การศึกษาการตอบสนองของอาคารต่อการสั่นสะเทือนของพื้นดินโดยประเมินจากการสั่นสะเทือนที่เกิดขึ้นตามธรรมชาติ

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A STUDY OF BUILDING RESPONSE TO GROUND VIBRATION: AMBIENT VIBRATION APPROACH

Mr. Sang Ping

A Thesis Submitted in Partial Fulfillment of the Requirements
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การศึกษาการตอบสนองของอาคารต่อการสั่นสะเทือนของพื้นดินโดยประเมินจากการสั่นสะเทือนที่เกิดขึ้นตามธรรมชาติ (A STUDY OF BUILDING RESPONSE TO GROUND VIBRATION: AMBIENT VIBRATION APPROACH) อ.ที่ปรึกษาวิทยานิพนธ์หลัก: รศ.ดร.ฐิรวัตร บุญญะฐี, 142 หน้า

การก่อสร้างในเมืองมีข้อจำกัดด้านขนาดของพื้นที่และข้อกำหนดเกี่ยวกับความปลอดภัยและผลกระทบต่ออาคารข้างเคียงที่มีอยู่เดิม ดังนั้นจึงจำเป็นต้องวางแผนการจัดการอย่างเหมาะสม สำหรับการควบคุมความเสียหายต่ออาคารเดิมที่เกิดจากการสั่นสะเทือนของการก่อสร้างนั้นจะทำได้ด้วยการปรับเปลี่ยนคุณสมบัติของปัจจัยหลักสามประการซึ่งได้แก่ แหล่งกำเนิด ตัวกลางที่คลื่นสั่นสะเทือนเดินทางผ่าน และ อาคารที่ได้รับผลกระทบจากการสั่นสะเทือน โดยการศึกษาในวิทยานิพนธ์นี้มีความเกี่ยวข้องกับปัจจัยข้างต้นประการสุดท้ายโดยมีวัตถุประสงค์เพื่อพัฒนาวิธีการประเมินผลตอบสนองของอาคารที่จะเกิดขึ้นเมื่อได้รับการสั่นสะเทือนจากพื้นดินโดยใช้ฟังก์ชันถ่ายโอน ฟังก์ชันถ่ายโอนแสดงถึงสัดส่วนระหว่างสัญญาณส่งออกต่อสัญญาณรับเข้าในโดเมนความถี่ของระบบเชิงเส้น สำหรับการสั่นสะเทือนทางพื้นดินนั้น สัญญาณส่งออกและสัญญาณรับเข้าเทียบได้กับการสั่นสะเทือนของอาคารและของพื้นดินตามลำดับ ในการศึกษานี้ได้ใช้ผลการตรวจวัดการสั่นสะเทือนตามธรรมชาติจากสองตำแหน่งพร้อมกันเพื่อสร้างฟังก์ชันถ่ายโอน หลังจากนั้นจึงได้ทวนสอบความถูกต้องของฟังก์ชันถ่ายโอนที่ได้โดยเทียบกับผลการตรวจวัดการตอบสนองของอาคารเดียวกันเมื่อได้รับแรงสั่นสะเทือนจากการรื้อถอนอาคารที่อยู่ใกล้กัน จากการศึกษาพบว่าผลประเมินมีค่าต่ำกว่าที่วัดได้จริงเล็กน้อย อย่างไรก็ตามพบว่าผลประเมินมีความสอดคล้องกับค่าที่วัดได้จริง

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In urban area where space is limited, it is unavoidable for construction works to be carried out near to existing structures. In such situation, the increasing risk of vibration-induced damage on the buildings can be seen and has to be managed appropriately. To alleviate the problem, there are three areas that measures can be taken: vibration sources, propagation mediums, and buildings subjected to vibration. This study focused on the last factor and tried to evaluate how buildings respond to ground motions by determining their transfer functions. The transfer function (TF) is the ratios between the output and input in frequency domain of a linear system. For ground-borne vibrations, the system is the soil through which elastic wave propagates and the output is the motion at any location of interest, for instance, on the surface or within the ground or anywhere in building subjected to vibration. In this study, two-point measurements of ambient vibration were used to derive a transfer function between ground and building motions. Then, the obtained function was used to predict the response of the same building against vibration due to the demolition of nearby structures. By verification with vibration generated by a demolition work, the measured Peak Particle Velocities seem to be slightly underestimated by the proposed method. Nonetheless, the study showed that ambient vibration can be used to predict the building response with a moderate degree of determination.

Department: Civil Engineering Student's Signature
Field of Study: Civil Engineering Advisor's Signature
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CONTENTS

LIST OF TABLES

Page

LIST OF FIGURES

CHAPTER I

INTRODUCTION

1.1 Background Review

In the history of structure, every building was built to serve some specific purpose and duration. But after the completion of construction, building may get destroyed before its expected life. There are two major loads that can be counted as the causes of this damage: static load and dynamic load. The frequent damage that cause by static load is settlement and the damage caused by dynamic load can be vast, such as sudden settlement, cracking on walls, falling parts of building, etc. The common sources of encounter dynamic loads can be classified into two main categories: natural phenomena (earthquakes, volcanic eruptions, sea wave, landslides, etc.) and manmade (explosions, machinery, traffic, trains, construction activities, etc.). Unlike the natural phenomena, damage caused by manmade vibration is an avoidable event. Of all the manmade vibration, construction vibrations and traffic vibration are of the greatest concern in the urban area. After Siskind (1981) the operation under construction vibration can potentially cause damage to building at distance of less than 7.5 m from the source. Extreme care must be taken when sustained pile driving occurs within 7.5 m, of any building, and 15-30 m of a historical building, or building in poor condition.

Days after days, the number of population keep growing, and therefore the land use for residential becomes smaller and smaller and this have forced every construction need to be built in a tiny place. Demolition and replacement of old building, constructions of new building next to an existing building are unavoidable. And there is no exception for the construction and circulation of traffic. Since then, many problems have occurred within this construction environment. Here below are some aspects of the existing problems that may occur in every urban area.

1.1.1 Construction Vibration

Most construction operations are the sources of harmful vibrations that can cause a serious damage to surrounding building. Common sources of construction vibration are blasting, building demolition, pile driving, dynamic compaction, and heavy equipment operation. The effects of these construction activities rang from nuisance for the local resident and disturbance of working conditions for sensitive devices, to diminution of structure serviceability and durability. Concerning to the problem of vibration coming from construction operation, many studies have been conducted by many researcher namely Dowding, C. H. (1996), Svinkin M. R. (1997), David Harrison (2009), Amick et al (2000)., etc. Svinkin (2004) concluded that ground vibration coming from construction sources may affect adjacent and remote structures in three major ways as follows: structure vibrations, resonant structure response, and dynamic settlements.

Another point of view of the construction vibration caused damage to building is soil excavation associated with pile driving. Dowding (1996) suggested taking into account the accumulated effect of repeated dynamic loads, for example from production pile driving. This approach is especially important for historic and old buildings. Lacy and Gould (1985) concluded that increasing the number of driven piles can change a situation from insignificant vibration effects to damaging settlements.

1.1.2 Traffic induced vibration

There is no exception for traffic construction and traffic circulation. As many building construction have bloom up in cities, therefore, to ensure the smooth running of traffic, new road construction need to be built and even close to the existing building. Like most vibration problems, traffic vibrations can be characterized by a source-path-receiver scenario (Figure 1-1). Traffic vibration can easily generate dynamic loads on pavements while vehicles contact with irregularities in road surface such as potholes, cracks and uneven manhole covers. These loads generate stress waves, which propagate in soil, eventually reach adjacent building foundation. Traffic vibrations are mainly caused by heavy vehicles such as buses and trucks. When a bus or truck strikes an irregularity in the road surface, it generates the impact load and an oscillation load due to the subsequence “axle hop” of the vehicle. The impact load generates ground vibrations that are predominant at the natural frequency of soil. If the natural frequencies of the soil coincide with any of the natural frequencies of building structures or its components, resonance occurs and vibration will be amplified. The possibility of causing damage to building is getting high when the resonance occurs. For the same reason, according to Institute for Research in Construction together with National Research Council of Canada (NRC-CNRC), at the natural frequencies, the soil, like any structural system, offers the least resistance and hence the greatest response to loads. Building components usually have residual strains as a result of uneven soil movement, moisture and temperature cycles, poor maintenance or past renovations and repairs.

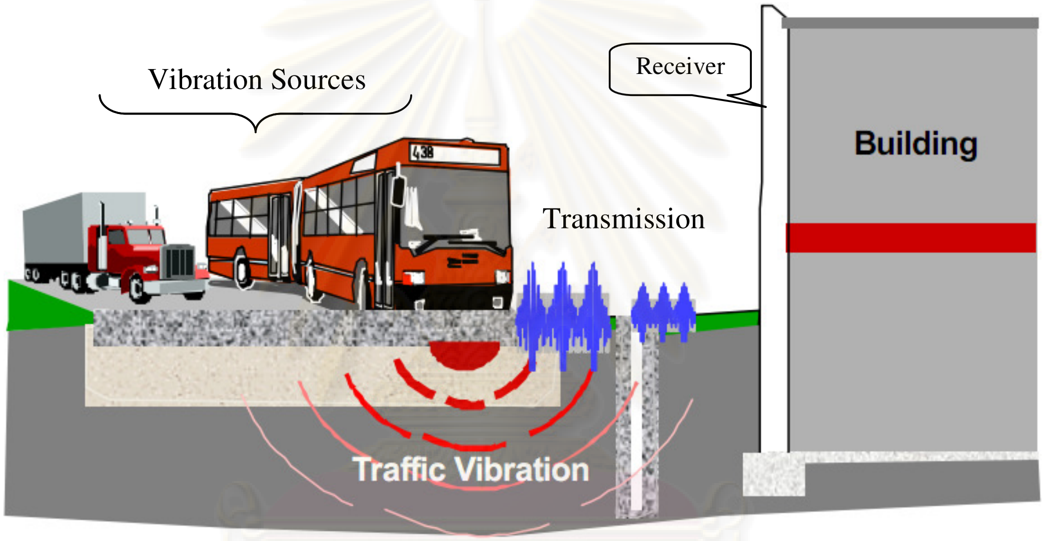


Figure 1-1 Scenario of Traffic Induced Vibration (Modify after ESI ENGINEERING, INC)

Therefore, small vibration levels induced by road traffic could trigger damage by “topping up” residual strains. From the same source, it is said that traffic vibrations are worst in areas underlain by a soft clay soil layer in the depth between 7 and 15 m. And this case seems too much sensitive for the subsoil of the Bangkok area as the subsoil in Bangkok area is underlain mostly by the soft clay.

1.2 Existing Standard

After having reviewed the above problems, it seems that those activities have lent itself slowly into the illegal act. In today’s legal environment, protecting those activities from fraudulent or errant claims is important. In this case a standard or law for the legal acts of those activities is needed. It is quite hard to have a unique standard of vibration control between countries and countries. But at less each country should have its own local standard to apply in its region and this is about what that many agencies in Thailand are trying to achieve. Some existing vibration standards that have been practicing in many counties around the world are DIN 4150, ISO 4866:1990(E), cet.

In effort to deal with problem cause by vibration, many Thai Government Agencies and Authorities have paid much attention on the influence of vibrations on surrounding buildings and now they are on the way to publish their own standard.

1.3 Research Motivation

Poor engineering properties of thick clay layer near the top surface and the scarcity of land in Bangkok necessitates the use of pile foundations for nearly all type of constructions. New constructions and replacement of old buildings in urban area entail the use of such pilling in close proximity to existing structures. It is the fact that vibration generated by the construction activities can sometime become a harmful to the nearby building. As the generated vibration can cause serious damage to the existing building, argument which can lead the construction need to be suspended between the property's owner and the contractor is frequently occurred. Another point of view of concerning vibration is the vibration that coming from the traffic. The heavy vehicles such as trucks, bus, and train or sky-train have always generated the vibration that should take into consideration of vibration control. There is an increasing need of vibration control to minimize the vibration effects imposed by construction activities. The dynamic effects of construction vibration can be assessed before the beginning of construction activities and at the time of construction. As construction vibration can cause damage to the existing building, monitoring of construction vibrations need to be started prior to the beginning of construction work at a site and be continued during construction to provide safety and serviceability of sound and vulnerable structure.

In today legal environment, protecting building from the construction vibrations become a must thing to be done for the government agencies. To protect all existing buildings to the vibration, standard of vibration control need to be established and enforced by the government agencies to prohibit some harmful construction activities and to limit the velocity of a specific weight of vehicle. To be able to create a standard of vibration control, government agencies need a lot of data. But unfortunately, there have very few data to support the to-be-established values to make it justify for the domestic practitioner and constructor. In order to fully understand and take control on the generated vibration, many category of vibration need to be study such as a study on the source of vibration, a study of the attenuation of vibration through various medium and finally a study of vibration transmitted from the traveling medium to the building. So to contribute to the inadequate data, the author would prefer to conduct a study on the vibration that transfer from the ground to the foundation of RC building by determining the Transfer Function using Ambient Vibration Approach (AVA).

1.4 Research Objectives

The objectives of this study are:

1. To define the Transfer Function of vibration from the ambient vibration and from the active source (dropping hammer onto the ground).
2. To predict the building response to ground vibration cause by the demolition of an old building.
3. To evaluate the applicability of ambient vibration and active vibration in predicting the building response.
4. To build up the data base for further research to establish the standard use for Vibration Control.
5. To use as the guideline for further research on vibration control.

1.5 Scope of Study

The scopes of this study are cover with the items below:

1. To perform a Nondestructive Test on RC building by conduction the Ambient Vibration Survey (AVS).
2. The determination the Transfer Function of building by using ambient vibration will be shown.
3. The concept (Convolution) of Digital Signal Processing (DSP) will be use as the method to define the Transfer Function:

$$X[n]*H[n]=Y[n] \tag{1-1}$$

$$H[n]=\frac{Y[n]}{X[n]} \tag{1-2}$$

where X[n]: the input signal

Y[n]: the output signal

H[n]: the transfer function

1.6 Research outcome

From this study, the author expects some benefits as below:

1. The response of building can be predicted from the Transfer Function.
2. Transfer function can determine form the ambient vibration.
3. The result from vibration investigation can be confidentially used and keep as a research document for Vibration Control in Thailand.
4. The procedure of vibration investigation will be introduce and use as the guidance for further research.
5. The application of impulse response is introduced to civil engineering community in Thailand.

CHAPTER II

LITERATURE REVIEW

2.1 Introduction

There are many aspects of vibrations sources in our daily life. For instance, the vibration cause by natural phenomena such as turbulent of wind flow, eruption of volcano, and earthquake...etc. On the other hand, several of vibration sources have been evoke by the human activities such as vibration coming from rotating machinery, circulation of traffic along the road and the vibration coming from construction activities: pile driving, building demolition, and dynamic compaction, etc. The problems of vibration have been known and studied for many centuries. Over the years, the use of vibration principles to understand and design systems has seen considerably grow in the diversity of systems that are designed with vibration in mind: mechanical, aerospace, electromechanical and micro-electromechanical devices and systems, biomechanical systems, ships and submarines, and civil structures (Balakumar Balachandran & Edward B. Magrab, 2004).

2.2 Impulse Response Function

To overcome how the building will exited when it is subjected to ground vibration, many studies and method have been proposed and conducted. The impulse response function prediction method (IRFP) is first proposed by Mark R. Svinkin in 1996. The Impulse Response Function (IRF) is base on the utilization of the impulse response technique for predicting complete vibration records on existing soils, buildings and equipment prior to installation of construction and industrial vibration sources. The impulse response function (IRF) in an output signal of the system base on a single instantaneous impulse input. Impulse response functions are applied in the analysis of any complicated linear dynamic system with unknown internal structure for which its mathematical description is very difficult. In the case under consideration, the dynamic system is the soil medium through which waves propagate outward from sources of construction and industrial vibrations. The input of the system is the ground at the place of pile driving, dynamic compaction of soil, or installation of a machine foundation; the output is a location of interest situated on the surface or inside the soil, or any point at a building subjected to vibrations. The outcomes can be obtained, for example, as the vibrations records of displacements or velocities at locations of interest.

Impulse response functions of considered dynamic system are determined by setting up an experiment in Figure (2-1). Such an approach:

- Does not require routine soil boring, sampling, or testing at site where waves propagate from the vibration source,
- Eliminates the need to use mathematical models of soil profiles, foundation and soil structures in practical applications, and
- Provides the flexibility of considering heterogeneity and variety of soil and structural properties.

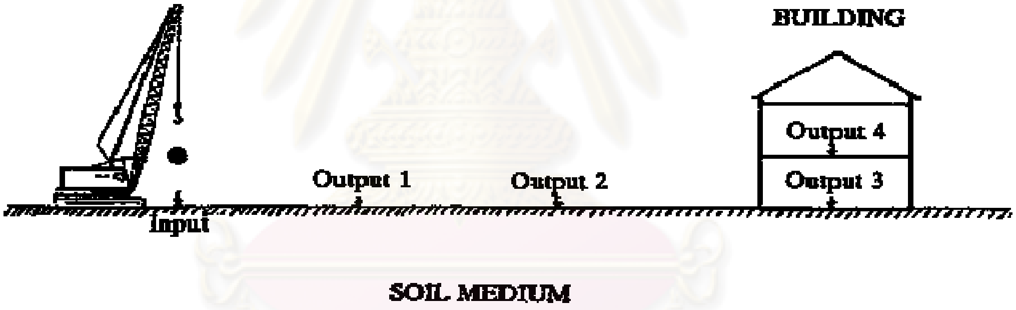


Figure 2-1 Experimental determination of impulse response function (After Mark R. Svinkin 1999)

To overcome in the research, some assumptions are needed. Here below are the assumptions in the Mark R. Svinkin's work to derive the (IRF) are:

1. Machine foundations and soil are linear system;
2. Impacts directly on the soil can be used for determining the impulse response functions; and
3. The dimensions of foundation contact area are considered not affect soil oscillations except within a limited field around foundation.

The general outlines of Mark R. Svinkin's work are as follow:

1. At the place of impact field for installation of the impact source, impacts of know magnitude are applied onto the ground (Figure 2-1). The impact can be created using a rigid *steel sphere or pear-shaped mass falling from a bridge or mobile crane*. At the moment of the impact onto the ground, oscillations are measured and recorded at the points of interest, for example, at the location of devices sensitive to vibration. These oscillations are the IRFs of the treated system which automatically take into account complicated soil conditions.
2. Various ways are used to determine the dynamic loads on the ground form different vibration sources. For pile driving, dynamic loads are computed by wave equation analysis. In the case of operation of machines on foundations, these loads can be found using existing foundation dynamics theories. For dynamic compaction sites, loads from the source are easily calculated with known falling weights and heights.
3. Duhamel's integral is used to compute predicted vibrations, which will arise after impact of the source.

In order to get the Impulse Response Function (IRF), it is required a rigid steel sphere or pear-shaped mass dropping from a bridge or mobile crane. This requirement may be difficult to perform in the tiny place like urban area. By take the advantage of ambient vibration, in this research, the author would like to determine the (IRF) from the ambient vibration by assuming that ambient vibration is the excitation source of soil – building system.

2.3 Ambient Vibration

Various types of vibration sources are always producing so called *Ambient Vibrations* on the Earth ground (also called *ambient noise*). These vibrations are mostly surface waves (Rayleigh waves, Love waves) propagating on the surface. Low frequency waves (below 1 Hz) are generally called microseisms and high frequency waves (above 1 Hz) are called micro-tremors. These ambient vibrations are used in practice to derive the elastic properties of the ground and the low-strain dynamic properties of civil-engineering structures (bridges, buildings, dams...). This information is useful for different purposes : fundamental seismology, engineering seismology, Earthquake engineering, Seismic microzonation, Structural health monitoring, but also Hydrology, Geotechnical Engineering, etc.

2.3.1 Physical Origin of Ambient Vibrations

After Bonnefoy-Claudet (2006), the source of ambient vibration at low frequency (below 1 Hz) comes from the ocean waves and large scale atmospheric phenomena. At high frequency (above 1 Hz), the wave field is mainly produced by human activities (road traffic, industrial work...) but there are also natural sources like rivers. Around 1 Hz, the local atmospheric conditions (wind...) are also major sources of ground vibrations. The amplitude of ground ambient vibrations is typically in the range of 1e-6 m/s. Peterson (1993) provided high and low noise models as a function of frequency. The ambient wave field is made of a small amount of body waves (P- and S-waves), and a most generally predominant part of surface waves, i.e. Love and Rayleigh waves. Theses waves are dispersive, i.e. their phase velocity varies with frequency (most generally, it decreases with increasing frequency). The dispersion curve (phase velocity or slowness as a function of frequency) is tightly related with the variations of the shear-wave velocity with depth in the different ground layers: it can thus be used as a non-invasive tool to investigate the underground structure.

2.3.2 History of the Use of Ambient Vibration

Ground ambient vibrations have very low amplitudes and cannot be felt by humans. Their amplitude was also too low to be recorded by the first seismometers at the end of 19th century. However, at that time, the famous Japanese seismologist F. Omori could already record ambient vibrations in buildings, where the amplitudes are magnified. He found their resonance frequencies and studied their evolution as a function of damage. After the 1933 Long Beach earthquake in California, a large experiment campaign led by Carder in 1935 allowed to record and analyzes ambient vibrations in more than 200 buildings. These data were used in the design codes to estimate resonance frequencies of buildings but the interest of the method went down until the 1950s. The interest on ambient vibrations in structures rose again thanks to famous earthquake engineers, especially in California and Japan (G. Housner, D. Hudson, K. Kanai and T. Tanaka...). Ambient vibrations were however supplanted - at least for some time - by forced vibration techniques that allow increasing the amplitudes and controlling the shaking source and their system identification methods. Even if Trifunac showed as early as 1972 that ambient and forced vibrations led to the same results, the interest in ambient vibration techniques rose again only in the late 1990s. The relatively low-cost and easiness of implementation, the improvement of the recording material and of the computation opportunities make these techniques very popular nowadays, especially as the low-strain dynamic characteristics they provide were shown to be close enough to the measured dynamic characteristics under strong shaking, at least as long as the buildings are not severely damages (Dunand, F. et al 2006). The use of noise recordings on the ground started in the 1950s with the enhancement of seismometers to monitor nuclear tests and the development of seismic arrays. The main contributions at that time for the analysis of these recordings came from the Japanese seismologist K. Aki in 1957 who first proposed the methods used nowadays (Spatial Autocorrelation method -SPAC-, Frequency-wave number -FK- method, correlation method...). However, the practical implementation of these methods was not possible at that time because of the low precision of clocks in seismic stations. Again, the opportunities of computations and the enhancements in the recording material led to a rise of interest in the 1990s. The first widely implemented method, rediscovered by Nakamura in 1989 is the Horizontal to Vertical Spectral Ratio (H/V) method to derive the resonance frequency of sites. In the late 1990s (Matshushima, T., and H. Okada 1990, Milana, G. et al 1996, Tokimatsu, K. , H. Arai, and Y. Asaka 1996, Chouet, B. 1998, among many others), the array methods on ambient vibration data started to allow deriving the ground properties in terms of shear waves velocity profiles. The European Research project SESAME (http://sesame-fp5.obs.ujf-grenoble.fr/index.htm) (2004-2006) was one of the first structured attempts to standardize the use of ambient vibrations to retrieve the properties of the ground, in the aim of estimating site amplifications in case of earthquake (site effects).

