Sensitivity: 94.75mV/V/inch
Location Used: East Tower

Transducer Type: Accelerometer
Brand Name: IC Sensor Model 3021
Serial Number: 1873-048
Sensitivity: 10 mV/g
Location Used: East Tower N-S Direction

Transducer Type: Accelerometer
Brand Name: IC Sensor Model 3021
Serial Number: 1873-026
Sensitivity: 10 mV/g
Location Used: East Tower E-W Direction

Transducer Type: Displacement - String Pot
Brand Name: Celsco Model PT101-10
Serial Number: A09292
Sensitivity: 94.75mV/V/inch
Location Used: West Tower

Transducer Type: Load Cell
Brand Name: AMTI Model MC5
Serial Number: M3253
Sensitivity: 1.894 mV/V-lbf
Location Used: East Tower Fy

Transducer Type: Load Cell
Brand Name: AMTI Model MC5
Serial Number: M3253
Sensitivity: 0.501 mV/V-lbf
Location Used: East Tower Fz

Transducer Type: Load Cell
Brand Name: AMTI Model MC5
Serial Number: M3253
Sensitivity: 0.501 mV/V-lbf
Location Used: East Tower Fx
Transducer Type: Load Cell
Brand Name: AMTI Model MC5
Serial Number: M3254
Sensitivity: 1.871 mV/V-lbf
Location Used: West Tower Fy

Transducer Type: Load Cell
Brand Name: AMTI Model MC5
Serial Number: M3254
Sensitivity: 0.496 mV/V-lbf
Location Used: West Tower Fz

Transducer Type: Load Cell
Brand Name: AMTI Model MC5
Serial Number: M3254
Sensitivity: 0.501 mV/V-lbf
Location Used: West Tower Fx

Transducer Type: LVDT
Brand Name: TRANS TEK Model 243-000
Serial Number: 2360
Sensitivity: ±0.5 in @ 7.5 V
Location Used: East Extension Cantilever Beams

Transducer Type: LVDT
Brand Name: TRANS TEK Model 243-000
Serial Number: 2359
Sensitivity: ±0.5 in @ 7.5 V
Location Used: West Extension Cantilever Beams

Transducer Type: Accelerometer
Brand Name: IC Sensor 2g Model 3110
Serial Number: 3B11070
Sensitivity: 1 V/g
Location Used: East Extension Cantilever Beams

Transducer Type: Accelerometer
Brand Name: IC Sensor 10g Model 3140-010
Serial Number: 3B13378
Sensitivity: 0.2 V/g
Location Used: West Extension Cantilever Beams
Transducer Type: Accelerometer  
Brand Name: IC Sensor 2g Model 3110  
Serial Number: 3B11072  
Sensitivity: 1 V/g  
Location Used: West Tower N-S Direction

Transducer Type: Accelerometer  
Brand Name: IC Sensor 10g Model 3140-005  
Serial Number: 3B12742  
Sensitivity: 400 mV/g  
Location Used: West Tower E-W Direction

Transducer Type: Piezoelectric Accelerometer  
Brand Name: PCB Model 320B41  
Serial Number: PCB 23542  
Sensitivity: 100 mV/g  
Location Used: Conductor

Transducer Type: Accelerometer  
Brand Name: Cross Bow  
Serial Number: 25749  
Sensitivity: 500 mV/g  
Location Used: East Tower

Transducer Type: Load Cell  
Brand Name: A-Tech Model LPU-10k  
Serial Number: 103816  
Sensitivity: 10000 lb @ 2.8148 mV/V  
Location Used: Conductor – Quasi-static Test
APPENDIX B

DRAWINGS
Geometry of the Conductor and Location of the Accelerometers

\[ x_0 := -35 \quad y_0 := 3736 \]
\[ x_1 := -10 \quad y_1 := 3736 \]
\[ x_2 := 75 \quad y_2 := 3710 \]
\[ x_3 := 160 \quad y_3 := 3664 \]
\[ x_4 := 285 \quad y_4 := 3566 \]
\[ x_5 := 725 \quad y_5 := 3057 \]
\[ x_6 := 765 \quad y_6 := 2999 \]
\[ x_7 := 1030 \quad y_7 := 2700 \]
\[ x_8 := 1153 \quad y_8 := 2620 \]

\[ x_9 := 1465 \quad y_9 := 2535 \]
\[ x_{10} := 1600 \quad y_{10} := 2545 \]
\[ x_{11} := 1800 \quad y_{11} := 2585 \]
\[ x_{12} := 2217 \quad y_{12} := 2790 \]
\[ x_{13} := 2442 \quad y_{13} := 2895 \]
\[ x_{14} := 2570 \quad y_{14} := 2927 \]
\[ x_{15} := 2665 \quad y_{15} := 2942 \]
\[ x_{16} := 2705 \quad y_{16} := 2942 \]
NAME: 5CB  
(East Tower)

4 BOLTS  
FOR  
FASTENING  
ONLY

WELDING  
DIRECTLY  
TO  
BOTTOM  
LAYER

118.11" LONG  
2.756" DIAMETER  
SOLID ROUND BAR  
WITH MIN YIELD  
STRENGTH \(\geq\)  
50,000 PSI  
ASTM A29  
GRADE 1040

WELDING

16 BOLTS  
DIAMETER  
\(\frac{3}{4}''\)

Not to scale
BASE PLATE B P 2 - LAYOUT

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**FIELD BOLTS**

**SOLID ROCK STEEL**

**CUSTOMER**: U.B.C

**NAME OF STRUCTURE**: SHAKE TABLE

**LOCATION**: OKAWKA, B.C

**TITLE OF DRAWING**: SUPPORTING BEAMS

**DRAWN BY**: A.

**DATE**: 1/2/01

**CHECKED BY**: A.

**DATE**: 1/2/01

**CONTRACT NO.**: 1357

**SIZE**: 3'
### Field Bolts

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<td>A</td>
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**SOLID ROCK STEEL**

- **Material:** 350 W
- **Holes:** 8 G unless noted
- **Paint:** One coat of
- **Contract No.:** U.B.S.
- **Enums:** SHAKE TABLE

**Location:**

**Title of Drawing:** BEAMS

**Drawn by:** AH
**Date:** Jan 12/01

**Checked by:**

**Date:** 1357

---

---

192
FIELD BOLTS

FBE 35 9 SPACES @ 130 = 1170 35
FBE 35 8 SPACES @ 130 = 1040 35

ONE ~ EB1 C 250 x 23 x 1240
ONE ~ EB2 C 250 x 23 x 1110

SOLID ROCK STEEL

FBE ONE C 250 x 23 1240 62
FBE TWO C 250 x 23 1110 56

CUSTOMER
U.S.C

NAME OF STRUCTURE SHAKE TABLE

LOCATION

TITLE OF DRAWING END CHANNELS

DRAWN BY

CHECKED BY

CONTRACT

END NO.

1367 EB
APPENDIX C

SELECTED TEST RESULTS
Set-up 1, Test 31

Shake Table

East Tower

West Tower

East North Side - Normal to Conductor
Set-up 1, Test 33
Set-up 3, Test 7
East Tower

West Tower Relative to East Tower

East North Side - Normal to Conductor

West North Side - Normal to Conductor
Set-up 3, Test 9