2.3.3 Current Use of Ambient Vibrations

The use of ambient vibration has applied into many branch of civil engineering. The Ambient Vibration Approach (AVA) can be used both to characterize the ground properties and to characterize the vibration properties of civil engineering structures. The analysis of AVA leads to different products used to characterize the ground properties. From the easiest to the most complicated, these products are: power spectra, H/V peak, dispersion curve, auto correlation function, and transfer function. On the other hand, like earthquake, ambient vibration force into of the civil engineering structures like bridges, buildings or dams. This vibration source is supposed by the greatest of the used methods to be a white noise, i.e. with a flat noise spectrum so that the record system response is actually characteristic of the system itself. Ambient vibrations of buildings are also caused by wind and internal sources (machines, pedestrians...) but these sources are generally not used to characterize structures. The branch that studies the modal properties of systems under ambient vibrations is called *Operational modal analysis* or *Output-only modal analysis* and provides many useful methods for civil engineering. The observed vibration properties of structures integrate all the complexity of these structures including the load-bearing system, heavy and stiff non-structural elements (infill masonry panels...), light non-structural elements (windows...) and the interaction with the soil (the building foundation may not be perfectly fixed on the ground and differential motions may happen). This is emphasized because it is difficult to produce models able to be comparable with these measurements.

2.3.4 Advantage and Limitation of Ambient

The advantages of ambient vibration techniques compared to active techniques commonly used in exploration geophysics or earthquake recordings used in Seismic tomography:

- Relatively cheap, non-invasive and non-destructive method
- Applicable to urban environment
- Provide valuable information with little data (e.g. HVSR)
- Dispersion curve of Rayleigh wave relatively easy to retrieve

- Provide reliable estimates of Vs30

Limitations of these methods are linked to the noise wavefield but especially to common assumptions made in seismic:

- Penetration depth depends on the array size but also on the noise quality, resolution and aliasing limits depend on the array geometry
- Complexity of the wavefield (Rayleigh, Love waves, interpretation of higher modes...)
- Plane wave assumption for most of the array methods (problem of sources within the array)
- 1D assumption of the underground structure

CHAPTER III

BASIC THEORICAL FOR VIBRATION ANALYSIS

3.1 Over View

In this part, the most important tool to overcome the expected benefit of this research, the author is going to show the aspects and important relationship that investigator should be family with. Since this research is much involved with the Digital Signal Processing (DSP), therefore, to cope up with the complicated excitation of the vibration, investigator should be family with not only the mathematical frame works but also some basic concept dealing with DSP. In order to come up with hierarchy flow of knowledge, first, the aspects vibratory motion is introduced and followed by an aspects and mathematical forms of Digital Signal Processing.

3.2 Type of Vibratory Motion

Oscillatory motion may repeat itself regularly, as in the balance wheel of a watch, or display considerable irregularity, as in earthquakes, after William T. Thomson (1988). According to Stevent L. Kramer (1996), vibratory motion can be divided into two broad categories: *periodic motion* and *nonperiodic motion*. Periodic motions are those which repeat themselves at regular intervals of time. Mathematically, a motion, $u(t)$, is periodic if there exists some period, T_f, for which $u(t + T_f) = u(t)$ for all t. The simplest form of periodic motion is *simple harmonic motion* in which displacement varies sinusoidally with time. Nonperiodic motion, which do not repeat themselves at constant interval, can result from impulsive loads (e.g., explosions or falling weights), or from longer duration transient loads (e.g., earthquakes or traffic). Examples of periodic and nonperiodic motions are shown in Figure 3-1. Some forms of periodic motion (e.g., Figure 3-1 (b)) may appear to be much more complex than simple harmonic motion, but with the use of mathematical described later in this chapter, they can be expressed as the sum of a series of simple harmonic motions.

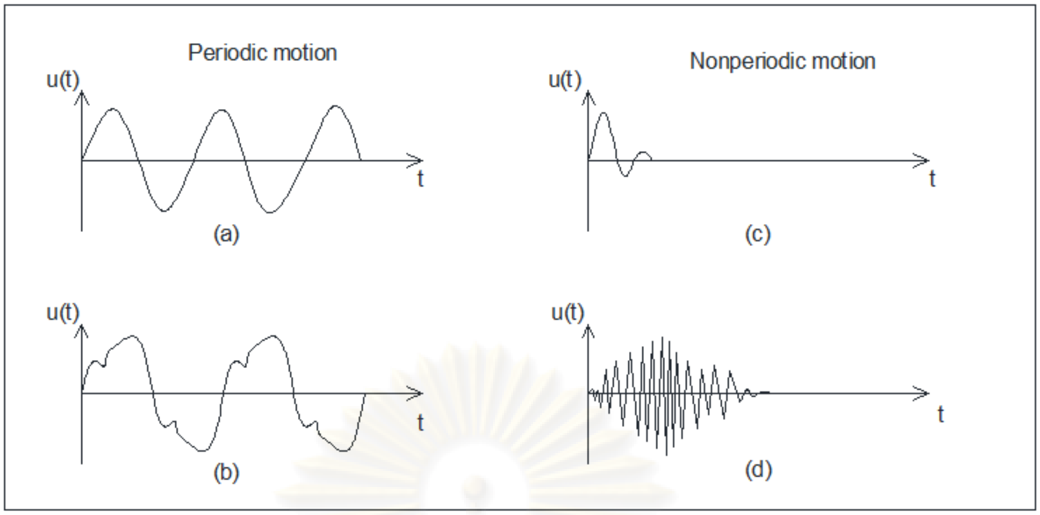


Figure 3-1 Periodic and nonperiodic motion: (a) simple harmonic motion, (b) general periodic motion, (c) transient motion (response to impact loading), (d) transient motion (earthquake ground motion). (Redraw after Stevent L. Kramer 1996)

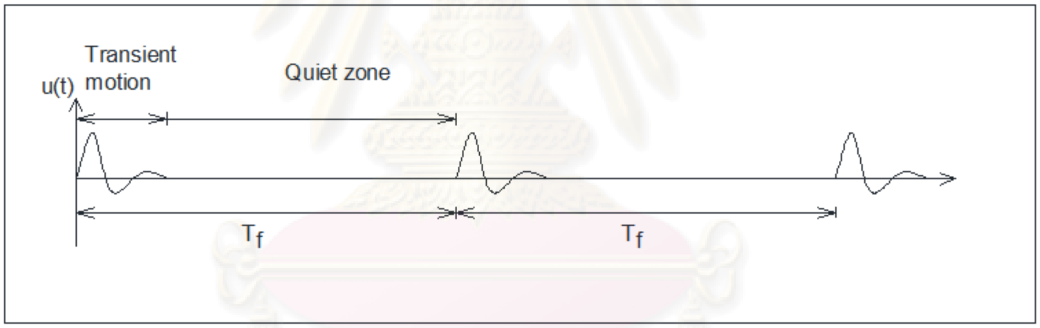


Figure 3-2 Representation of a transient motion as a periodic motion using an artificial quiet zone. The motion repeats itself indefinitely at period T_f. (Redraw after Stevent L. Kramer 1996)

With the technique of inventing a quiet zone, even the transient, nonperiodic motions such as those of Figure 3-1 (c) and (d) can be represented as periodic motions (Figure 3-2). This inventing technique becomes a powerful tool for the dynamic analysis of linear systems, where the principle of superposition allows the response to transient loading to be expressed as the sum of the responses to a series of simple harmonic loads.

3.3 Simple Harmonic Motion

According to Stevent L. Kramer (1996), simple harmonic motion can be characterized by sinusoidal motion at constant frequency. Its most important features can be defined by three quantities: *amplitude, frequency, and phase.* Simple harmonic motion can represent in different ways two of which are commonly used in geotechnical earthquake engineering will be presented in the following section: trigonometric notation and complex notation.

3.3.1 Trigonometric Notation for Simple Harmonic Motion

The simplest form of harmonic motion represented in trigonometric notation is written in Equation 3.1

$$u(t) = A\sin(\omega t + \phi) \qquad \text{(3-1)}$$

where u(t) = the particle motion which can be the displacement, velocity or accelerometer
A = amplitude
Φ = phase
ω = circular frequency = 2π*f*
f = 1/T, T = 2π/ω

Simple harmonic motion can also be described as the sum of a sine function and a cosine function, that is:

$$u(t) = a\cos\omega t + b\sin\omega t \qquad \text{(3-2)}$$

As shown in Figure 3-3, the sum of sine and cosine functions is also a sinusoid that oscillates at circular frequency, ω.

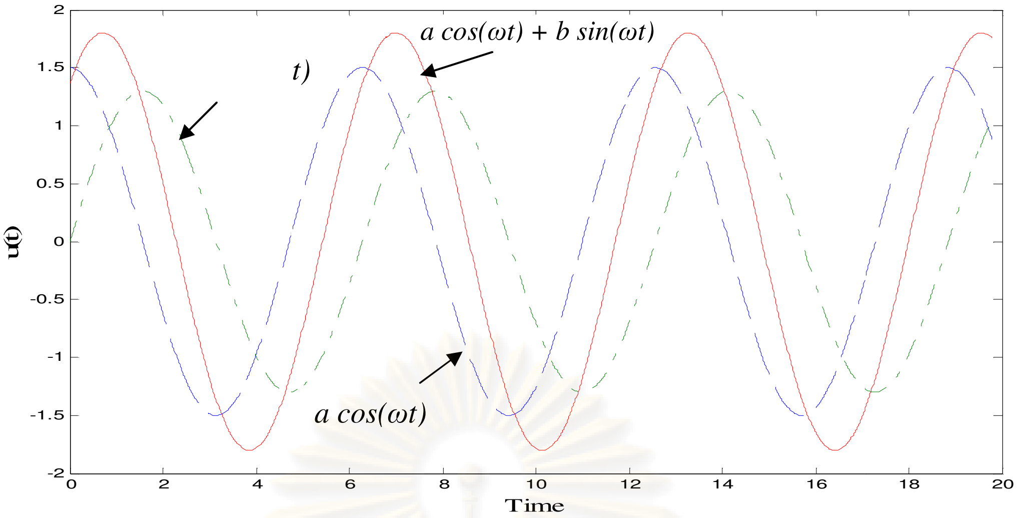


Figure 3-3 Summation of sine and cosine function of the same frequency produces a sinusoid of the same frequency. (Redraw after Stevent L. Kramer 1996)

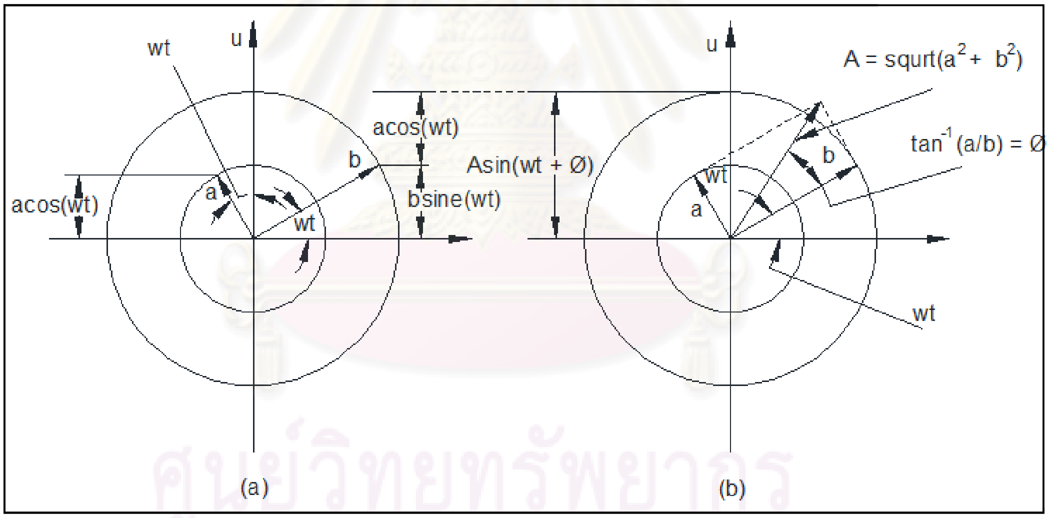


Figure 3-4 Rotating vector representation of simple harmonic motion. Sum of vertical components of sine and cosine components is (a) is equal to vertical component of resultant of sine and cosine component in (b). (Redraw after Stevent L. Kramer 1996)

However, its amplitude is not the simple sum of the amplitudes of the sine and cosine functions, and its peaks do not occur at the same times as those of the sine or cosine functions. The rotating vector representation of this function is illustrated in Figure 3-4. Since $\cos\theta = \sin(\theta + 90^{o})$, the rotating vector of length *a* must be ahead 90^{o} of vector of length *b*. the vertical component of vector *a* and *b* are ***a* cos ωt** and ***b* sin *ωt*** respectively**.** As illustrated in Figure 3.6a, the total value of $u(t)$ is given by $u(t) = a\cos\omega t + b\sin\omega t$. The motion can be expressed in a different form by considering the resultant of vectors *a* and *b*, as in Figure 3.6. The length of the resultant will be $\sqrt{a^2+b^2}$ and it will lead *b* by an angle $\Phi = \tan^{-1}(a/b)$. Accordingly, the vertical component of the resultant is

$$u(t) = A\sin(\omega t + \phi) \tag{3-3}$$

where $A = \sqrt{a^2+b^2}$ is the amplitude and

$\phi = \tan^{-1}(a/b)$ is the phase angle of the motion.

3.3.2 Complex Notation for Simple Harmonic Motion

Trigonometric descriptions of simple harmonic motion use familiar functions that are easy to visualize. For many dynamic analyses, however, the use of trigonometric notation leads to very long and awkward equations. These analyses become much simple when motions are described using complex notation. Complex notation can be derived directly from trigonometric notation using *Euler's law:*

$$e^{i\alpha} = \cos\alpha + i\sin\alpha \tag{3-4}$$

where *i* is the imaginary number $i = \sqrt{-1}$. The quantity $e^{i\alpha}$ is a complex number; it has two parts, *a real part* and an *imaginary part*, which can be written as

$$\mathrm{Re}(e^{i\alpha}) = \cos\alpha \tag{3-5}$$

$$\mathrm{Im}(e^{i\alpha}) = \sin\alpha \tag{3-6}$$

Euler's can be use to show that

$$\cos\alpha = \frac{e^{i\alpha} + e^{-i\alpha}}{2} \tag{3-7}$$

$$\sin\alpha = -\frac{e^{i\alpha} - e^{-i\alpha}}{2} \tag{3-8}$$

Substituting Equation (3-7) and (3-8) into the general expression for harmonic motion Equation (3-2)

$$u(t) = a\frac{e^{i\omega t} + e^{-i\omega t}}{2} - bi\frac{e^{i\omega} - e^{-i\omega t}}{2} \tag{3-9}$$

$$= \frac{a-bi}{2}e^{i\omega t} + \frac{a+ib}{2}e^{-i\omega t} \tag{3-10}$$

Displacement is not the only parameter that can be used to describe vibratory motion. In fact, other parameters- velocity and acceleration- are often of greater interest. Among these tree parameter of interest, if one of which is known, the other can be derived by differentiation and integration.

Examination of Equation (3-10) reveals that in addition to have different amplitudes, the displacement, velocity, and acceleration are out of phase with each other. The velocity lead the displacement by π/2 radians, or 90^{o}, and the acceleration lead the velocity by the same amount. The relationships between displacement, velocity, and acceleration for harmonic motions, in both trigonometric and complex notation, are as below respectively:

$$u(t) = A\sin\omega t \qquad u(t) = Ae^{i\omega t} \tag{3-11}$$

$$u'(t) = \omega A\cos\omega t = \omega A\sin(\omega t + \pi/2) \qquad u'(t) = i\omega Ae^{i\omega t} \tag{3-12}$$

$$u''(t) = -\omega^2 A\sin\omega t = \omega^2\sin(\omega t + \pi) \qquad u''(t) = i^2\omega^2 Ae^{i\omega t} = -\omega^2 Ae^{i\omega t} \tag{3-13}$$

The relationship between harmonic displacements, velocities, and accelerometers can be visualized in terms of three vectors rotating counterclockwise at an angular speed *ω* Figure (). The acceleration vector is 90^{o} (or π/2 radians) ahead of the velocity vector and 180^{o} (or π radians) ahead of the displacement.

3.4 Fourier Series

According to Stevent L. Kramer (1996) and Steven W. Smith (1999), Fourier analysis is name after **Jean Baptiste Joseph Fourier** (1768- 1830), a French mathematician and physicist. While studying heat flow problems in the early nineteenth century, J. B. J. Fourier showed that any periodic function that meets certain conditions can be expressed as the sum of a series of sinusoids of different amplitude, frequency, and phase. Since the conditions for existence of a Fourier series are nearly always met for functions that accurately describe physical processes, it is an extraordinarily useful tool in many branches of science and engineering and there is no exception for the branch of geotechnical engineering. By breaking down a complicated loading function into the sum of a series of simple harmonic loading function, the principle of superposition allows available solutions for harmonic loading to be used to compute the total response as illustrated schematically in Figure (3-5)

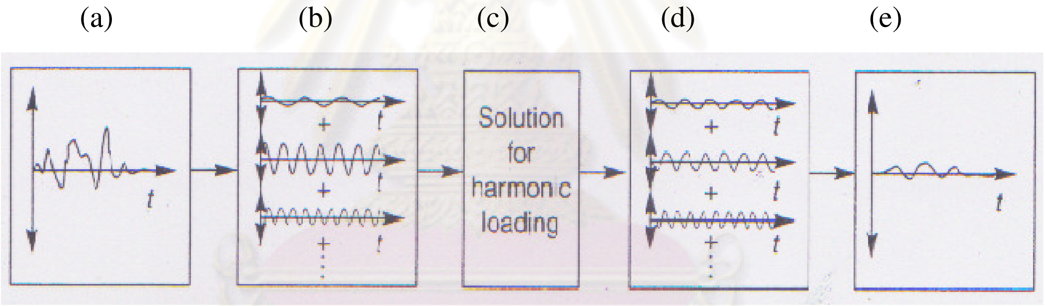


Figure 3-5 Process by which Fourier series representation of complicated loading can allow relatively simple solution for harmonic loading to be used to produce the total response: (a) time history of loading; (b) representation of time history of loading of loading as sum of series of harmonic loads; (c) calculation of response of each harmonic load; (d) representation of response as sum of series of harmonic responses; (e) summation of harmonic responses to produce time history of response.

3.4.1 The Fourier Transform

Fourier transform is an important tool which is used to transform the signal in time domain to frequency domain and back again which is based on its inverse. This Fourier transform pair is defined as:

$$X(f)=\int_{-\infty}^{+\infty} x(t)e^{-i2\pi ft}dt \qquad \text{(Forward Transform)} \qquad (3\text{-}14)$$

$$x(t)=\int_{-\infty}^{+\infty} X(f)e^{i2\pi ft}df \qquad \text{(Inverse Transform)} \qquad (3\text{-}15)$$

where x(t) = time domain representation of the signal x

X(f) = frequency domain representation of the signal x

$i=\sqrt{-1}$

The Fourier transform is valid for both periodic and non-periodic x(t) that satisfy certain minimum conditions. All signals encountered in the real world easily satisfy these requirements, according to Application 243 (2000).

3.4.2 The Discrete Fourier Transform

In many engineering applications, loading or motion parameters are described by a finite number of data points rather than by an analytical function. In such case the Fourier coefficients are obtained by summation rather than integration. For a variable $x(t_k)$, k= 1,N, where $t_k = k\Delta t$, the D*iscrete Fourier Transform* (DFT) is given by:

$$X(\omega_n)=\Delta t\sum_{k=1}^{N} x(t_k)e^{-i\omega_n t_k} \qquad (3\text{-}16)$$

where $\omega_n = n\Delta\omega = 2\pi n/N\Delta t$

The DFT can also be inverted, that is, a set of data spaced at equal frequency intervals, $\Delta\omega$, can be expressed as a function of time, using the inverse discrete Fourier Transform (IDFT):

$$x(t_k)=\Delta\omega\sum_{n=1}^{N} X(\omega)e^{i\omega_n t_k} \qquad (3\text{-}17)$$

These expressions can easily be programmed on a personal computer; since *n* takes on *N* different values, the summation operation will be performed *N* times. The time required for computation of a DFT or IDFT, therefore, is proportional to N^2.

3.4.3 Fast Fourier Transform

The DFT was developed long before computers were available, and its use, for even modest values of *N*, was extremely labor intensive. Fast Fourier Transform (FFT) is an algorithm for computing the DFT. Before the development of the FFT, the DFT required excessive amounts of computation time, particularly when high resolution was required (large N). The FFT forces on further assumption, that N is a multiple of 2. This allows certain symmetries to occur reducing the number of calculation which have to be done.

3.5 Digital Signal Processing (DSP)

3.5.1 Over view

Why Digital Signal Processing (DSP)?

It is just simply what the words imply. DSP is a combination of words Digital plus Signal and plus the word Processing. The first step to look into this world should start from the word Signal. A *signal* is a varying phenomenon that can be measured, after Michael Weeks (2007). It is often a physical quantity that varies with time, though it could vary with another parameter, such as space. In most cases, signals originate as sensory data from the real world for example seismic vibrations, visual images, sound waves, etc. To accelerate and ease in the calculation, most of the engineer's works are interacting with the computer. Therefore, to be able to interact with the computer, all the analog signals need to be conveyed into the digital signals. This technique is often known under the process of Analog-to-Digital Converter (ADC) and Digital-to-Analog Converter.

Since the hold world of this study is about the digitized signals, the most important tool to process within this work is nothing more than the Digital Signal Processing (DSP). Digital Signal Processing is one of the most powerful tools for engineer to deal with the unique data that is the *signals* which are needed to take into the analysis. DSP is the mathematics, the algorithms, and the technique used to manipulate signals after they have been converted into a digital form.

3.5.2 Linearity of Systems

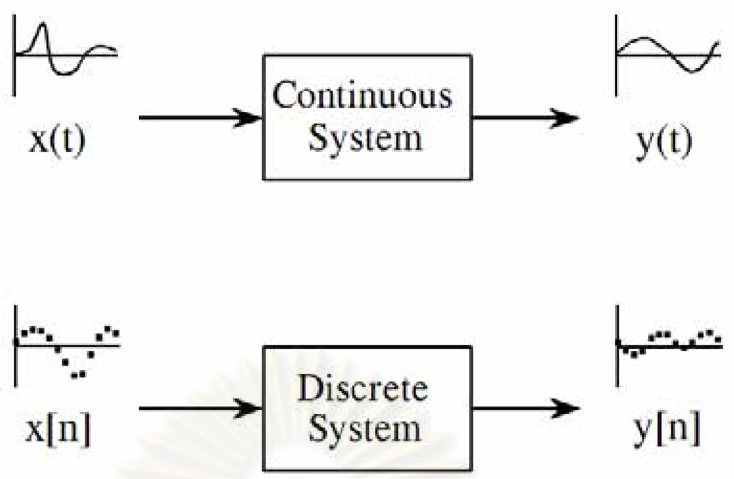
Most DSP techniques are based on a divide-and-conquer strategy called *superposition*. The signal being processed is broken into simple components, each component is processed individually, and the results reunited. This approach has the tremendous power of breaking a single complicated problem into many easy ones. Superposition can only be used with *linear systems*, a term meaning that certain mathematical rules are applied, according to Steven W. Smith (1999). The following section is an illustration of linearity of system. The author will not go in detail for this section. For further reading, please refer the mentioned reference above.

3.5.2.1 Signals and Systems

As what have described above, a *signal* is a description of how one parameter varies with another parameter. And a *system* is any process that produces an *output signal* in response to an *input signal*. This is illustrated by the block diagram in Figure 3-6. Continuous system input and output continuous signals, such as in analog electronics. Discrete systems input and output discrete signals, such as computer programs that manipulate the values stored in arrays. As the naming of signal can significantly different from one author to another, to help reader easy to follow up the terminology used in this study, the naming of signals are as follow. Fire, *continuous signals* name by using parentheses, such as: $x(t)$ and $y(t)$, while *discrete signals* mane by using brackets, as in: $x[n]$ and $y[n]$. Second, signals use lower case letters. Upper case letters are reserved for the frequency domain.

3.5.2.2 Requirement for linearity

A system is called linear if it has two mathematical properties: *homogeneity* and *additively*. A third property, *a shift invariance,*, is not a strict requirement for linearity, but it is a mandatory property for most DSP techniques. These three properties form the mathematic of how linear system theory is defined and used.



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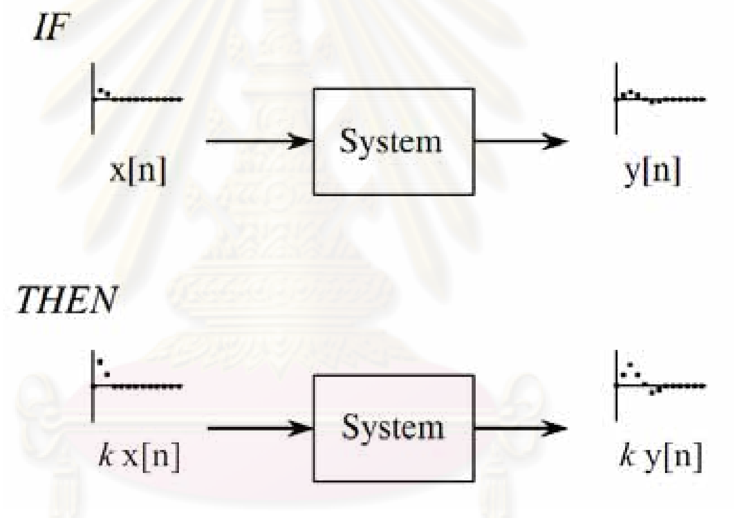

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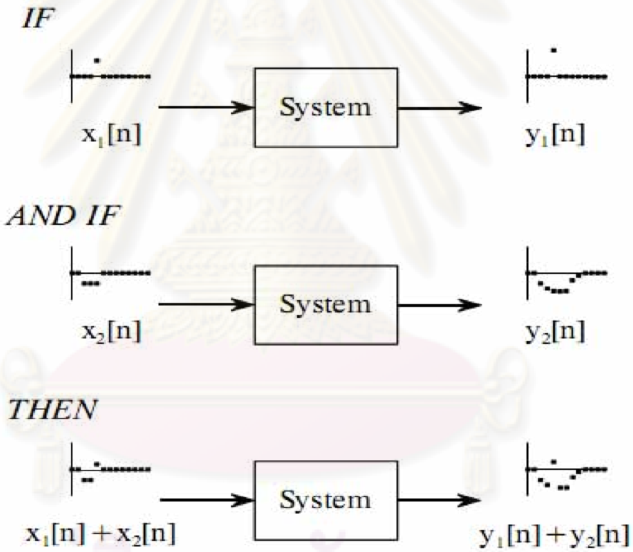
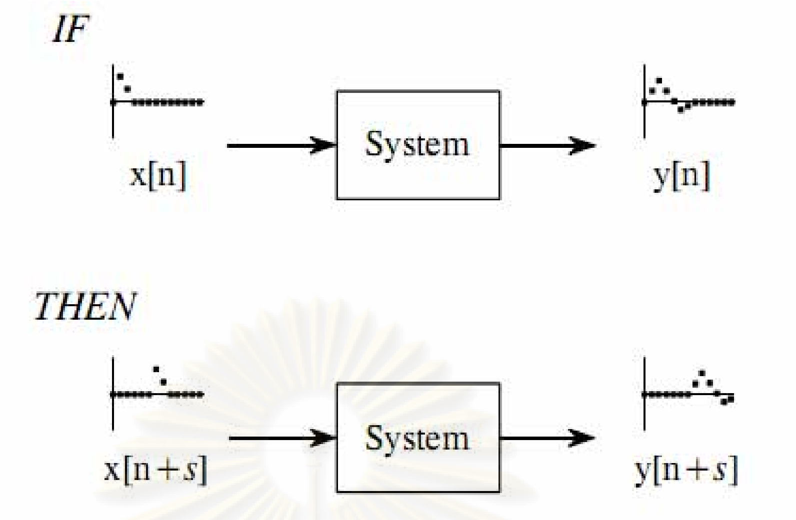
As illustrated in Figure 3-7, homogeneity means that a change in the input signal's amplitude results in a corresponding change in the output signal's amplitude. In mathematic terms, if an input signal of x[n] results in an output signal of *x*[*n*]m an input of *kx*[*n*] results in an output of *ky*[*n*], for any input signal and constant, *k*.

To see more clearly how this does make sense let us go further into the following example. In this case the use of resistor is a good example to illustrate the homogenous and non-homogeneous of the system. If the input of the system is the voltage across the resistor, *v*(*t*), and the output from the system is the current through the resistor, *i*(*t*), the system is homogeneous. Ohm's law guarantees this; if the voltage is increased or decreased there will be a corresponding increase or decrease in the current. Now, consider another system where the input signal is the voltage across the resistor, $v(t)$, but the output signal is the power being dissipated in the resistor, $p(t)$. Since power is proportional to the square of the voltage, if the input signal is increased by a factor of t*wo*, the output signal is increase by a factor of *four*. This system is not homogeneous and therefore cannot be linear.

The property of additivity is illustrated in Figure 3-8. Consider a system where an input of $x_1[n]$ produce an output of $y_1[n]$. Further suppose that a different input, $x_2[n]$, produces another output, $y_2[n]$. The system is said to be *additive*, id an input of $x_1[n]$ + $x_2[n]$ results in an output $y_1[n]$ + $y_2[n]$, for all possible input signals. In word, signals added at the input produce signals that are added at the output.



Shift invariance, as illustrated in Figure 3-9, means that a shift in the input signal will result in nothing more than an identical shift in the output signal. In more formal terms, if an input signal of $x[n]$ results in an output of $y[n]$, an input signal of $x[n+s]$ results in an output of $y[n+s]$, for any input signal and any constant, s. By adding a constant, s, to the independent variable, n, the waveform can be advanced or retarded in the horizontal direction. For example, when s = 2, the signal is shift *left* by two samples; when s = -2, the signal is shifted *right* by two samples. Shift invariance is important because it means the characteristics of the system do not change with time.



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3.5.3 Superposition

Superposition is the heart of the Digital Signal Processing. It is the overall strategy for understanding how signals and system can be analyzed. In the superposition, two fundamental concepts are used: *synthesis* and *decomposition*.

Synthesis is the process of combining signals through scaling and addition. This process is done by *scaling* (multiplication of the signals by constants) and follows by addition. Figure 3-10 shows an example of three signals: $x_0[n]$, $x_1[n]$, and $x_2[n]$ are added to form a fourth signal, $x[n]$.

Decomposition is the inverse operation of synthesis, where a signal is broken into two or more additive components. This is more involved than synthesis, because there are infinite possible decompositions for any given signal.

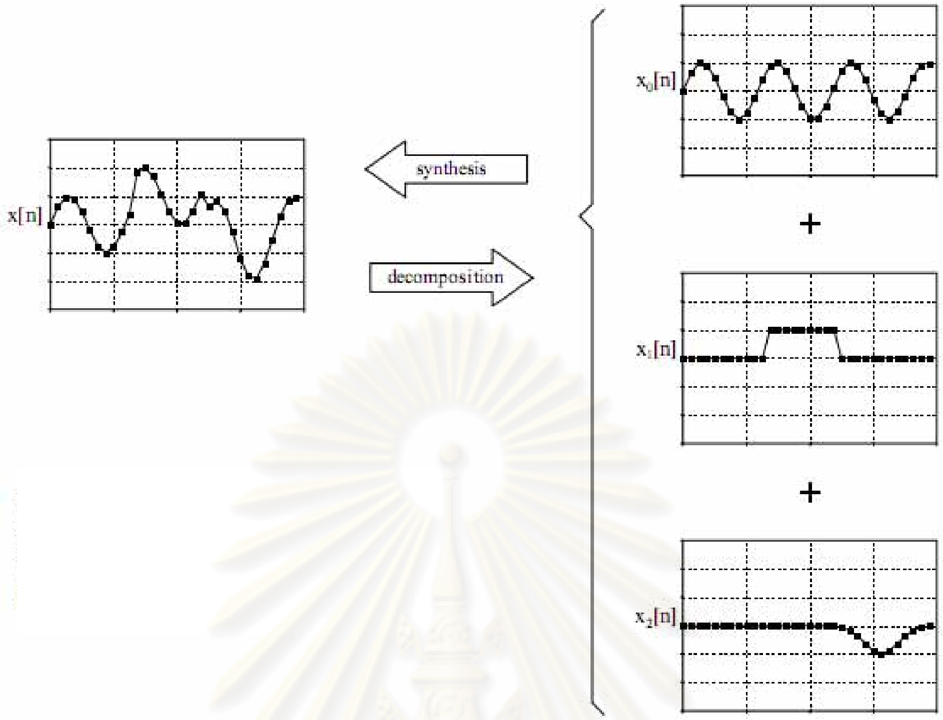
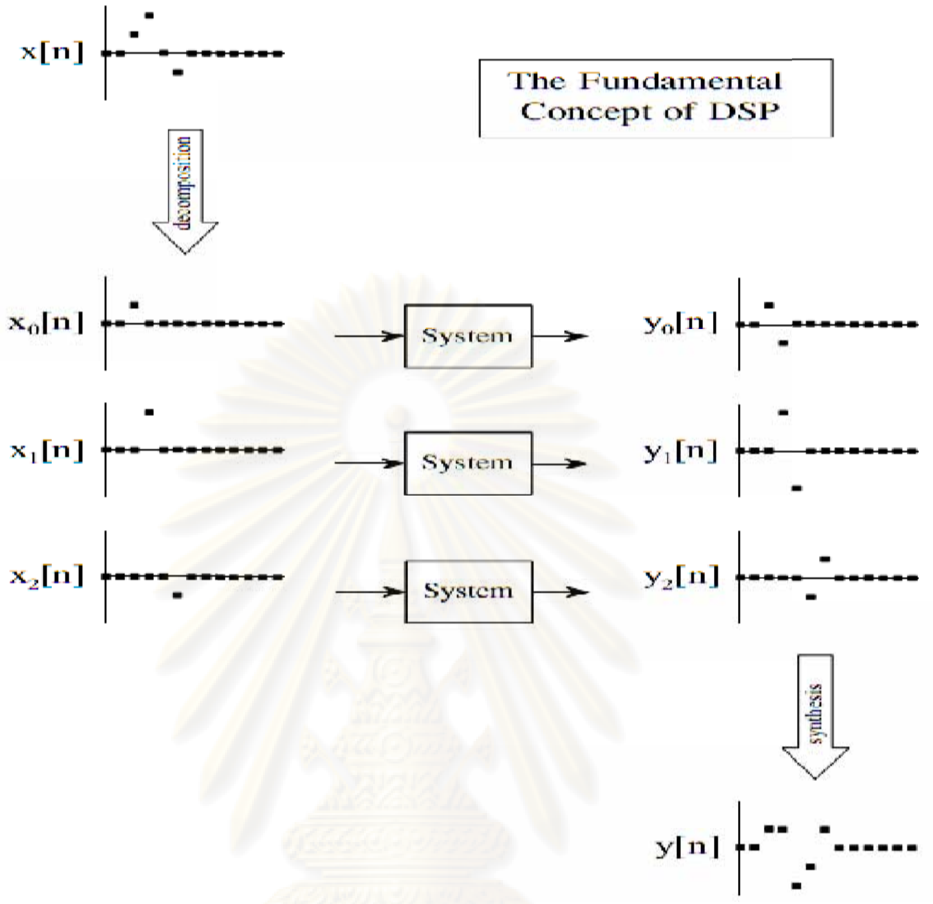


Figure 3-10 Illustration of synthesis and decomposition (After Steven W. Smith 1999)

After having view the two fundamental concepts of superposition, the following section is about how the superposition technique deal with the complicated signals. Consider an input signal, called $x[n]$, passing through a linear system, resulting in an output signal, $y[n]$. As illustrated in Figure 3-11, he input signal can be decomposed into a group of simpler *input signal components*: $x_0[n]$, $x_1[n]$, $x_2[n]$, etc. Next, each input signal component is individually passed through the system, resulting in a set of *output signal components*: $y_0[n]$, $y_1[n]$, $y_2[n]$, etc. These output signal component then synthesized into the output signal, $y[n]$. Here is the important part: the output signal obtained by this method is *identical* to the one produced by directly passing the input signal through the system. This is a very powerful idea. Instead of trying to understanding how *complicated* signals are changed by a system, all that need to know is how *simple* signals are modified. In the jargon of signal processing, the input and output signals are viewed as a superposition (sum) of simpler waveforms.



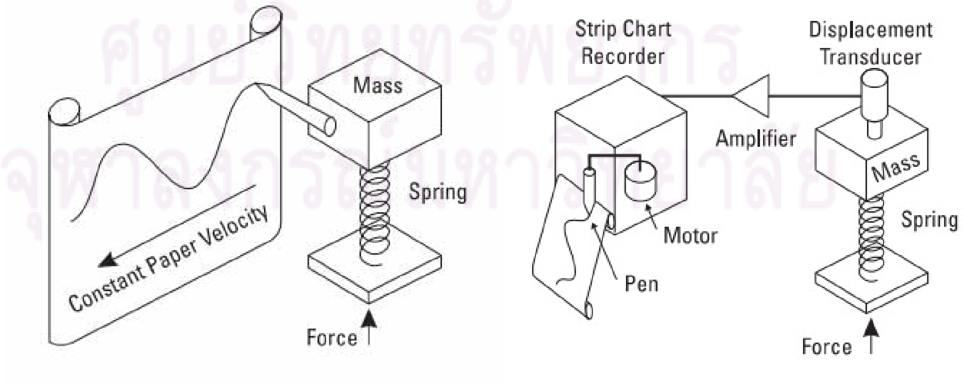
fter Steven W.

3.5.4 Signal and Graph Perspective

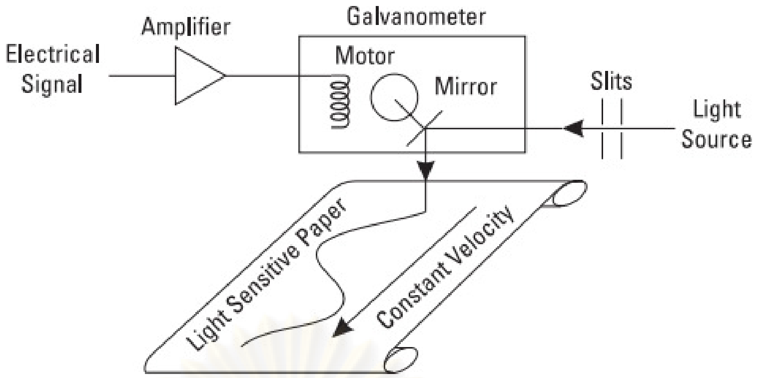
A signal can be represented either in terms of time domain and frequency domain. These are just the way of looking into the problem. There is no information loss in the interchange from either time domain to frequency domain and vise versus. The different way of looking into the problem from time domain to frequency domain is just about the different of perspective. By changing *perspective* from time domain, the solution to difficult problems can often be quite clear in the frequency domain.

3.5.4.1 The time domain

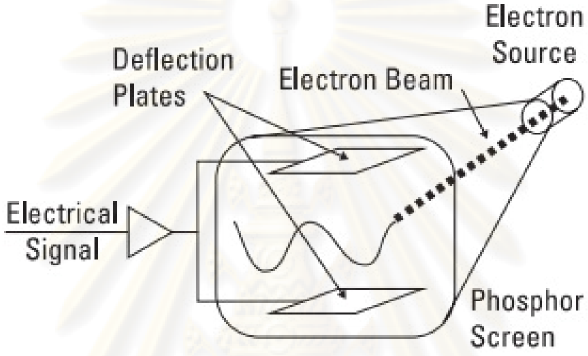
The traditional way of observing signals is to view them in the time domain. The time domain is a record of what happened to a parameter of the system versus time, according to Agilent Technologies (1999), an application No 243. For instant, Figure 3-12(a) shows a simple spring-mass system with which a pen is attached to the mass and pulled a piece of paper past the pen at a constant rate. The resulting graph is a record of the displacement of the mass versus time, *a time domain view of displacement*. Such direct recording schemes are sometimes used, but it usually is much more practical to convert the parameter of interest to an electrical signal using a transducer. Of cause, the immediate problem is not electrical signal, but by mean of *transducer*, the basic parameters of interest can be changed into the electrical signal. Transducers are commonly available to change a wide variety of parameters to electrical signal. To ensure the accuracy of representing the analog signal by electrical signal, many steps in improving the capabilities of transducer have been developed for instance, the *Strip Chart Recorder* in Figure 3-12(b), *Oscillograph* in Figure 3-12(c), *Oscilloscope* in Figure 3-12(d), and lastly an analog signal can even record and display by using a personal computer in term of digital signal (electrical signal). The strip chart, oscillograph, oscilloscope and computer all show, say displacement, versus time. It is say that changes in the displacement represent the variation of some parameters in time domain. In the next section, another perspective of representing an analog signal is shown.



(a) (b)



(c)



(d)

t-a time domain
d oscillograph
tted for clarity)

3.5.4.2 Frequency domain

It was shown over one hundred years ago by Jean Baptiste Joseph Fourier that any waveform that exists in the real world can be generated by adding up sine waves. This statement is illustrated in the Figure 3-13 for a simple waveform composed of two sine waves. By picking the amplitudes, frequencies and phases of the sine waves correctly, the desired signal can identically generate. Conversely, we can break down our real world signal into these same sine waves. It can be seen that this combination of sine waves is unique; any real world signal can be represented by only one combination of sine waves.

Figure 3-14 is a three dimensional graph of this addition of sine waves. Two of the axes are time and amplitude, familiar from the time domain. The third axis is a frequency which allows us to visually separate the sine waves which add to give us our complex waveform. If this three dimensional graph is viewed along the frequency axis, the time domain of sine wave is viewed as illustrated in Figure 3-14(b). By adding all the consisting sine wave at each constant time, the original waveform will be derived. On the other spectacle of view, if the three dimensional is viewed along the time axis, a different picture will be shown as illustrated in the Figure 3-14(c). In this Figure, the axis system is a combination of amplitude as the ordinate of the system and frequency as the axis of the system. This graph is commonly called the representation of signal in the *frequency domain.* Every separated sine wave is appeared as a vertical line. Its height represents its amplitude and its position represents its frequency. Since it is known that each line represents a sine wave, this mean that the input signals have uniquely characterized in the frequency domain. This frequency domain representation of signal is called the *spectrum* of the signal. Each sine wave of the spectrum is called a *component* of the total.

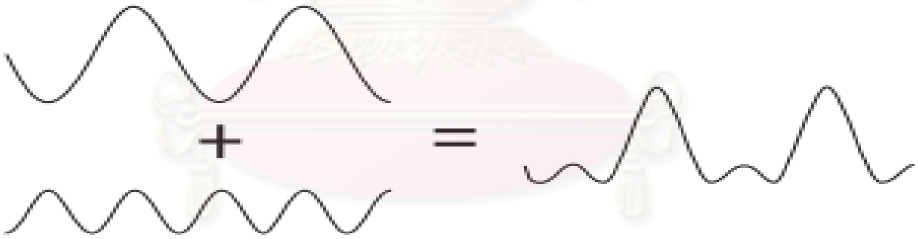


Figure 3-13 Any real waveform can be produced by adding sine wave together. (After Agilent Technologies, Application Note 243 (2000))

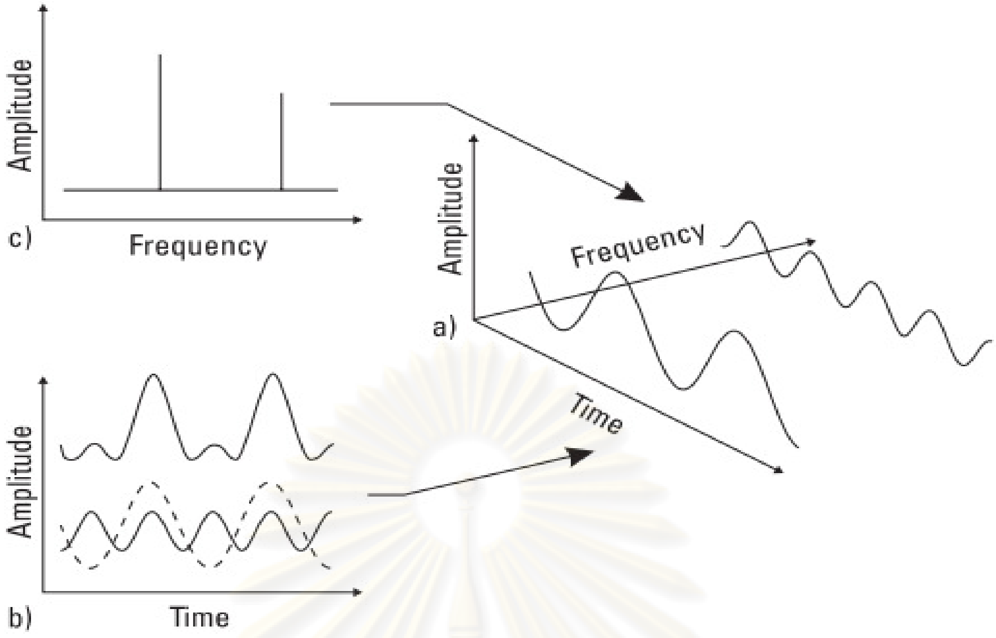
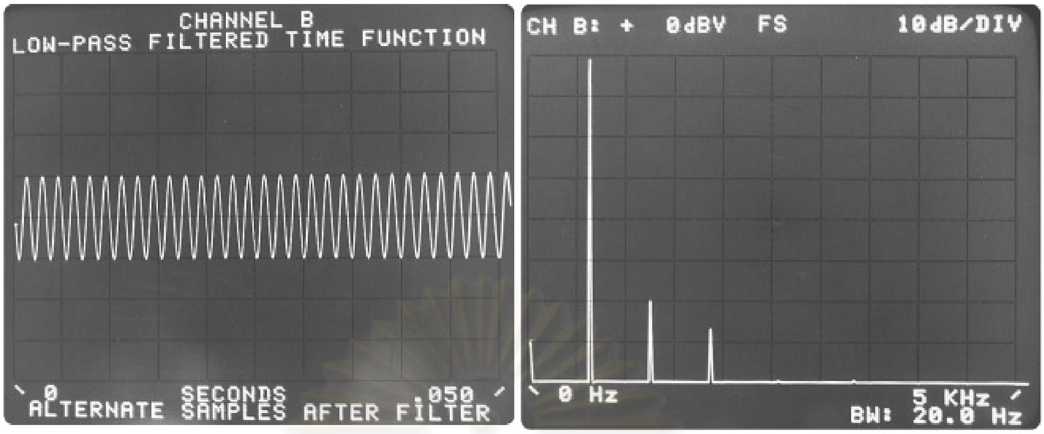


Figure 3-14 The relationship between the time and frequency domains. (a) Three dimensional coordinates showing time, frequency and amplitude, (b) Time domain view, (c) Frequency domain view (After Agilent Technologies, Application Note 243 (2000))

Why the Frequency Domain?

Suppose we wish to measure the level of distortion in an audio oscillator. In this case, we are trying to detect a small sine wave in the presence of large signals. Figure 3-15(a) shows a time domain waveform which seems to be a single sine wave. But Figure 3-15(b) shows in the frequency domain that the same signal is composed of a large sine wave and significant other sine wave components. When these components are separated in the frequency domain, the small components are easy to see because they are not masked by larger ones.

The frequency domain’s usefulness is not restricted to electronics or mechanics. All fields of science and engineering have measurements like these where large signals mask others in the time domain. The frequency domain provides a useful tool in analyzing these small but important effects.



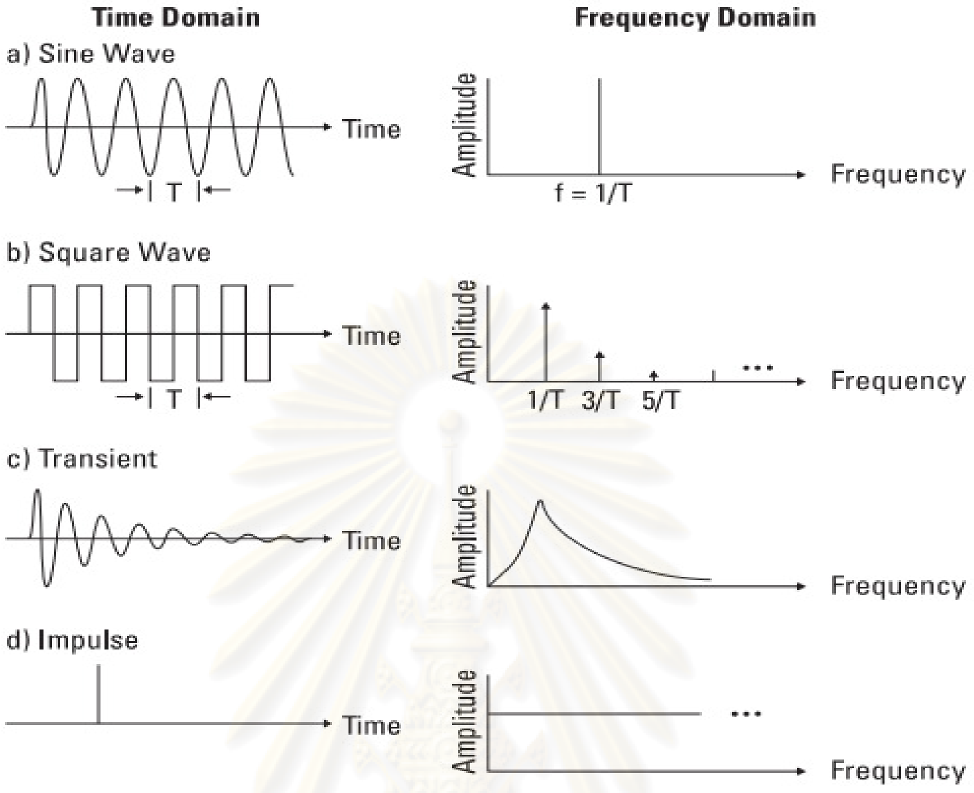
a) Time Domain - small signal not visible

b) Frequency Domain - small signal easily resolved

t Technologies,

Different View of Spectrum

Let us now look at a few common signals in both the time and frequency domains. In Figure 3-16(a), we saw that the spectrum of a sine wave is just a single line. We expect this from the way we constructed the frequency domain. The square wave in Figure 3-16(b) is made up of an infinite number of sine waves, all harmonically related. The lowest frequency present is the reciprocal of the square wave period. These two examples illustrate a property of the frequency transform: a signal which is periodic and exists for all time has a discrete frequency spectrum. This is in contrast to the transient signal in Figure 3-16(c) which has a continuous spectrum. This means that the sine waves that make up this signal are spaced infinitesimally close together. Another signal of interest is the impulse shown in Figure 3-16(d) the frequency spectrum of an impulse is flat, i.e., there are energy at all frequencies. It would, therefore, require infinite energy to generate a true impulse. Nevertheless, it is possible to generate and approximation to an impulse which has a fairly flat spectrum over the desired frequency range of interest.



ation Note 243

3.5.5 Sampling theorem

It is quite important to take the sample that can completely represent the actual signal. To get the data that can exactly reconstruct the actual signal, the *proper sampling* is needed. After Steven W. Smith (1999), the definition of proper sampling is quite simple. Suppose one sample a continuous signal in some manner. If one can exactly reconstruction the analog signal from the samples, one have done the sampling properly. Even if the sampled data appears confusing or incomplete, the key information has been captured if one can reverse the process. To help readers better understand about the proper sampling; let us look closely into the illustration in Figure 3-17 below. Figure 3-17 shows several sinusoids before and after digitization. The continuous line represents the analog signal entering the analog-to-digital converter (ADC), while the square markers are the digital signal leaving the ADC.

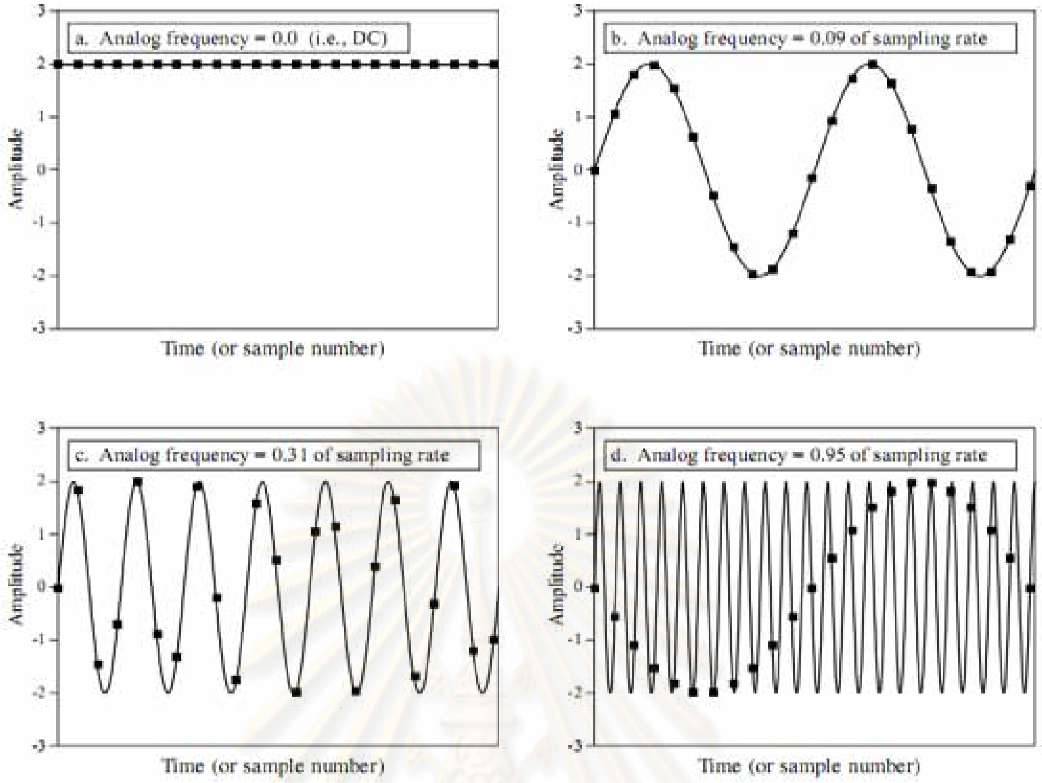


Figure 3-17 Illustration of Proper and Improper Sampling (After Steven W. Smith 1999)

In (a), the analog signal is a constant DC value, a cosine wave of zero frequency. Since the analog signal is a series of straight lines between each of the samples, all of the information needed to reconstruct the analog signal is contained in the digital data. According to the above definition, this is *proper sampling*.

The sine wave shown in (b) has a frequency of 0.09 of the sampling rate. This might represent, for example, a 90 cycle/second sine wave being sampled at 1000 samples/second. Expressed in another way, there are 11.1 samples taken over each complete cycle of the sinusoid. This situation is more complicated than the previous case,, because the analog signal con not be reconstructed by simply drawing straight lines between the data points. Do these samples properly represent the analog signal? The answer is yes, because no other sinusoid, or combination of sinusoids, will produce this pattern of samples. These samples correspond to only one analog signal, and therefore the analog signal can be exactly reconstructed. Again, this is an instance of proper sampling.

In (c), the situation is made more difficult by increasing the wave's frequency to 0.31 of the sampling rate. This results in only 3.2 samples per sine wave cycle. Here the samples are so sparse that they don't even appear to follow the general trend of the analog signal. Do these samples properly represent the analog waveform? Again, the answer is yes, and for exactly the same reason. The simples are a unique representation of the analog signal. All of the information needed to reconstruct the continuous waveform is contained in the digital data. Obviously, it must be more sophisticated than just drawing straight lines between the data points. As strange as it seems, this is *proper sampling* according to the above definition.

In (d), the analog frequency is pushed even higher to 0.95 of the sampling rate, with a mere 1.05 samples per sine wave cycle. Do these samples properly represent the data? *No, they don't!* The samples represent a different sine wave from the one contained in the analog signal. In particular, the original sine wave of 0.95 frequencies misrepresents itself as a sine wave of 0.05 frequencies in the digital signal. This phenomenon of sinusoids changing frequency during sampling is called *aliasing*. Just as a criminal might take on an assumed name or identity (an alias), the sinusoid assumes another frequency that is not its own. Since the digital data is no longer uniquely related to a particular analog signal, an unambiguous reconstruction is impossible. There is nothing in the sampled data to suggest that the original analog signal had a frequency of 0.95 rather than 0.05. The sine wave has hidden its true identity completely; the perfect crime has been committed! According to the above definition, this is an example of *improper sampling.*

This line of reasoning leads to a milestone in Digital Signal Processing, the *sampling theorem***.** Frequently this is called the *Shannon Sampling Theorem*, or the *Nyquist Sampling Theorem*. The sampling theorem indicates that a continuous signal can be properly sampled, *only if it does not contain frequency components above one-haft of the sampling rate.* For instance, a sampling rate of 2000 samples/second requires the analog signal to be composed of frequencies below 1000 cycle/second. If frequencies above this limit are present in the signal, they will be aliased to frequencies between 0 and 1000 cycles/second, combining with whatever information that was legitimately there. Two terms are widely used when discussing the sampling theorem: the *Nyquist frequency* and *Nyquist rate*. Unfortunately, their meaning is no standardized. To understand this, consider an analog signal composed of frequencies between DC (0

Hz) and 3 kHz. To properly digitize this signal it must be sampled at 6000 samples/second (6 kHz) or higher. Suppose we choose to sample at 8000 samples/second (8 kHz), allowing frequencies between DC and 4 kHz to be properly represented. In this situation there are important frequencies: (1) the highest frequency in the signal, 3 kHz; (2) twice this frequency, 6 kHz, (3) the sampling rate 8 kHz; and (4) one-haft the sampling rate, 4 kHz. Which of these four is the *Nyquist frequency* and which is the *Nyquist rate*? By definition given by the author (Steven W. Smith 1999), all of the possible combinations are used. The Nyquist frequency and Nyquist rate are obviously refer to the sampling theorem but are used in different ways by different authors. These terms can be used to mean four different things: the highest frequency contained in a signal, twice this frequency, the sampling rate, or one-haft the sampling rate.

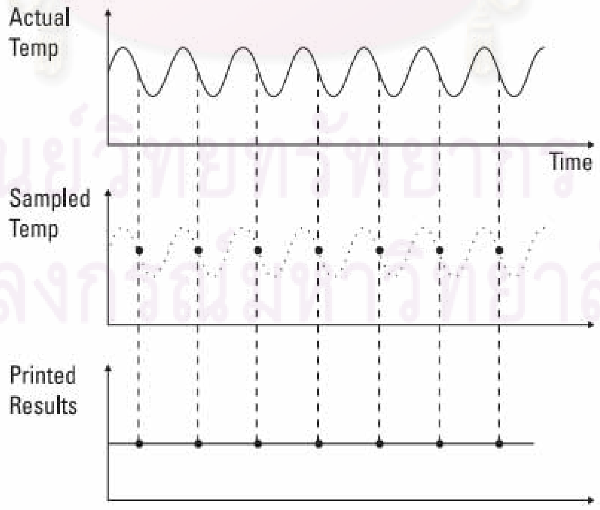
However, after Helmut Wenzel and Dieter Pichler (2005), showed that the minimum scanning rate should correspond to the fivefold maximum identified target frequency. This means that the scanning rate, e.g. for the highest noticeable eigenfrequency of 10Hz, should be at least 50Hz. This value has been verified for several measurements carried out until the time publishing his book and represents a clear increase in the required sampling rate compared to the well-known *Shannon* scanning theorem (Nyquist Frequency). This criterion is necessary to be able to determine the frequency curve reliably. If additional information on short events is required, higher scanning rates have proved to be successful. According to the same source, the scanning rate of 100 Hz has proved appropriate for registering individual events.

3.6 Encounter Problem in DSP

The frequently encounter problem in Digital Signal Processing (DSP) are aliasing and leakage. Aliasing is a phenomenon of miss representing an analog signal and leakage is a phenomenon that leads to a leakage of power in the frequency domain. Here below are the illustrations of how these phenomena can affect onto the DSP and how those problems can be avoided.

3.6.1 Aliasing

Aliasing is a potential problem in any sampled data system that leads to miss representation of the analog signal. To see what the aliasing is and how it can be avoided, let us have a look at simple data logging example. Consider the example of recording temperature. In this recording, a thermocouple is connected to a digital voltmeter which is in turn connected a printer. The system is setup to print the temperature every second. If the temperature of the room changes slowly, the result of the every reading is expected to be almost the same as the previous one. And in fact, the sampling in this condition is much more than necessary to determine the temperature of the room with time. On the other hand, the temperature in the room changes rapidly, say, cycled exactly once every second. As shown in Figure 3-18, the printer says that the temperature never changes. What has happened is that, the system has sampled at exactly the same point on the periodic temperature cycle with every sample. The system have not sampled fast enough to see the temperature fluctuations. This problem will happen when the different between sampling frequency and the frequency of the input signal fall into the frequency range of interest. In other word, aliasing will occur when the sampling rat is less than twice of the frequency of the input signal. Therefore, to prevent this phenomenon not to happen, one has to set the sampling rate of at less twice of the highest frequency of the input signal.



3 (2000))

3.7 Operation in DSP (Convolution)

Convolution is a mathematical way of combining two signals to form a third signal. It is the single most important technique in digital signal processing and also is the first step toward what this research is being about. Convolution is a formal mathematical operation, just as multiplication, addition, and integration. Addition takes two numbers and produces a third number, while convolution takes two signals and produces a third signal. In *linear systems*, convolution is used to describe the relationship between three signals of interest: the input signal, the impulse response, and the output signal. Figure 3.19 shows the convolution operation between two signals- the input signal **x[n]** which can be the signal of the excitation getting from the ground, , and the another one is the impulse response (Transfer Function) **h[n]-** to produce the output signal **y[n]** which can be the signal of excitation of the building. By writing in the equation form (Equation 3.18), the convolution operation is represented by the star, *****, just like others operation such as addition is represented by the plus, **+**, and multiplication is represented by the cross, **×**. All the operated signals can be either in time domain or in the frequency domain. In time domain, the " * " will become " X " operation. In concept, the Transfer function can simply be derived from Equation (3-19). The detail calculation of Transfer Function is shown below.

$$x[n]*h[n] = y[n] \qquad (3.18)$$

From equation (3.18), the impulse response of the system can be defined as below:

$$h[n] = \frac{y[n]}{x[n]} \qquad (3.19)$$

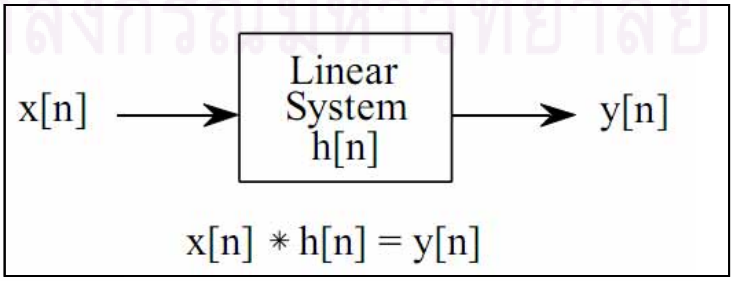


Figure 3-19 Convolution Operation (After Steven W. Smith 1999)

3.8 Transfer Function Calculation

The Transfer Function can be derived from only the two point measurement. If we have an input signal and the output signal of the system, the Transfer Function can be derive from the relationship between the input and output. This, however, does not necessarily tell us the true Transfer Function because the output measurement may have large components due to noise or non-linearity in the system. According to Smith J. D. and Butterworths (1989), to obtain a valid Transfer Function, the cross-spectrum density is first obtained by multiplying input values (at a given frequency) by output values (at the same frequency) and averaging. The Transfer Function is given by the ratio of the cross-spectrum density to the input spectrum density. Base on the application Note 243 (2000), *the cross power spectrum,* $G_{xy,}$ is defined as taking the Fourier Transform of two signals separately and multiplying the result together as follows:

$$G_{xy}(f) = S_x(f)\,S_y^*(f) \tag{3-20}$$

where “ *” indicates the complex conjugate of the function.

$S_x(f)$ = Fourier Transform of input signal x

$S_y(f)$ = Fourier Transform of output signal y

With the cross-power spectrum, we can define the Transfer Function, $H(f)$, using the cross power spectrum and the spectrum of the input signal as follows:

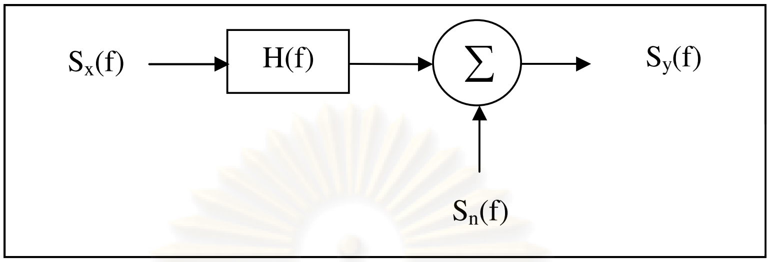
$$H(f) = \frac{\overline{G_{yy}}(f)}{\overline{G_{xx}}(f)} \tag{3-21}$$

where “¯” denotes the average of the function.

At first glance it may seem more appropriate to compute the Transfer Function as follow:

$$\left|H(f)\right|^2 = \frac{\overline{G_{yy}}}{\overline{G_{xx}}} \tag{3-22}$$

This is the ratio of two signal channel, averaged measurements. Not only does this measurement not give any phase information, it also will be error when there is noise in the measurement. To see why let us solve the equations where noise is injected into the output as show in Figure 3-20.



es, Application

The output signal is:

$S_y(f) = S_x(f)H(f) + S_n(f)$, *$S_n(f)$* is the Fourier Transform of noise signal.

So

$$G_{yy} = S_y S_y^{*} = G_{xx}\left|H\right|^2 + S_x H S_n + S_x^{*} H^{*} S_n + \left|S_n\right|^2 \qquad (3\text{-}23)$$

If we RMS average this result to try to eliminate the noise, we find the S_xS_n term approach zero because S_x and S_n are uncorrelated. However, the $\left|S_n\right|^2$ term remains as an error and so we get

$$\frac{\overline{G_{yy}}}{\overline{G_{xx}}} = \left|H^2\right| + \frac{\overline{\left|S_n\right|}^2}{G_{xx}} \qquad (3\text{-}24)$$

Therefore, if we try to measure $\left|H\right|^2$ by this single channel technique, our value will be high by noise to signal ratio. If instead we average the cross power spectrum, we will eliminate this noise error. This can be shown by the same technique as follow:

$$\overline{G_{yx}} = S_y S_x^{*} = \overline{\left(S_x H + S_n\right) S_x^{*}} = \overline{G_{xx} H} + \overline{S_n S_x^{*}} \qquad (3\text{-}25)$$

So

$$\frac{\overline{G_{yx}}}{\overline{G_{xx}}} = H\left(f\right) + S_n S_x^{*} \qquad (3\text{-}26)$$

Because S_n and S_x are uncorrelated, the second term will average to zero, making this function a much better estimate of the Transfer Function.

3.9 The Coherence Function

The majority of twin channel vibration analyzers now have readout of coherence and it is thus a simple matter to check the validity of Transfer Function by glancing at the coherence function. The coherence function has the value between 0 and 1. A coherence of 1 confirm that “input” and “output” are linked and there is a strong temptation to say that if two measurement are made of , say, force and vibration, a coherence of 1 proves that the vibration is a result of force. In contrast, a coherence value of zero means that all the output at a given frequency is due to noise or unrelated effects in the system and so the Transfer Function deduced is not valid and should be ignored.

The coherence function $\gamma^2{}_{xy}(f)$ is defined as the ratio of the squared modulus of the cross spectral density function to the auto-spectral density functions $S_x(f)$ and $S_y(f)$:

$$\gamma^2{}_{xy}(f) = \frac{\overline{G_{yx}(f)}\,\overline{G_{xy}{}^*(f)}}{\overline{G_{xx}(f)}\,\overline{G_{yy}(f)}} \tag{3-27}$$

CHAPTAER IV
RESEARCH METHODOLOGY

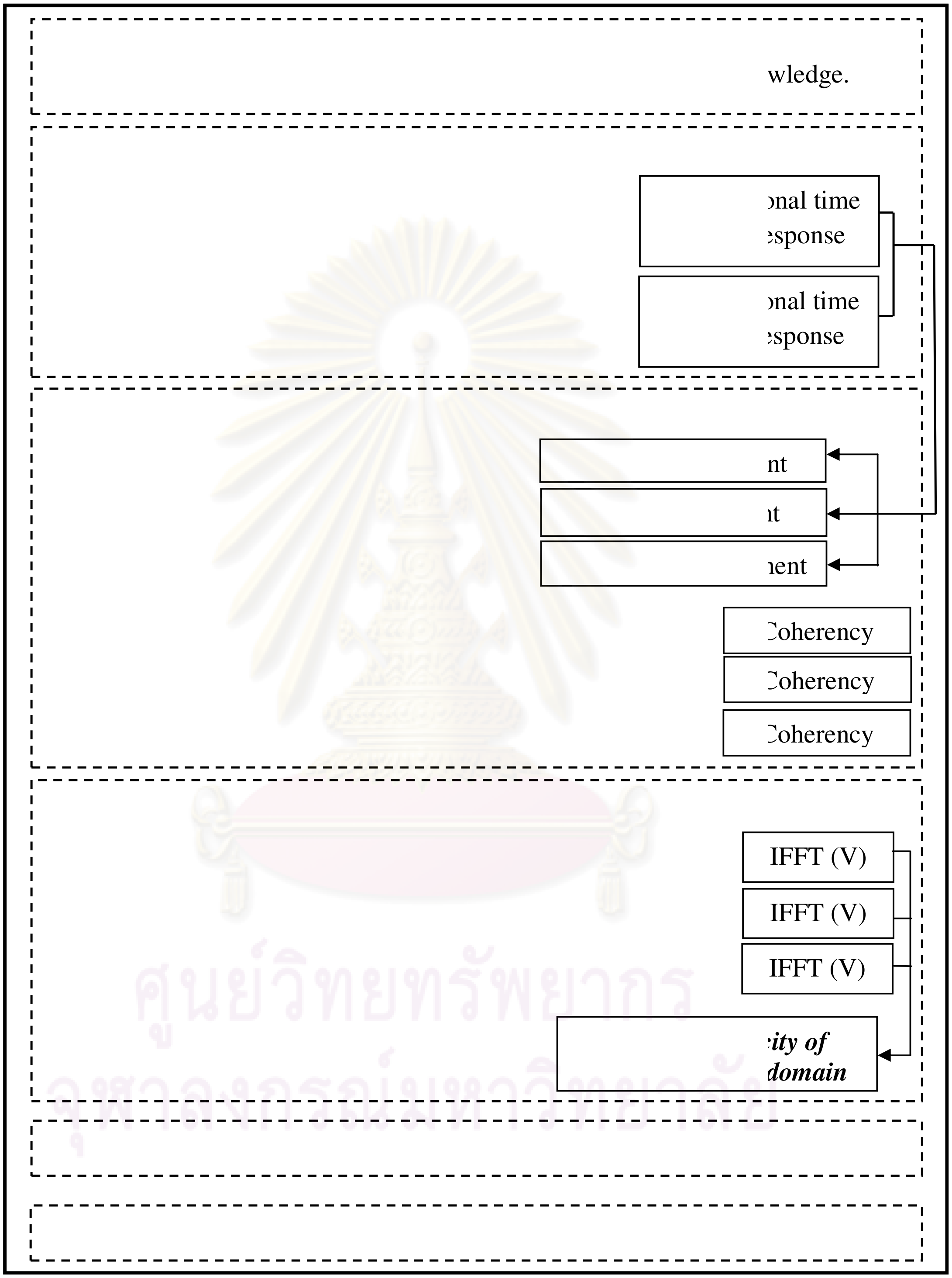
4.1 Overview

To ensure a smooth running of research plan, a thorough planning and scheduling stating from the introduction until the last point in methodology have been organized. The steps of conducting this study have devised into two sections. First, a roughly description of conducting this research was introduced and followed by detail description of each step.

The study was done by conducting tests on RC-building in Chulalongkorn University. Two kinds of test were performed. The first kind of test was the measurement of ambient vibration in order to derive the Transfer Function. Then, to verify the accuracy of the Transfer Function, a measurement of vibration from construction site was done followed. The processes in obtaining and analyzing of the two data above were divided in steps below:

1. Data acquisition: the process to obtain the raw data in term of time domain
2. Data processing: the step of
    - transferring the signal from time domain into frequency domain by performing Fast Fourier Transform (FFT),
    - deriving the Transfer Function from cross spectrum and auto spectrum from the input signal and output signal.
3. Verification: evaluate the Transfer Function by making use of it to predict the response of the building shacking by the vibration from the construction site.

4.2 Research Framework



4.3 Research Assumption

To achieve what it is expected for this research, some assumption were needed. Below were the assumptions made in this study:

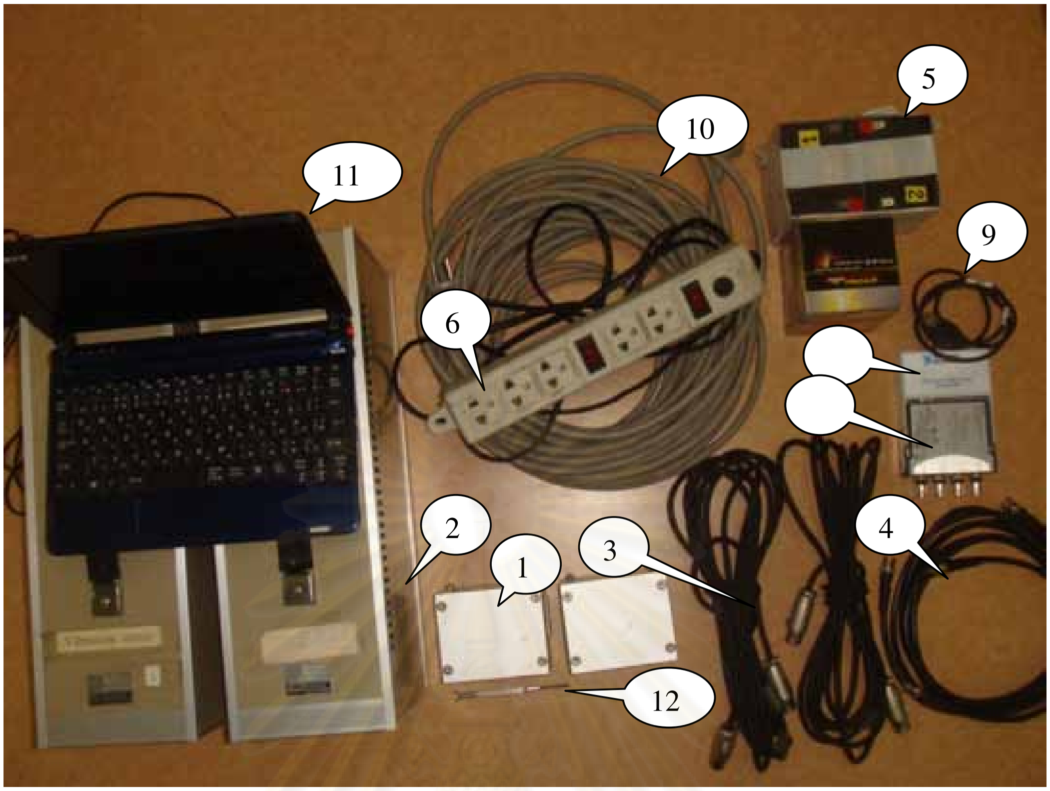
- The amplitude of excitation from ambient source is high enough to excite the soil and building system.
- The system of ground and building vibration is a linear system.

4.4 Data Collection

Data collection is the significant part to get the samples and then take it into the analysis. To perform the data collection, a successive step was need. It started from preparing equipment for conducting the test, test setup, and storing the data.

4.4.1 Test Equipment

To conduct this research, three necessary parts of the equipment were needed: sensors, signal conditioners, and data loggers. Since this study is about measuring the ambient vibration which vibrates soil-building system at very low amplitude and frequency, a very sensitive sensor was needed. In this research, two set of very sensitive SERVO TYPE VIBRATION METER with the model of VM – 5112 were used as the vibration sensor. This sensor was manufactured by IMV Corporation in Japan, in 1991. Each set of these equipments consist of one Servo type Acceleration Pickup with the model of VP – 5112, a 5 meter long of pickup cable typed HCVV-S, a 1.5 meter long of output cable, and a mental case packed together with a Low Band Vibration Meter type VM – 5112, Amplifier Unit type VA – 5112, and a Power Unit type PS – C1015B. This equipment was built up with a high accuracy and stability by servo type acceleration pickup. This compacted equipment is a switchable instrument which can be used to measure acceleration, velocity, displacement, and tilt. Its sensitivity is ranging from DC to 100 Hz which is suitable for low band measurement such as earthquake motion, structure, and also for the ambient excitation, etc. Figure 4-2 shows the overall of the equipments use in the data collection followed by description of each item in the list.

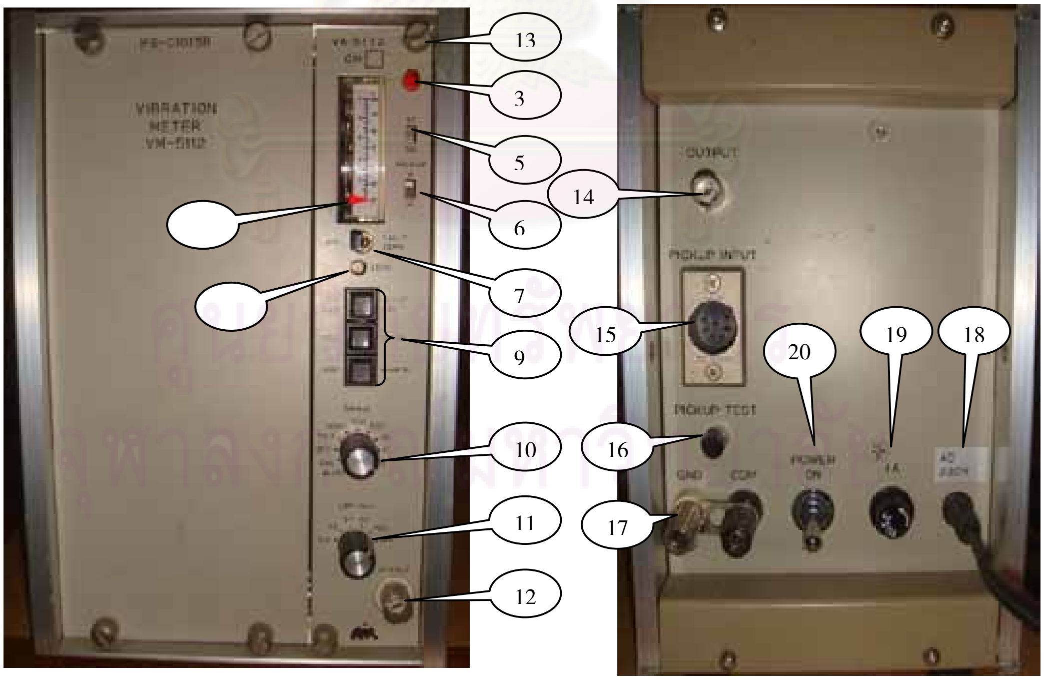


Items description

1. Acceleration pickup VP – 5112
2. A compact case consist of Low Band Vibration Meter type VM – 5112, Amplifier Unit type VA – 5112, and Power unit type PS – C1015B.
3. Two 5 meter long of pickup cables
4. Two of 1,5 meter long of output cables
5. Batteries use as power supply in case there is no electricity supply
6. DC-to-AC converter
7. National Instruments Hi-Speed USB Carrier: NIUSB-9162 used as adapter
8. National Instruments NI 9234, 4 channel ± 5V 24 Bit, SW selectable IEPE & AC/DC ±2v AI- -to-Earth Ground, - 40 ^{o}C ≤ Ta ≤ 70 ^{o}C, used as Analog-to-Digital Converter (ADC)
9. National Instruments 192256A-01 TYPE USB A/B 2.0 1meter long
10. Electric wire
11. Minicomputer use as oscilloscope, data storage, and data processor.
12. Drive: use to calibrate the Vibration Meter

13. Hammer use to generate the impulsive source
14. Plastic and steel plat use to generate the vibration at different frequency

Figure 4-3 and Figure 4-4 show a layout of the installation of general composition of this SERVO VIBRO TYPE VIBRATION METER and a function description of each item of Vibration Meter respectively.



er VM - 5112

Function description of Vibration Meter VM – 5112

1. Unit fitting Volt	
2. Lamp	Lam lighting indicates the power feeding.
3. AC – DC selector switch	When set at “DC”, frequency from DC is measured. When set at “AC”, measurement from 0.1 Hz and DC component is cut off.
4. Pickup V-H selector switch	It is set at “H” when pickup is installed in horizontal direction and set at “V” when pickup is stalled in vertical direction.
5. Meter	It indicates vibration level, calibration voltage, offset voltage, tilt and pickup test level.
6. VIB.-ZERO selector switch	Vibration level is indicated when set at “VIB.”
7. ZERO adjuster	Adjust (7) so that (5) indicates “zero” with setting (6) at ZERO.
8. Selector switch	Acceleration, velocity or displacement is selected.
9. Range selector switch	Select suitable range according to vibration level. Calculate the vibration with reference to unit conversion in table of Appendix B below.
10. Low pass filter selector switch	It attenuates over 2, 10, 30, 50, 100 Hz and OFF (f_o = -3dB) by – 18dB/octave. Select suitable range.
11. Monitor output	It is monitor terminal for waveform output. The full scale of the output graph is fluctuate in the range of ± 5 V.
12. Output connector	Monitor terminal for waveform output. The full scale of the output graph is fluctuate in the range of ± 5 V.
13. Pickup input connector	It is where the pickup cable is connected.
14. Pickup test switch	By pushing this trig, the signal equivalent to approximately 4 Hz, 1.000 cm/s^2 is generated from the pickup. To perform the test, set (9) at “1000 cm/s^2” and (8) at “ACC (acceleration)”.

15. GND-COM terminal	When GND terminal is not grounded, short-circuit between GND and COM by short bar and take away the short bar when grounded.
16. Power cable	Feed power supply.
17. Fuse holder	Inserted fuse is blown out with over current.
18. Power switch	Power ON/OFF switch.

4.4.2 Equipment Note

a. Unit

Since this equipment was manufactured in Japan and the Japanese Industrial Standard (JIS Z8203) is different from the International System unit (SI), there are some different conversions unit between the (JIS Z8203) and (SI). The different between these two units is given in the table below.

Table 4-1 Conversion Factor from JIS to SI (Instruction Manual of SERVO VIBRATION METER VM-5112)

Item	Symbol	Conversion factor	Symbol in SI unit
Degree	O ‘	π/180	rad
Acceleration	m/s^2	1	m/s^2
	G	9.80665	
	Gal	1	cm/s^2
Frequency (Cycle)	S^{-1}	1	Hz
Temperature	C^o	+273.15	K

b. Meter Indication

Vibration meter VM – 5112 is very sensitive low band sensor which can be used to measure acceleration, velocity, and displacement. However it should be noted that, the reading of Vibration Meter will give an error reading when the frequency of vibration is below 0.4 Hz.

c. Noise

When low pass filter switch is set at "OFF", natural frequency of pickup and carrier component of pickup built – in oscillator may be taken out a little.

4.4.3 System Specification of Vibration Meter

4.4.3.1 General Specification

Right below are the general specifications of the Vibration Meter.

Measuring Rang	
Acceleration:	0.1 – 1000 cm/s^2
Velocity:	0.02 – 100 cm/s
Displacement	0.06 – 100 mmP-P
Frequency Rang	
Acceleration:	DC – 100 Hz ± within 5%
Velocity:	1 – 50 Hz ± within 5%
Displacement:	1 – 20 Hz ± within 5%
Meter Indication	
Acceleration, velocity:	Peak value (average value x $\pi/2$)
Displacement:	Peak-peak value (average value x $\pi/2$)
Meter Rang:	0.4 – 100 Hz ± 2%
Low Pass Filter	
Cut – off Frequency:	2, 10, 30, 50, 100 Hz, OFF
Characteristic:	Butter worse characteristic (f_o = approx. – 3dB)
Damping Factor:	Over f_o – 18dB/octave
Tilt:	30^o full scale (0.523599 rad)

$$Degree = \sin^{-1}\frac{OutputVoltale(v)}{10}$$

Output	
Monitor Output:	± 5 V full scale, load over 10 KΩ
Output (rear panel)	± 5 V full scale, load over 10 KΩ
Temperature Range:	0 – 50 ^oC
Humidity:	0 – 85 %RH
Power Supply:	220 VAC, 1Φ, 47 – 63 Hz

Allowable Rang: 198 – 242 VAC
Power Consumption: Below 25 VA
Dimension: See the outside view
Weight: Approximately 5.5 Kg

4.4.3.2 Acceleration Pickup

Table 4-2 Pickup Specifications

Model	VP – 5115
Max. Acceleration	± 20 m/s^2
Sensitivity	± 0.2 m/s^2 ± within 5 %
Frequency Range	DC – 100Hz
Output Resistance	1.1 KΩ
Natural Frequency (f_n)	Over 250 Hz
Resolution (DC)	Below 0.1 cm/s^2
Noise	Below 1.7 mVrms (DC – 100 Hz) Below

4.4.4 Mounting Direction of Pickup

The arrow sign on the pickup is used to show the vibration detecting direction. Therefore, to measure the vibration in vertical direction, the pickup should be mounted in the direction with the arrow sign point upward (↑). In the same context, to measure the vibration in horizontal direction, the pickup should be mounted in the direction perpendicular to the vertical direction with the arrow sign of (→) or (←).

4.4.5 Equipment Calibration

To ensure the quality of the collected data, calibration of the equipment is a necessary and primary thing to do. Here below are a few steps in doing the calibration:

1. **Power Feeding**

   Feed the power with pushing (18), the power switch, at power on and check the light of power lam at (2) is turned on.
2. **Zeros Point Adjustment**

Set (9), Range selector switch, at “X1000” and adjust (7), ZERO adjuster, using driver to turn the (7) in the direction of clockwise of counterclockwise in order to put the (5), Meter indicator, point at zero, “0” (the center position) . The same process are repeated for all others range, turning (9) to “X300” → “X100” so on and so forth. Each time turning (9); slightly turn (7) to the right of left to make Meter indication point at zero.

3. **Check the Operation of Pickup**

   There two ways to check the normality operation of the pickup:

   a) *Pickup Test 1*

      Set (6) at “VIB”, (9) at “X1000”, and (10) at “100 Hz” and then push (14), the Pickup test switch, and hold for a while. While pushing (14), there two points to check the normality of the pickup. First, the Meter indicator will point at “0.99” of “1” at the full scale. Another check point is to observe the sine wave of the oscilloscope. While holding (14), the sine wave of 4 Hz with the equivalent amplitude of 1000cm/s^2 should be shown up.

   b) *Pickup Test 2*

      The pickup test can be performed by taking advantage of gravity acceleration, “980.665cm/s^2. turn (4), Pickup V – H Selector Switch, to the position at “H” and turn (6) to point at “CAL. T. ZERO”. After performing all the steps in point 2, Zero Point Adjustment, mount the pickup in vertical direction (↑) and check that (5), Meter indicator, point at “0.99” of “1” at the full scale. And then mount the pickup in the reverse direction (in turn of 180^o), (↓), and check the meter point at “0.01”.

4.4.5.1 Lest Location

Figure 4-5 show the layout location of the construction site and the target building where the tests were conducted. Figure 4-6 show the activities of the building demolition and the location of the sensor on the building respectively. The red thick line in Figure 4-5 shows the vibration traveling path from the vibration source to the investigated building and the yellow points show the location of pickup sensors.

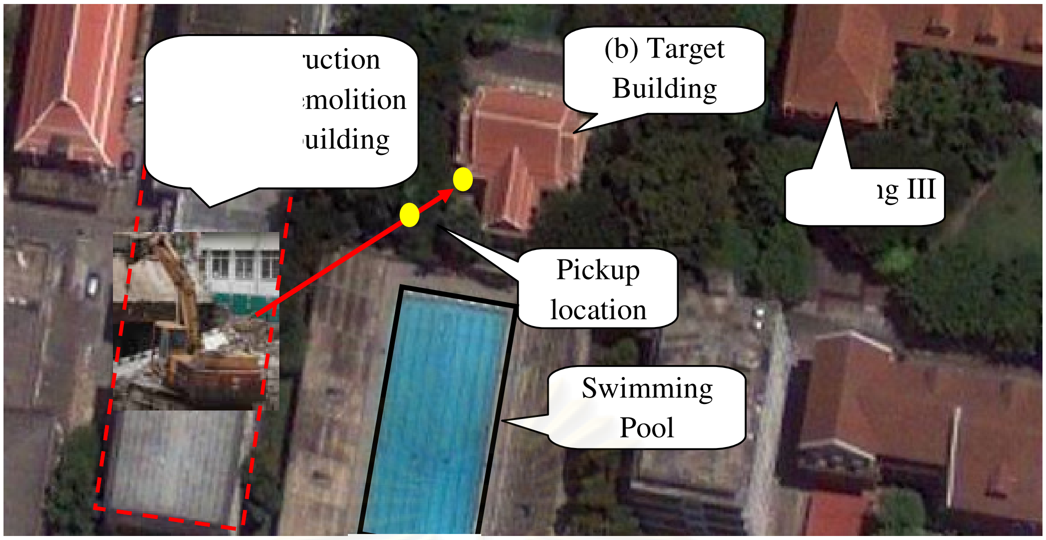


Figure 4-5 Layout of the construction site and the location of data collection

b) the location

4.4.6 Test Setup

The experiments were conducted in three different phases: data collection from ambient vibration, data collection from the performing active source using the drop hammer, and the data collection from the construction site. The field test was carried out on August 2010. To ensure the quality and adequate data for the analysis, many factors have been taken into account such as the sampling rate, duration for collecting data, and the location of the sensors, and the number of needed data. In this experiment, excitation from ambient and from the construction vibration, the sampling rate of *2000 Hz* was used and thirty set of data with the duration of *30* *second* for each was collected. For the excitation generated by dropping hammer, the duration of 1 second was used. The selecting Range of 1 on the Vibration Meter was applied throughout the whole experiment. The records were performed in three different directions: Vertical, Radial, and Transversal (Figure 4-6). The Low Past Filter of 100 Hz was selected to observe the vibration in a broad band. To avoid the distorted of vibration on the ground that can be caused by the near field effect of the building, the ground sensor was placed at 3.5 meter off set from the building, Figure 4-7.

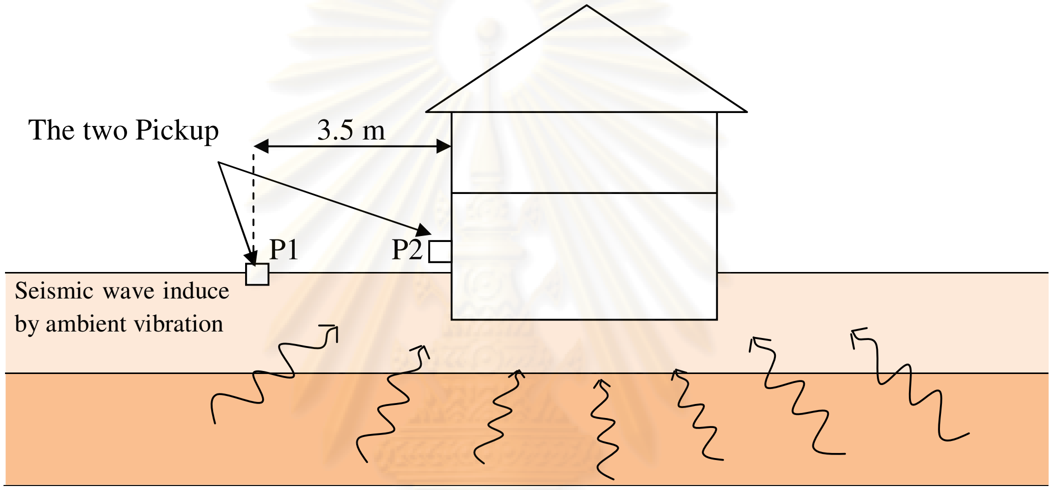


Figure 4-7 Instrumentation for ambient measurements (Redraw and modify after Helmut WENZEL and Günther ACHS 2006)

4.4.7 Raw Data

The raw data were simultaneously collected and stored in the mini-computer for later take into the analysis. It should notice that, the collected data was not properly stored in the engineering format (mm/s). Therefore, before taking these data into analysis, the data conversion was applied. The conversion were done by multiplying the raw data with the conversion factor supplied by the manufacturer in the Table A-1 of appendix A.

4.5 Data Processing

In this section, the process was device into two phases: the determinations of Transfer Function followed by its coherence function and the verification of this Transfer Function by making use of this Transfer Function to prediction building excitation caused by construction activities.

4.5.1 Determination of Transfer Function and its Coherency

Equation (3-26) and (3-27) were used to derive the Transfer Function and its corresponding coherence function respectively. The step in getting the Transfer Function was carried out as follow:

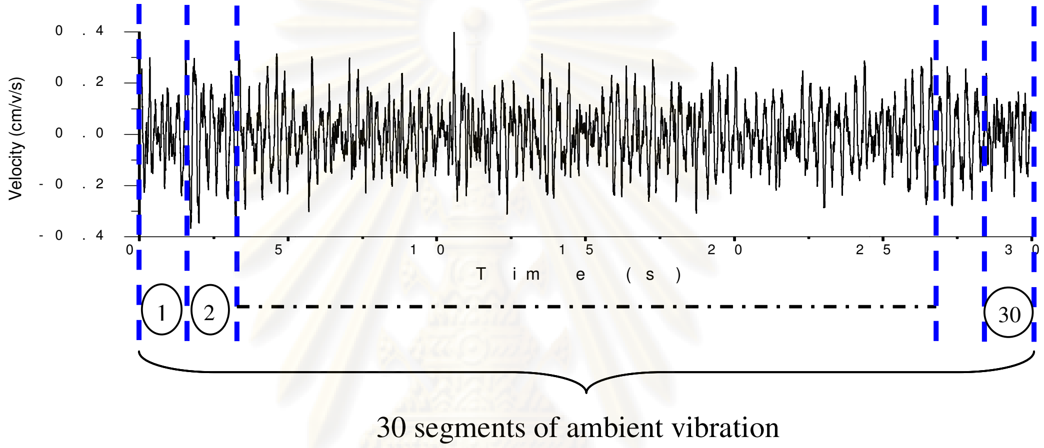
1. First the raw data was instructed to load into the M-script written in Matlab
2. Truncated the long signal into 30 segments (for the ambient case), and for the vibration generated by hammer, the data which last for one second was loaded successively for 30 set of data and each of which have cut only for the impulsive range lasted for only 0.2 seconds (see Figure 4-5(a) and 4-5(b) respectively).
3. Decomposed each segment into the frequency domain by performing the FFT.
4. Cross spectrum and auto spectrum density were derived from FFT of the input and output using the Equation (3-20).
5. The Transfer Function and its coherence function then determine from the results getting in step 4 by using the Equation (3-26) and Equation (3-27) respectively.
6. To get the transfer function in time domain, the inverse fast Fourier transform was performed.

4.6 Prediction of Building Response

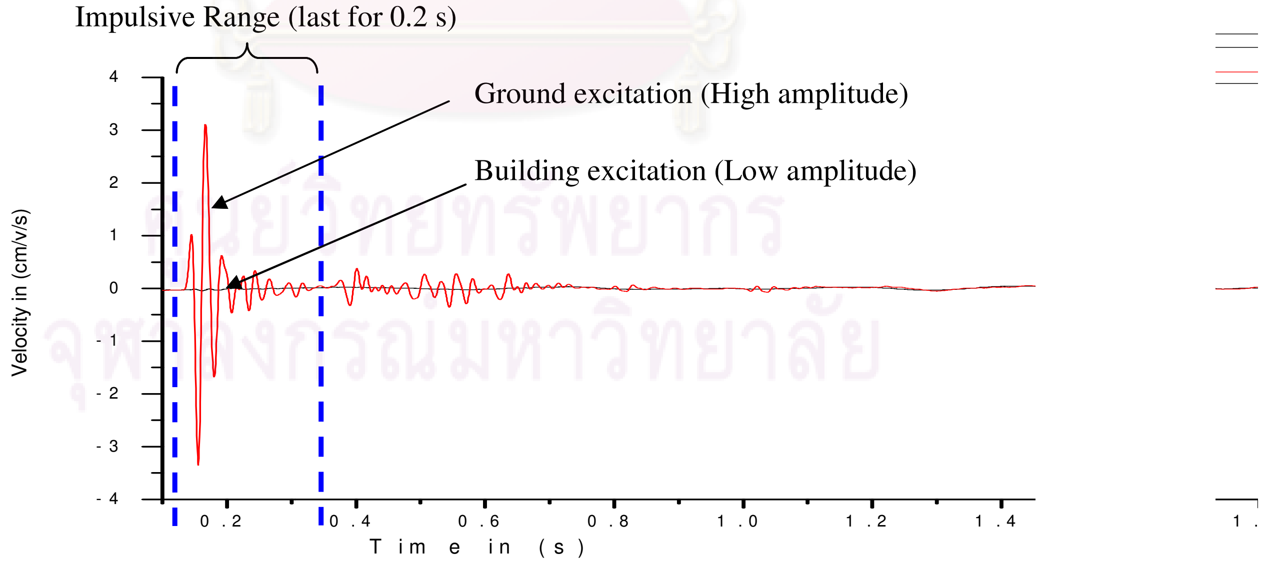
The prediction of building response was conducted by making use of the Transfer Function. The step of prediction of building response was carried out as follow:

1. The excitations of ground and building were fist record at the construction site.

2. The ground excitations were used as the input signal and the building excitations were used as the output signal of the soil-building system.
3. The input signals in time domain then transferred into frequency domain by applying (FFT).
4. To get the prediction of building response, multiplication between the input spectrum and the calculated Transfer Function was performed.
5. The result of this prediction, then, was compared with the actual measurement getting from the construction site.



(a)



(b)

of ambient

struction site

CHAPTER V

RESULTS AND INTERPRETATION

5.1 Over view

In this section, the results of this study are presented. First, characteristic of each vibration is presented. Then, the results of defining the Transfer Function in each direction are shown. To evaluate the accuracy of the Transfer Function, the comparisons of the predicted with the actual measurement were followed.

5.2 Vibration Characteristics

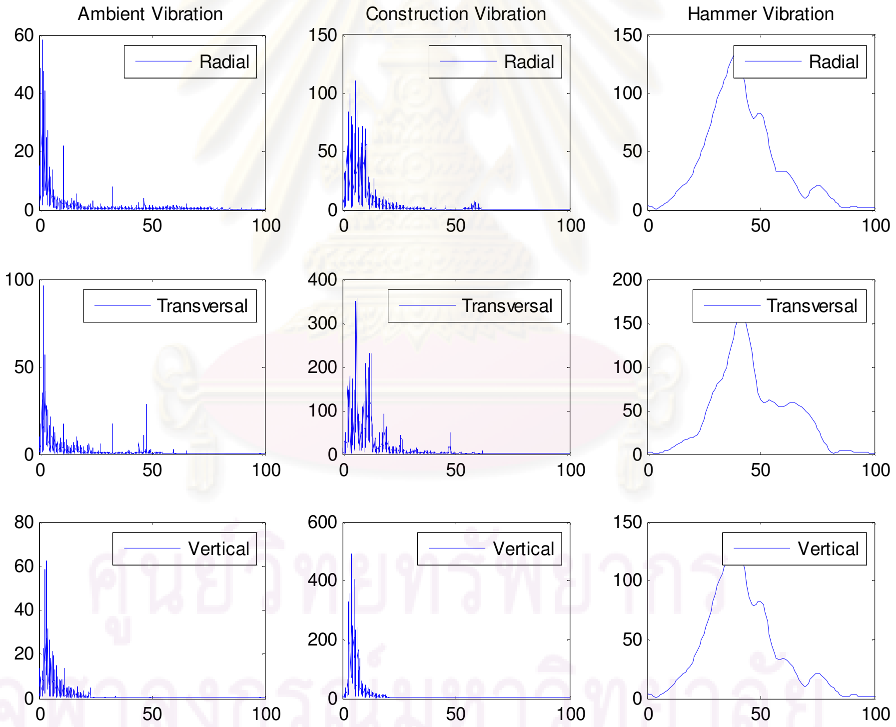


Figure 5-1 The characteristics of the ambient vibration, construction vibration and Hammer vibration

Figure 5-1 shows the characteristic of excitation of ground vibration from three different sources: ambient vibration, construction vibration, and vibration generated by dropping. The study shows that the three motions have different characteristics.

Under ambient excitation, the ground excited at the dominance frequency less than 10 Hz (1 to 4 Hz). And under construction vibration, ground vibrated at the frequency range of 4 to 7 Hz. Meanwhile, under the vibration of dropping hammer, the ground vibrated predominantly at the frequency range of 10 to 30 Hz, 40 to 50 Hz, and 30 Hz and 50 Hz respectively in vertical direction, radial, and transversal direction.

5.3 Transfer Function from Ambient Vibration

Here below are the Transfer Function and the coherence function getting from the ambient vibration in vertical, Radial, and Transversal respectively shown in Figure 5-2 through Figure 5-4.

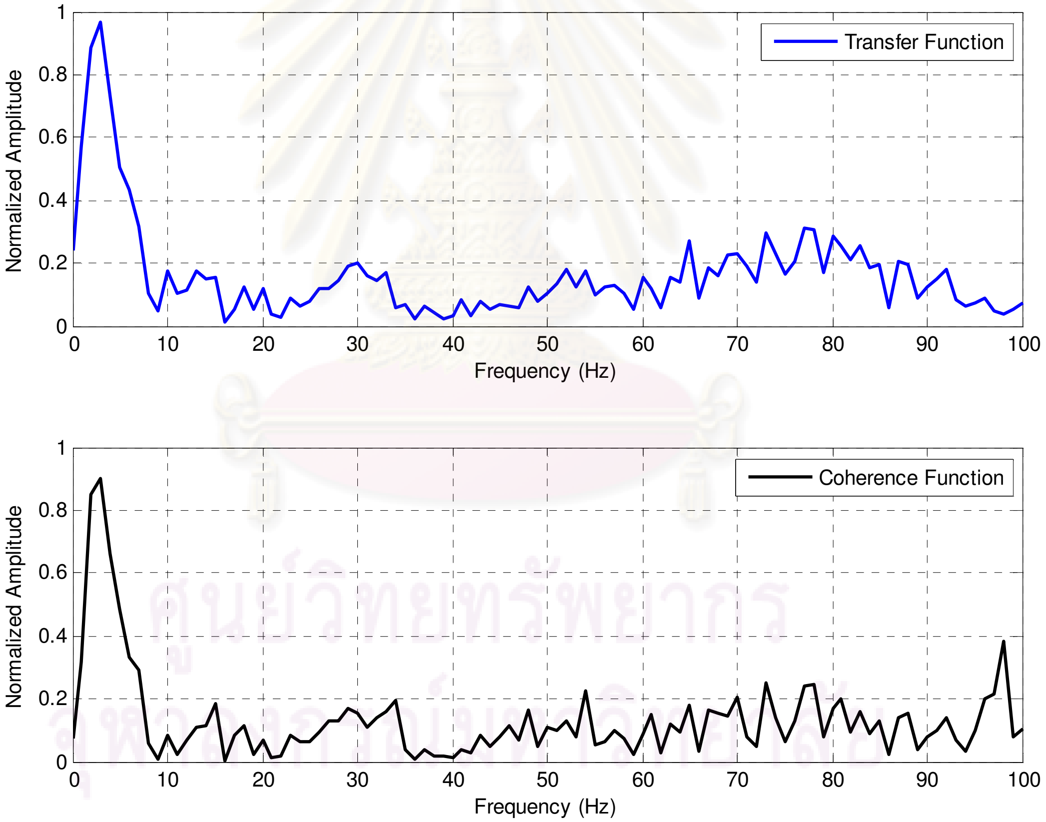


Figure 5-2 Transfer Function and its Coherence function derived from Ambient vibration in Vertical direction

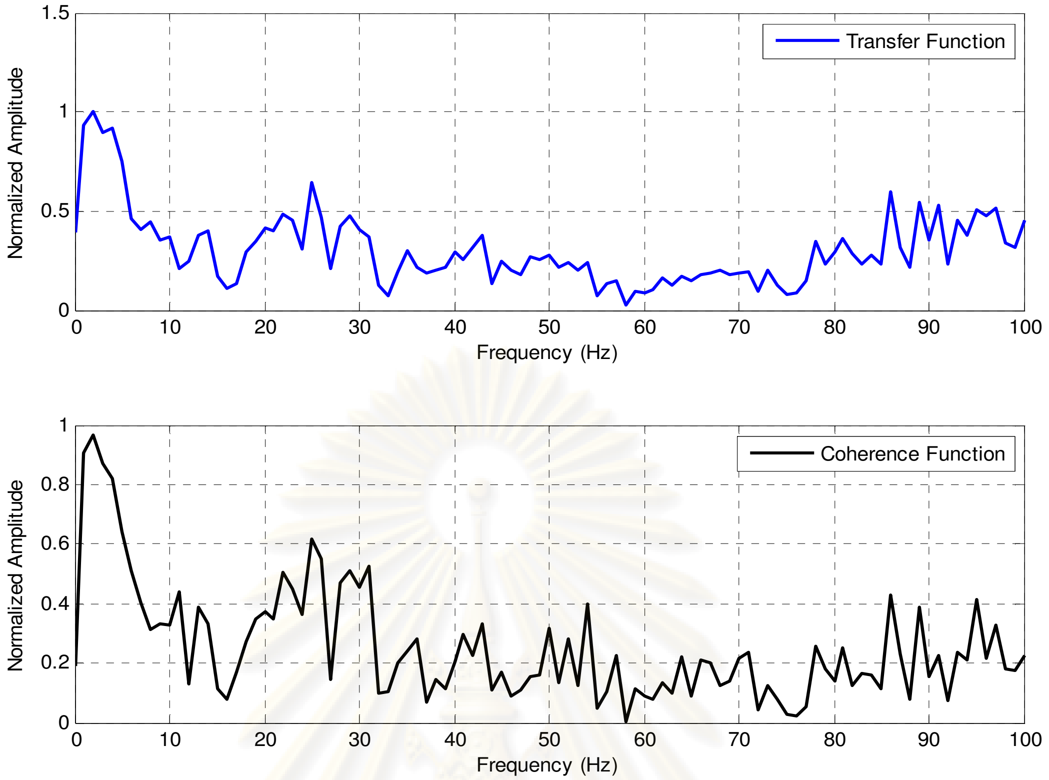


Figure 5-3 Transfer Function and its Coherence Function in derived from Ambient vibration in Radial direction

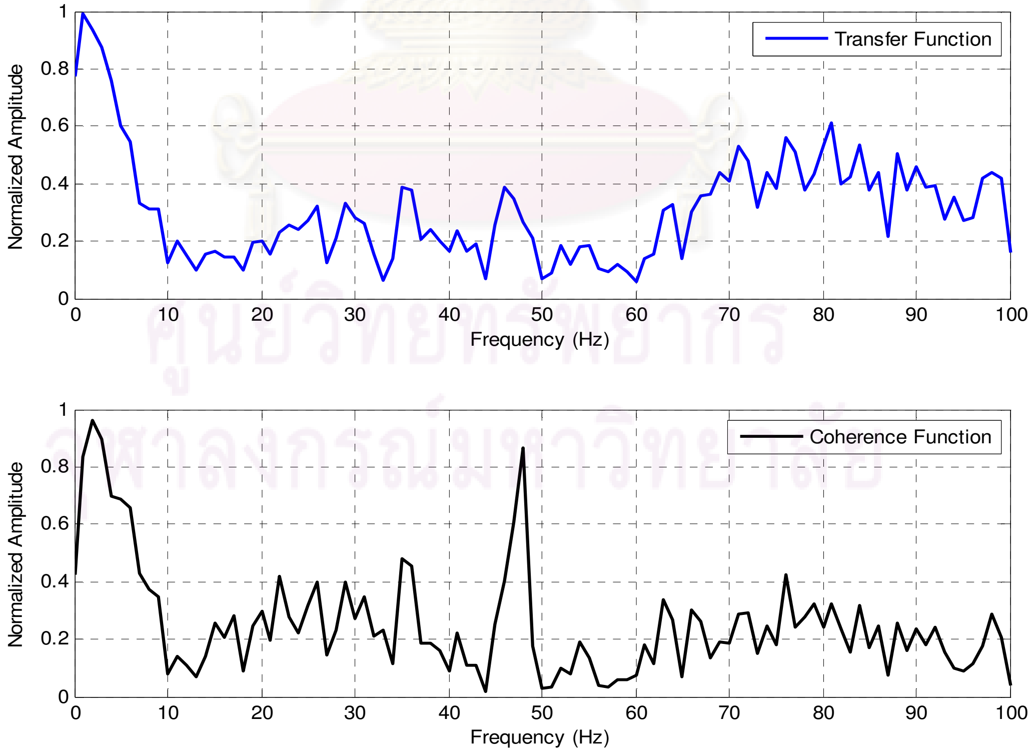


Figure 5-4 Transfer Function and its Coherence Function derive from Ambient vibration in Transversal direction

As mentioned in the previous section, coherence goes from 1 (all the output power at frequency is caused by the input) to 0 (none of the output power at that frequency is caused by the input). From the figures above, the coherence functions (in all directions) show that the system ground-building vibrated with a lot of interference vibration especially in the frequency range of greater than 10Hz. However, the ground-building system shows a good coherence between input signal and output signal at the frequency of 3 – 5 Hz (coherence function close to 1). This illustration agrees well with the spectrum analysis of ground vibration under the ambient vibration since, under the ambient vibration, the ground vibrated at the dominance frequency of 1 to 4 Hz. However, it should notice that in radial and transversal direction, the system seem get the noticeable interference from others vibrations which vibrated at the frequency of 10 to 30 Hz, and at 48 Hz respectively.

5.4 Transfer Function from active source (drop hammer)

Here below are the Transfer Function and the coherence function getting from the vibration generated by dropping hammer in vertical, Radial, and Transversal respectively shown in Figure 5-5 through Figure 5-7.

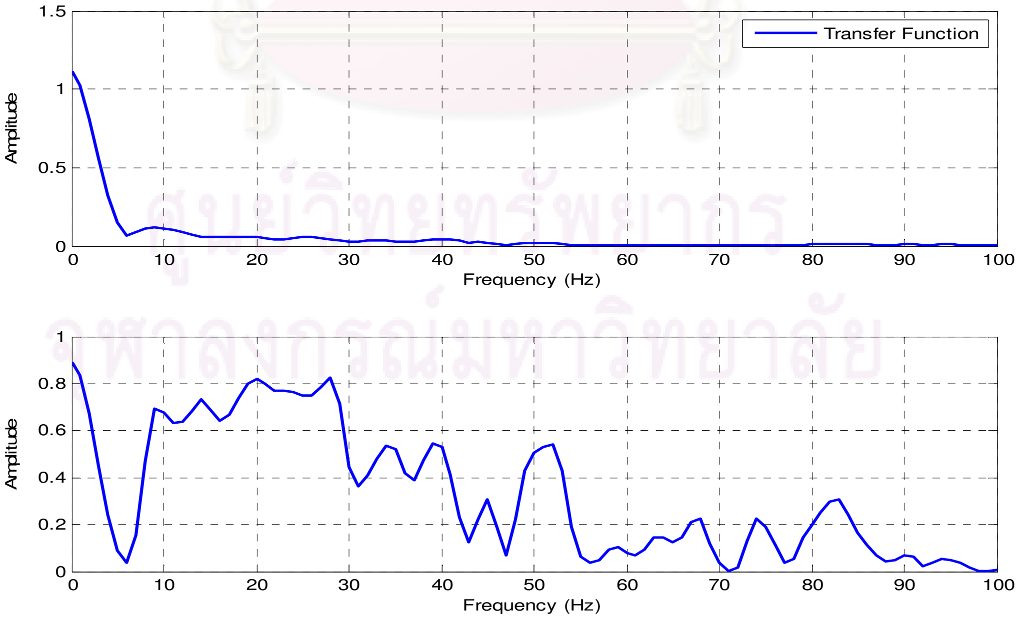


Figure 5-5 Plot of the average Transfer Function and its Coherency Function in vertical direction from 30 separated data of the active source

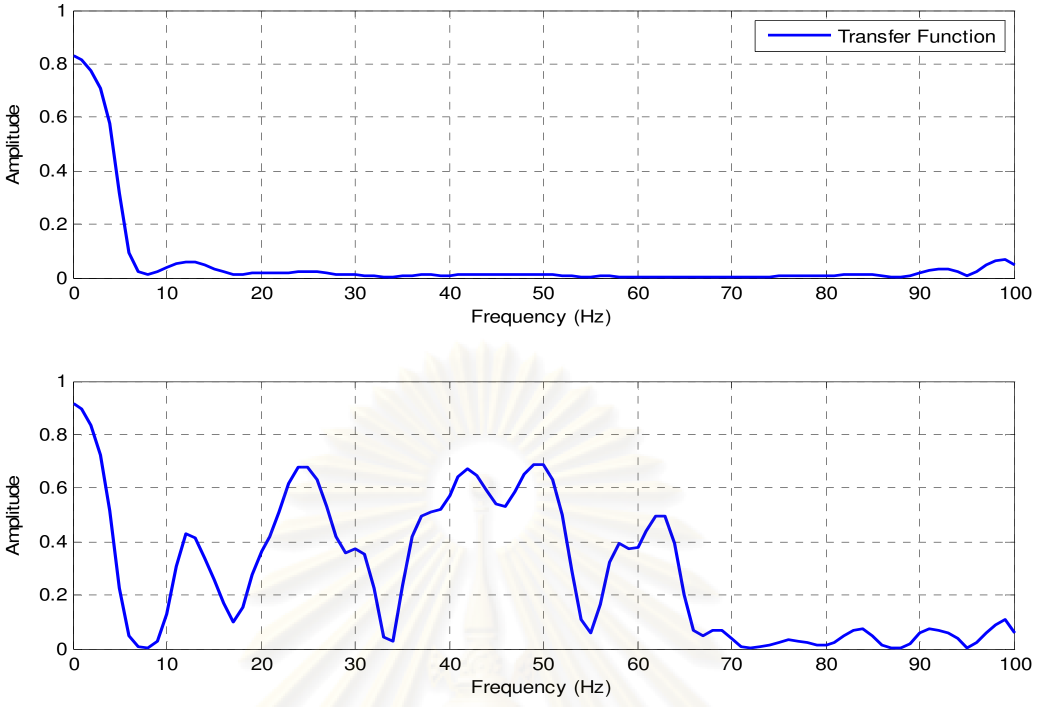


Figure 5-6 Plot of the average Transfer Function and its Coherency Function in radial direction from 30 separated data of the active source

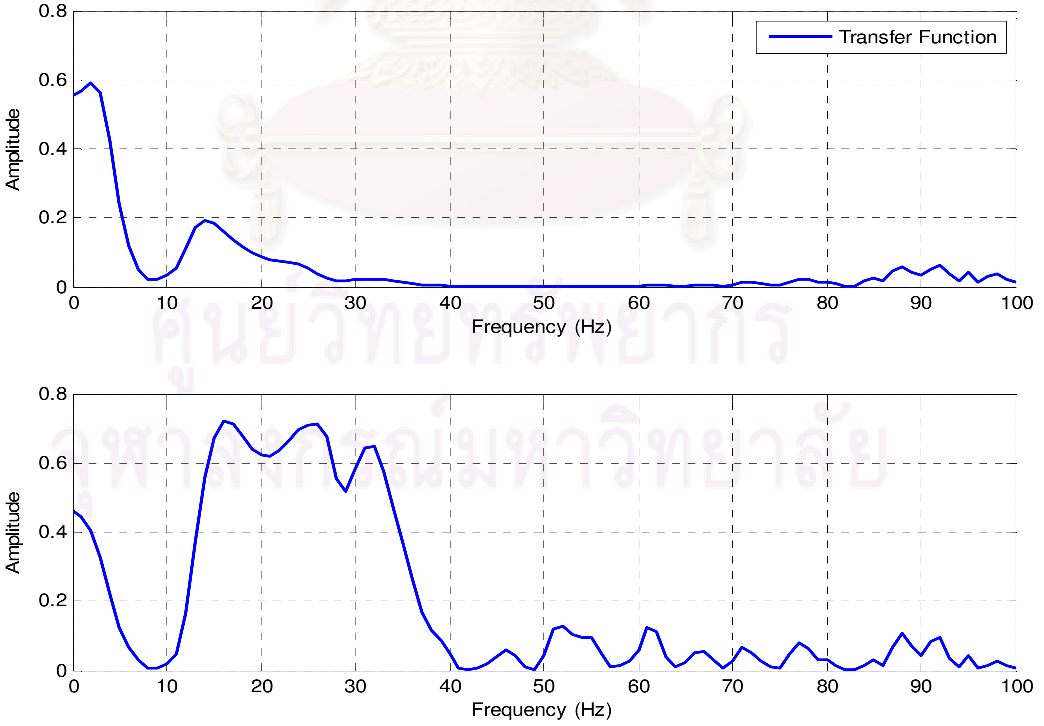


Figure 5-7 Plot of the average Transfer Function and its Coherency Function in transversal direction from 30 separated data of the active source

From the figures above, we can say that there is a good coherence between the input and output because most part of the coherence function gets close to the value of one in the frequency range of 10 Hz to 50 Hz and this is the frequency range at with it was generated by the dropping hammer.

5.5 Making of use of Transfer Function

Here below are the predictions of the building response comparing with the actual measured from the construction site. First the predictions by making use of Transfer Function deriving from ambient vibration are introduced and follow by the predictions by making use of Transfer Function deriving from the hammer vibration. In case, only a typical prediction in each direction is illustrated and follows by the plot of the predicted Peak Particle Velocity (PPV) versus the actual measurement (PPV) of the building response taking from 30 different events. All the 30 predicted events of building response in each case and in each direction are illustrated in the appendices B, C, D, E, F, and G. Below are some typical predictions of building response in three different directions. Each figure below consists of four row and two columns (each column for each event). In each event, from the top to bottom, the plot shows all together in one row, (top row), the particle velocity of input motion, predicted output motion and the measured output motion and constitutively follows by the spectrum of Transfer Function (TF), predicted output spectrum, and the measured spectrum. The input motion is represented by a dash thin-line "—— " and the predicted motion is represented by thick dash with point line " −. " while the measured motion is represented by solid thick-line "—". This configuration is used throughout all events in appendices B to G.

5.5.1 Prediction of Building Response by Making Used TF Derive From Ambient Vibration

5.5.1.1 Prediction in Vertical direction

Figure 5-8 show the predicted building response of two events. For all the predicted 30 events can be found in appendix B. In event 1, the predicted motion has Peak

Particle Velocity (PPV) of 0.47 mm/s and its spectrum shows the dominance frequency at 6 Hz meanwhile the measured motion has PPV of 0.55 mm/s and vibrated at the dominance frequency of 6 Hz.

Table 5-1 is the summery of the 30 predicted PPVs and the dominance frequencies. The predicted and measured Peak Particle Velocities (PPVs) are plotted in Figure 5-9 to check the consistency between the predicted and measured PPVs. Then the pair value of PPVs and its dominance frequencies are used to plot in standard of DIN 4150 in Figure 5-10 to check the severity of the generated vibration onto the building. The description of DIN 4150 can be found in the appendix H.

Figure 5-9 show the plot of the predicted PPVs versus the measured PPVs. In this plot, the predicted lie on the horizontal axis and the measured lie on the vertical axis. The thick-red line (45^{o} line) is used as the consistency reference between the predicted and measured motion. If the predicted equal to the measured, the point will lie on this reference line. Otherwise, the point will appear in the upper line (under estimated) or in the lower line (over estimated).

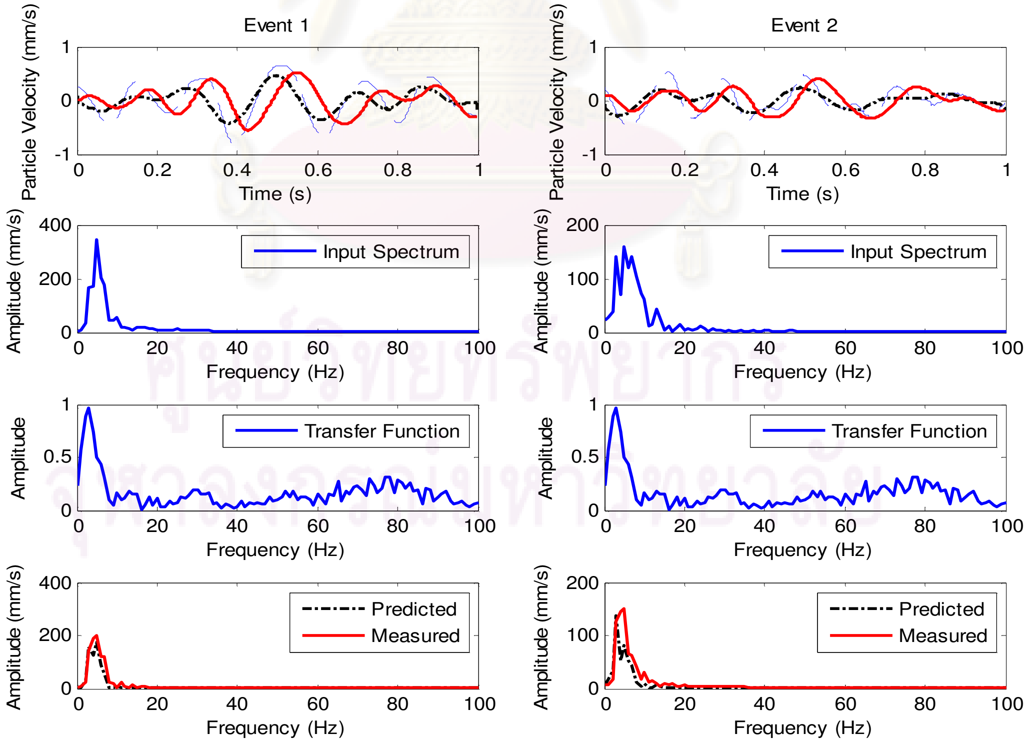


Figure 5-8 Particle velocity of input, predicted, and measured motions (top), input spectrum, transfer function, and the spectrum of predicted and measured motion (bottom) of event 1 and 2 (Ambient vertical).

Table 5-1 Summarized of the predicted and measured of PPVs and Dominance Frequency (Ambient vertical)

Events	PPVs		Dominance Frequency		Events	PPVs		Dominance Frequency	
	Predicted	Measured	Predicted	Measured		Predicted	Measured	Predicted	Measured
1	0.4754	0.5575	6	6	16	0.4258	0.5196	6	6
2	0.2914	0.4026	4	6	17	0.0881	0.0696	6	4
3	0.1669	0.3396	6	5	18	0.1637	0.2044	5	5
4	0.3301	0.3527	4	4	19	0.0863	0.1013	6	6
5	0.4446	0.499	4	4	20	0.1514	0.1676	4	4
6	0.459	0.7634	4	5	21	0.1282	0.1809	4	5
7	0.3872	0.3077	6	6	22	0.239	0.2571	4	4
8	0.284	0.3643	6	6	23	0.1902	0.251	4	4
9	0.2985	0.524	6	5	24	0.1282	0.1714	4	4
10	0.4154	0.5005	6	5	25	0.1403	0.2146	4	5
11	0.3289	0.4549	6	7	26	0.1781	0.236	5	5
12	0.2172	0.3132	4	7	27	0.3319	0.4667	4	4
13	0.206	0.4189	4	4	28	0.2632	0.3641	4	4
14	0.126	0.2011	7	7	29	0.2487	0.3109	6	6
15	0.2009	0.286	4	4	30	0.204	0.3298	5	5

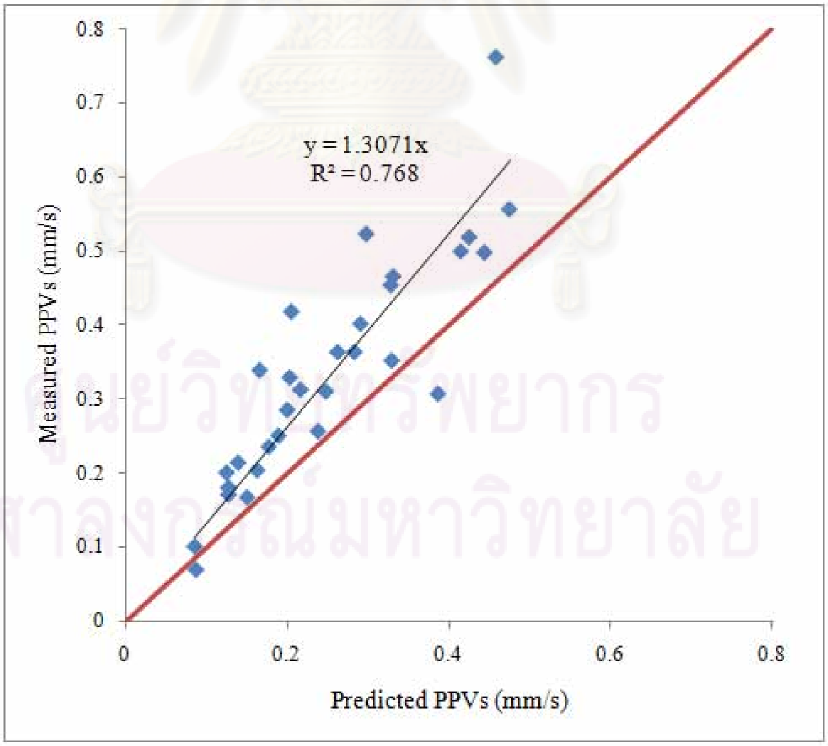


Figure 5-9 Predicted PPVs versus measured PPVs for 30 events (Ambient vertical)

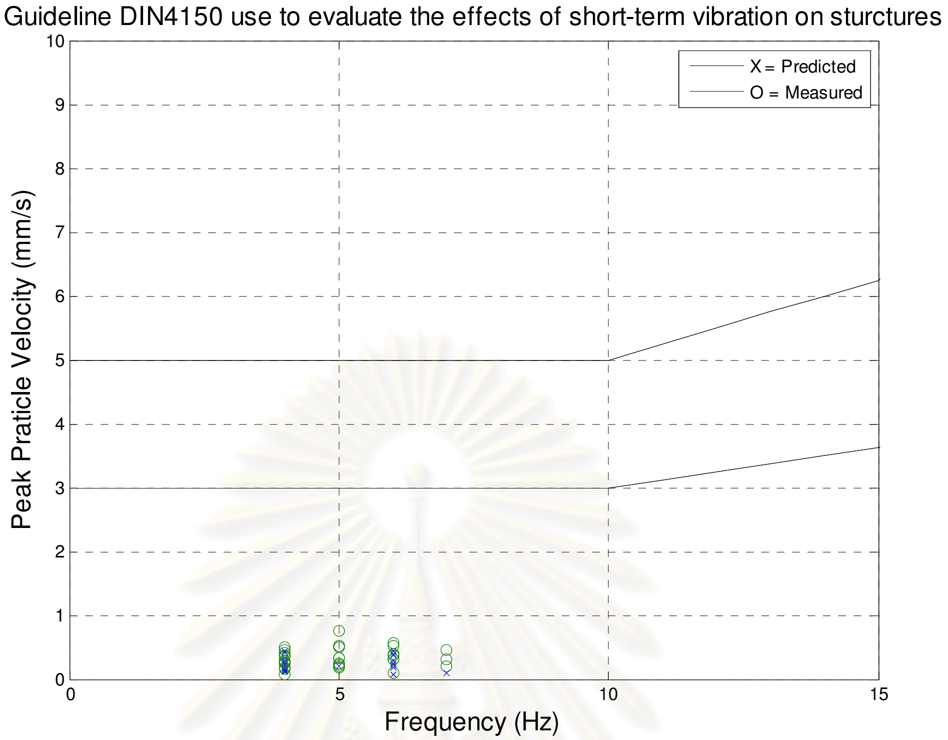


Figure 5-10 Plot of peak particle velocities versus the dominance frequency in DIN 4150 (Ambient vertical)

According to the following reference, http://www.tutorvista.com/answers/how-to-find-r-square/31597(September 2010), the consistency between the predicted and measured can be evaluated by the value of R^2. The value R^2 can be classified as below:

R^2 <30% are considered to have no correlation and behavior is explained by chance
R^2 of 30% to 49.99% are considered to be a mild relationship
R^2 of 50% to 69.99% are considered to be a moderate relationship
R^2 of 70% to 100% are considered to be a strong relationship.

From Figure 5-9, the prediction in this direction shows a bit under estimated with the coefficient of $y = 1.30x$. And base on the R^2 value in this direction, there is a strong relationship between the predicted and the measured since $60\% < R^2 = 76.8\% < 100\%$.

The plot in Figure 5-10 shows that all the generated vibrations are in the safe level.

5.5.1.2 Prediction in Radial direction

Figure 5-11 is a typical predicted building response for two events followed by the Table 5-2 summarized all the predicted and measured of PPVs and the dominance frequency in radial direction. All the 30 predicted events can be found in the appendix C. The predicted motion in this direction, Figure 5-12, shows the value of slightly over estimated with the coefficient of $y= 0.96x$. The consistency between the predicted and measured is in the moderate level ($50\% < R^2 = 51.63\% < 69.99\%$). And the plot in DIN 4150, Figure 5-13, shows that the generated vibrations in this direction are in the safe level.

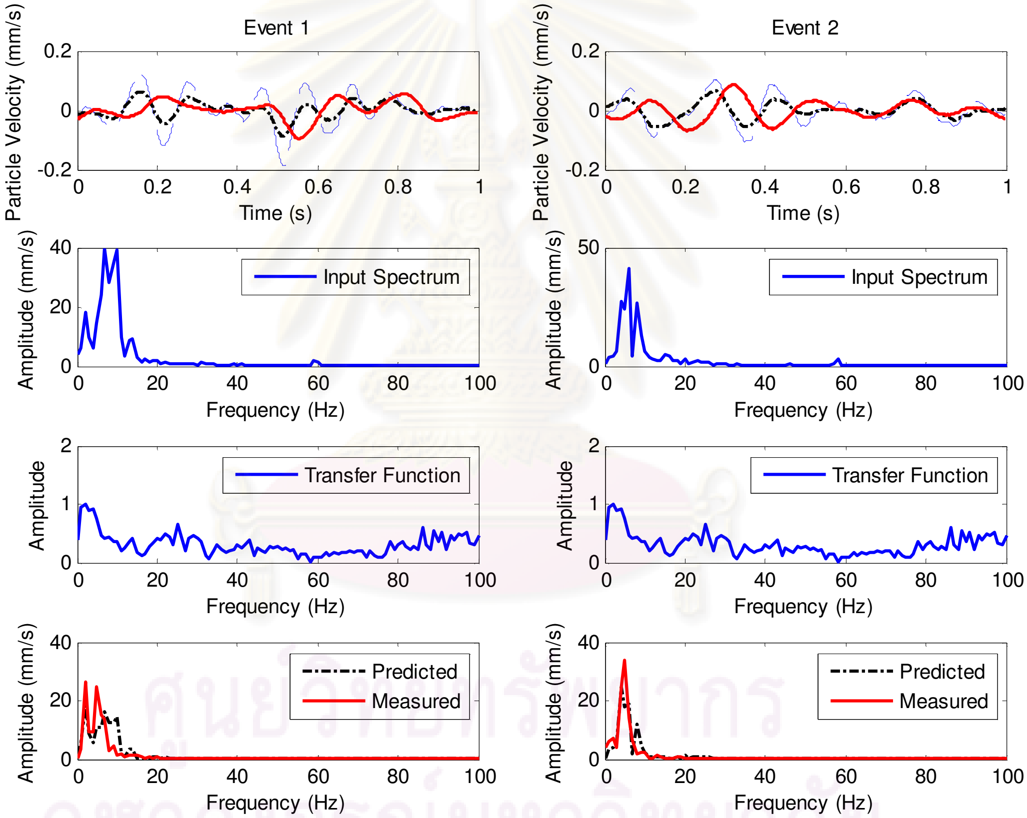


Figure 5-11 Particle velocity of input, predicted, and measured motions (top), input spectrum, transfer function, and the spectrum of predicted and measured motion (bottom) of event 1 and 2 (Ambient radial).

Table 5-2 Summarized of the predicted and measured of PPVs and Dominance Frequency (Ambient radial)

Events	PPVs		Dominance Frequency		Events	PPVs		Dominance Frequency	
	Predicted	Measured	Predicted	Measured		Predicted	Measured	Predicted	Measured
1	0.0885	0.0952	3	3	16	0.098	0.1098	3	3
2	0.0669	0.0861	5	6	17	0.1047	0.1142	3	3
3	0.0613	0.0481	4	4	18	0.12	0.0777	3	3
4	0.0633	0.0527	3	3	19	0.0908	0.1008	5	5
5	0.0698	0.0666	5	5	20	0.142	0.1478	4	4
6	0.0707	0.0561	4	4	21	0.0732	0.0614	4	3
7	0.1278	0.1418	5	5	22	0.1104	0.0932	4	6
8	0.1876	0.1431	5	5	23	0.1312	0.1349	4	4
9	0.1989	0.1493	4	4	24	0.0812	0.0949	3	5
10	0.1516	0.1541	5	5	25	0.0974	0.0899	4	3
11	0.1296	0.1294	3	6	26	0.0794	0.0633	4	4
12	0.1389	0.0823	4	4	27	0.1315	0.1426	3	3
13	0.1456	0.1802	3	3	28	0.0617	0.0753	4	4
14	0.0805	0.1456	4	4	29	0.0621	0.0621	4	5
15	0.1099	0.1133	4	4	30	0.0853	0.1204	4	5

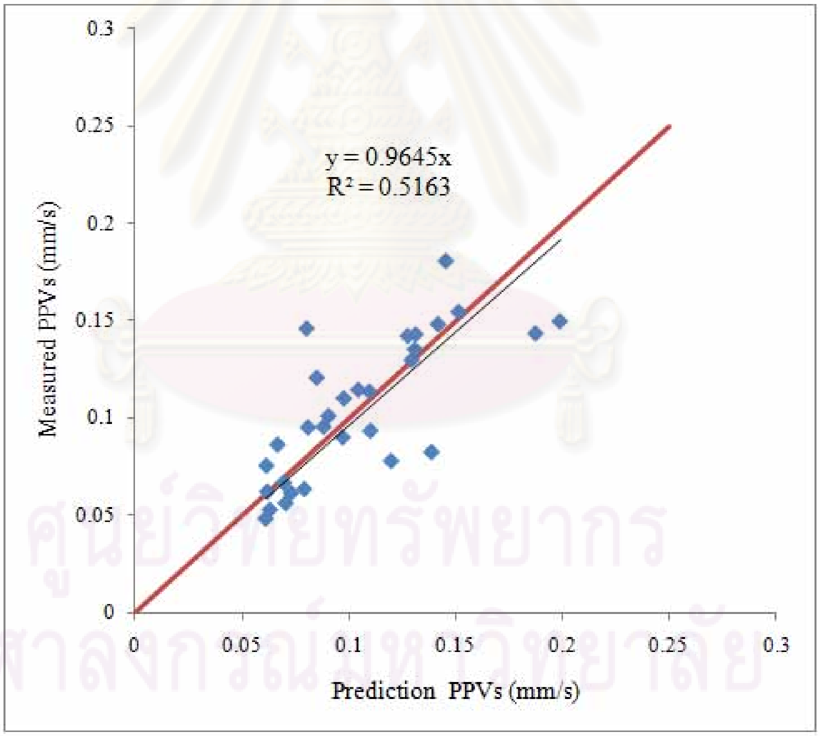


Figure 5-12 Predicted of PPVs versus measured PPVs for 30 events (Ambient radial)

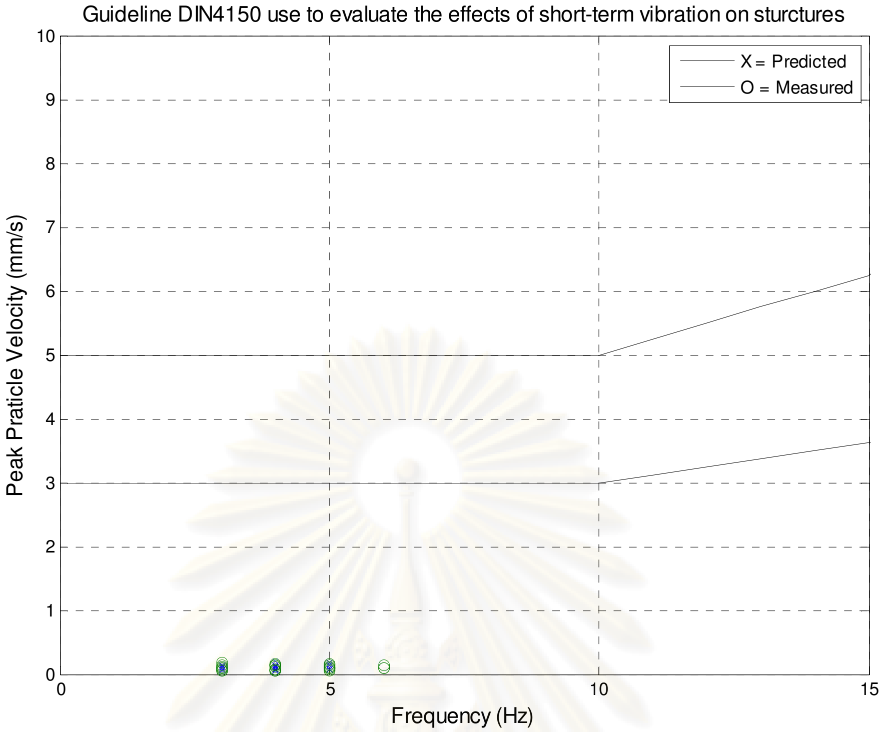


Figure 5-13 Plot of peak particle velocities versus the dominance frequency in DIN 4150 (Ambient radial)

5.5.1.3 Prediction in Transversal direction

Figure 5-14 is a typical predicted building response for two events followed by the Table 5-3 summarized all the predicted PPVs and measured PPVs in transversal direction. All the 26 predicted events can be found in the appendix D. The plot in Figure 5-15 shows that the predicted value is a bit over estimated with the coefficient of $y= 0.89x$. The consistency between the predicted and measured is in the moderate level ($50\% < R^2 = 68.73\% < 69.99\%$). And the plot in DIN4150, Figure 5-16, shows that the generated vibrations are in safe level.

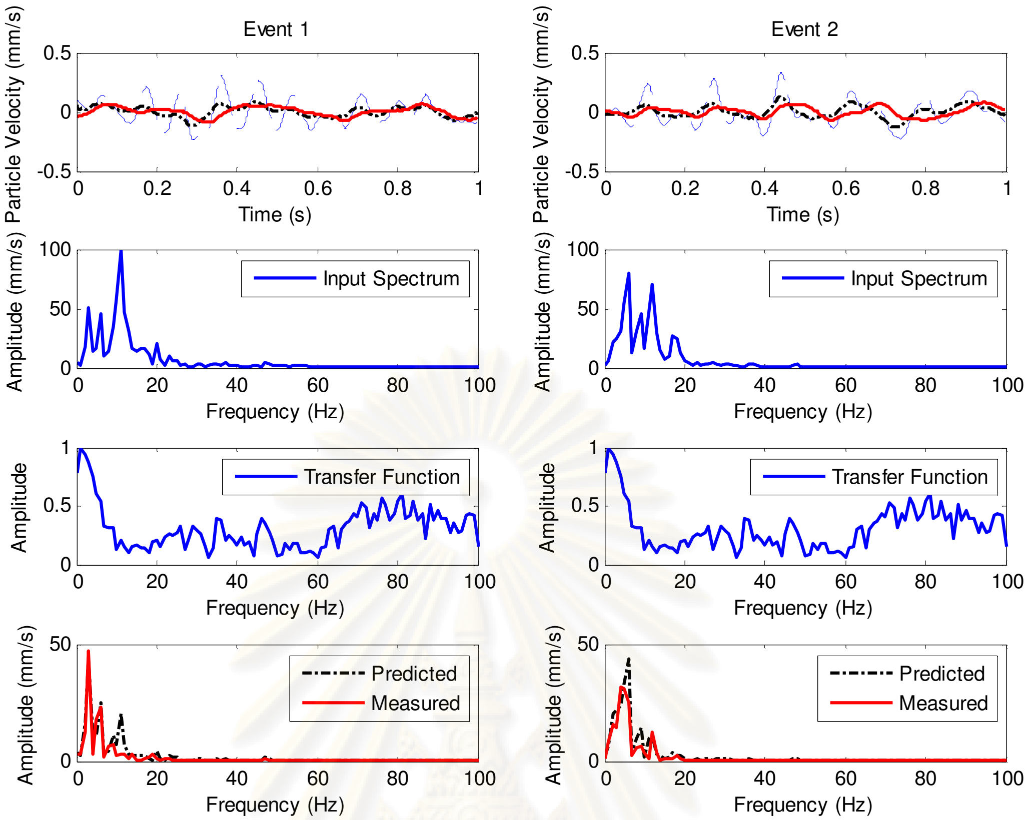


Figure 5-14 Particle velocity of input, predicted, and measured motions (top), input spectrum, transfer function, and the spectrum of predicted and measured motion (bottom) of event 1 and 2 (Ambient Transversal).

Table 5-3 Summarized of the predicted and measured of PPVs and Dominance Frequency (Ambient transversal)

Events	PPVs		Dominance Frequency		Events	PPVs		Dominance Frequency	
	Predicted	Measured	Predicted	Measured		Predicted	Measured	Predicted	Measured
1	0.1169	0.0916	4	4	14	0.1882	0.1459	4	4
2	0.1265	0.08	7	5	15	0.1381	0.1001	6	6
3	0.2207	0.2086	4	4	16	0.2557	0.2345	4	4
4	0.1367	0.1681	4	4	17	0.1065	0.0613	7	4
5	0.1448	0.1505	4	4	18	0.1458	0.1329	6	4
6	0.0996	0.1177	4	4	19	0.1463	0.1463	6	6
7	0.1786	0.1541	7	4	20	0.1629	0.1885	6	6
8	0.2018	0.1648	7	5	21	0.1319	0.0955	7	7
9	0.1758	0.1671	4	4	22	0.1797	0.179	6	6
10	0.1424	0.1704	4	4	23	0.1872	0.1504	6	6
11	0.1661	0.1202	7	7	24	0.0889	0.0929	4	4
12	0.1395	0.1036	7	7	25	0.1622	0.1546	6	7
13	0.2475	0.2176	4	4	26	0.193	0.1447	6	6

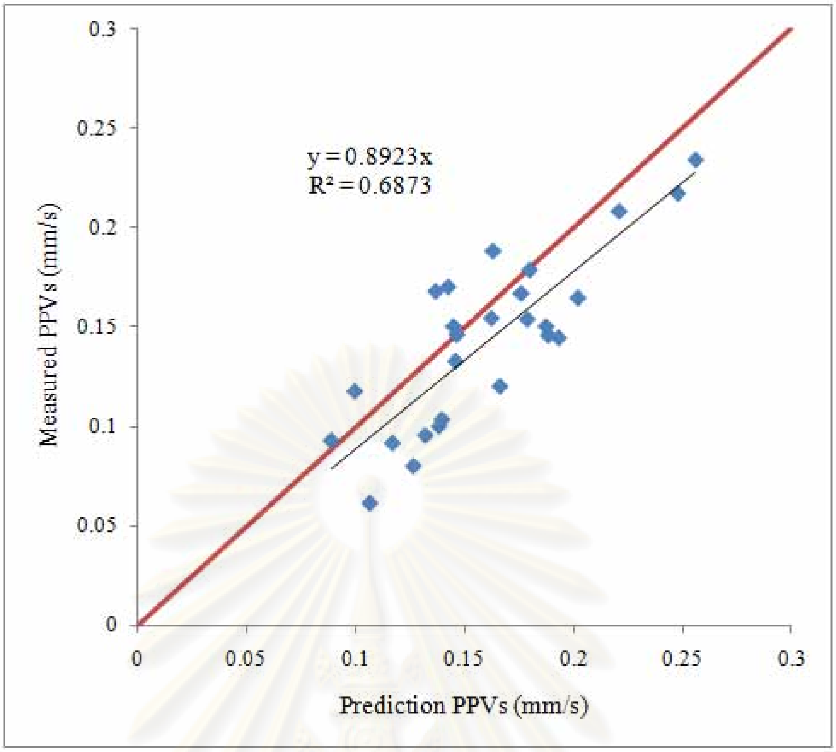
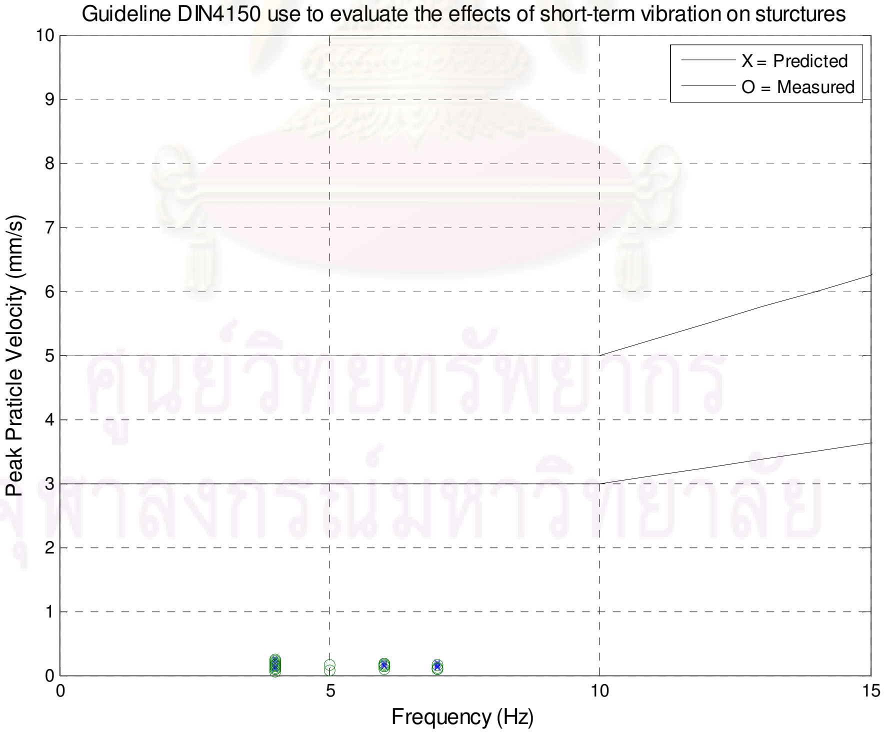


Figure 5-15 Predicted of PPVs versus measured PPVs for 26 events (Ambient transversal)



n DIN 4150

5.5.2 Prediction of Building Response by Making Used TF Derive From Hammer vibration

By applying the same process of data analysis, here below are the results of the predicted building response by making used of Transfer Function deriving from hammer vibration.

5.5.2.1 Prediction in Vertical direction

Figure 5-17 is a typical predicted building response for two events followed by the Table 5-4 summarized all the predicted and measured of PPVs and the dominance frequency in vertical direction. All the 30 predicted events can be found in the appendix E. The predicted motion in this direction, Figure 5-18, shows the value of much under estimated with the coefficient of $y= 3.07\,x$. The consistency between the predicted and measured is in the moderate level ($50\% < R^2 = 69.26\% < 69.99\%$). And the plot in DIN 4150, Figure 5-19, shows that the generated vibrations in this direction are in the safe level.

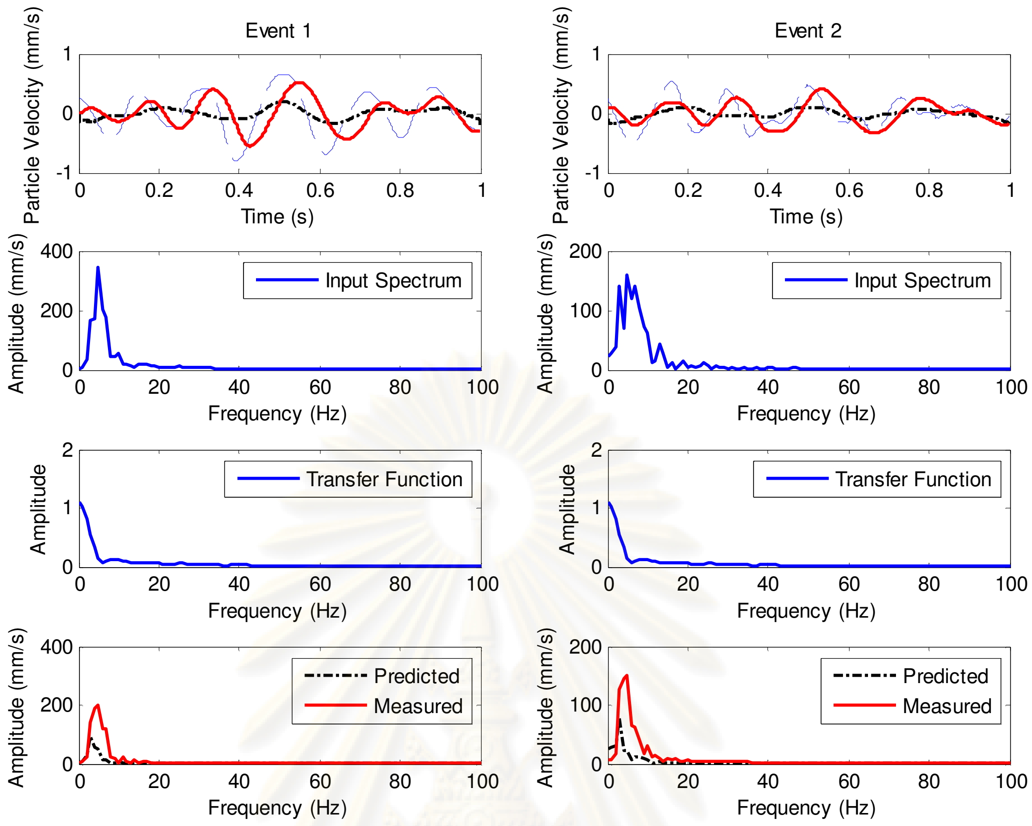
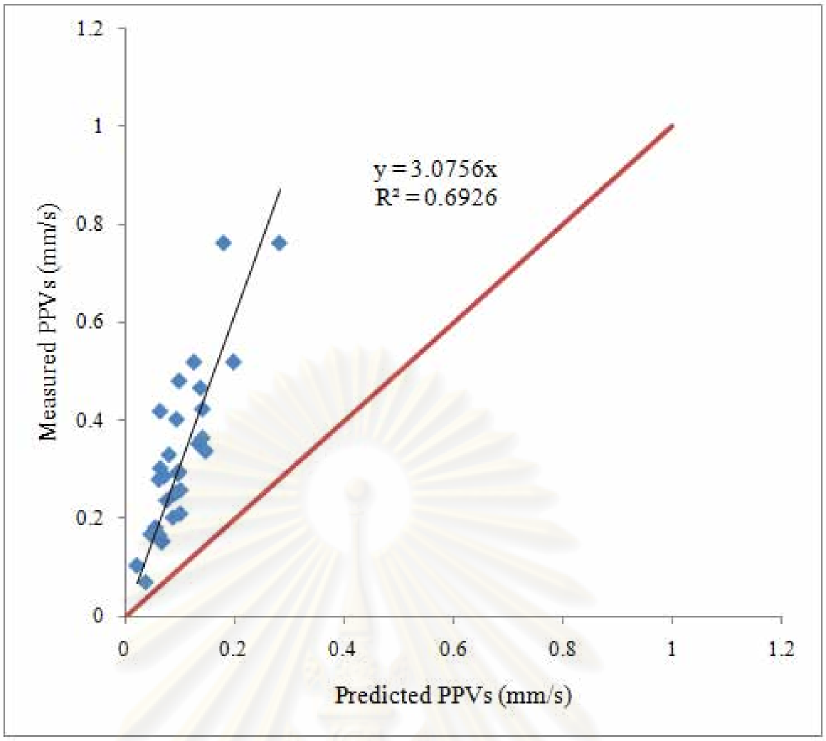


Figure 5-17 Particle velocity of input, predicted, and measured motions (top), input spectrum, transfer function, and the spectrum of predicted and measured motion (bottom) of event 1 and 2 (Hammer vertical).

Table 5-4 Summarized of the predicted and measured of PPVs and Dominance Frequency (Hammer vertical)

Events	PPVs		Dominance Frequency		Events	PPVs		Dominance Frequency	
	Predicted	Measured	Predicted	Measured		Predicted	Measured	Predicted	Measured
1	0.1993	0.5197	4	6	16	0.1268	0.5196	6	6
2	0.095	0.4026	4	6	17	0.0383	0.069	4	4
3	0.0626	0.2792	5	5	18	0.0671	0.1518	4	5
4	0.1349	0.3527	4	4	19	0.0222	0.1031	6	6
5	0.1811	0.7634	4	4	20	0.0638	0.1654	4	4
6	0.283	0.7634	4	5	21	0.0565	0.1809	4	5
7	0.1017	0.20895	4	6	22	0.102	0.2571	4	4
8	0.1424	0.3643	5	6	23	0.0926	0.251	4	4
9	0.0997	0.481	6	5	24	0.0694	0.1527	4	4
10	0.1425	0.4232	4	5	25	0.0478	0.167	4	5
11	0.1481	0.3374	4	7	26	0.0768	0.236	4	5
12	0.0652	0.302	4	7	27	0.1387	0.4667	4	4
13	0.0649	0.4189	4	4	28	0.0978	0.291	4	4
14	0.0885	0.2011	4	7	29	0.0988	0.2958	4	6
15	0.0732	0.286	4	4	30	0.0812	0.3298	5	5



: vertical)

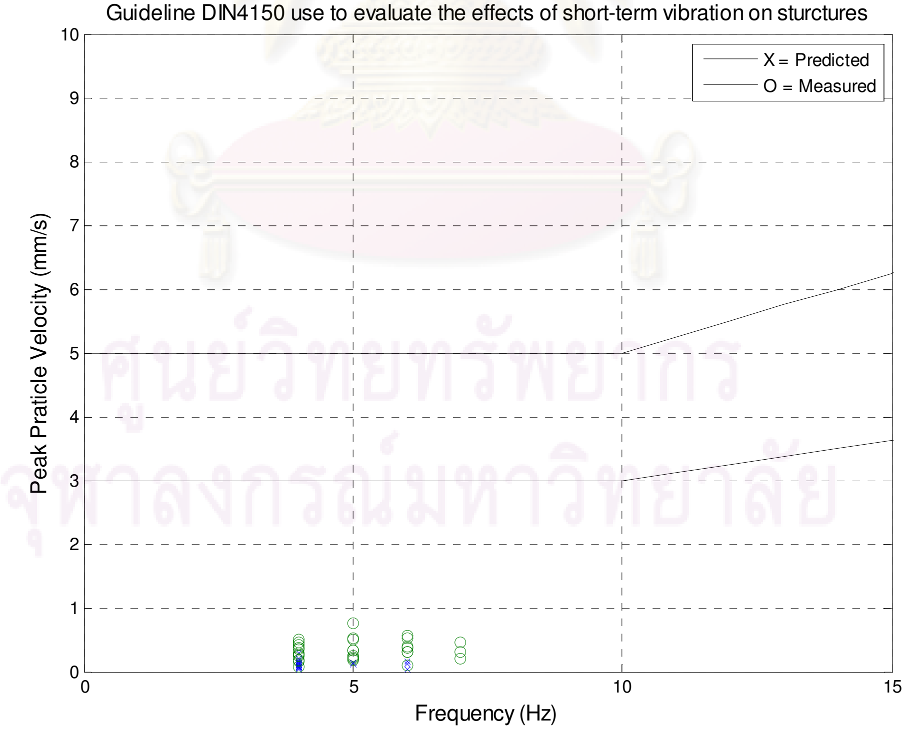


Figure 5-19 Plot of peak particle velocities versus the dominance frequency in DIN 4150 (Hammer vertical)

5.5.2.2 Prediction in Radial direction

Figure 5-20 is a typical predicted building response for two events followed by the Table 5-5 summarized all the predicted and measured of PPVs and the dominance frequency in vertical direction. All the 30 predicted events can be found in the appendix F. The predicted motion in this direction, Figure 5-21, shows the value of a bit under estimated with the coefficient of $y = 1.66x$. The consistency between the predicted and measured is in the moderate level ($50\% < R^2 = 64.96\% < 69.99\%$). And the plot in DIN 4150, Figure 5-22, shows that the generated vibrations in this direction are in the safe level.

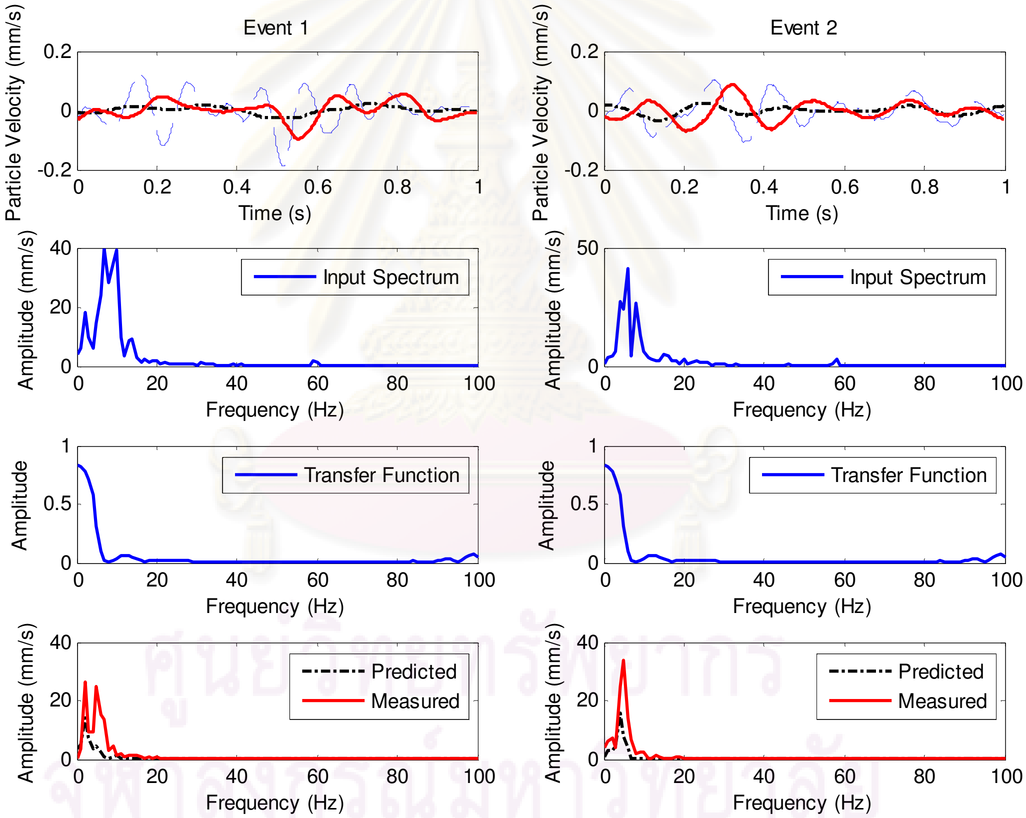
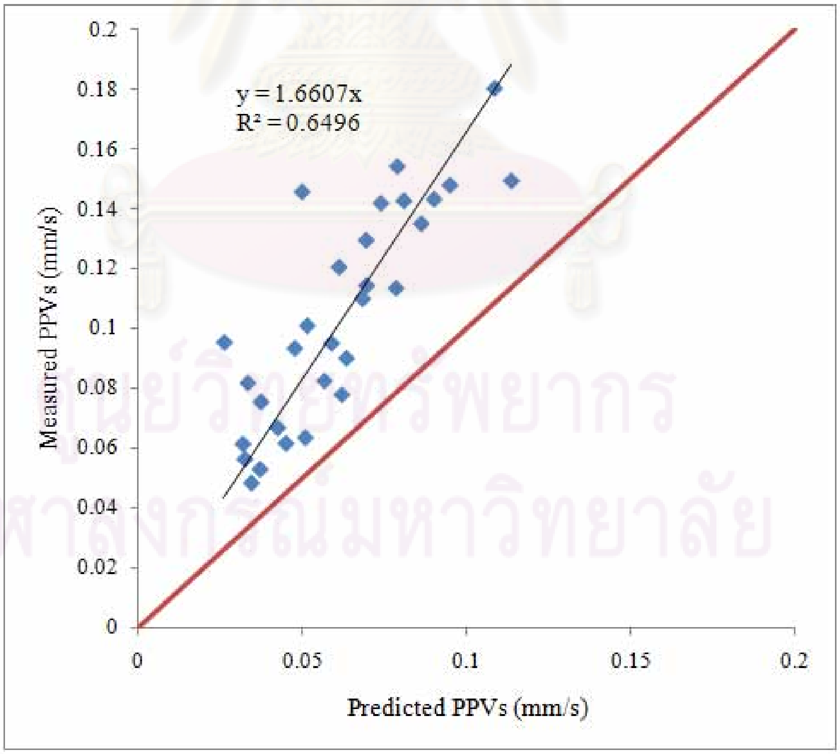


Figure 5-20 Particle velocity of input, predicted, and measured motions (top), input spectrum, transfer function, and the spectrum of predicted and measured motion (bottom) of event 1 and 2 (Hammer radial).

Table 5-5 Summarized of the predicted and measured of PPVs and Dominance Frequency (Hammer radial)

Events	PPVs		Dominance Frequency		Events	PPVs		Dominance Frequency	
	Predicted	Measured	Predicted	Measured		Predicted	Measured	Predicted	Measured
1	0.0261	0.0952	3	3	16	0.0681	0.1098	3	3
2	0.0332	0.0816	5	6	17	0.0693	0.1142	3	3
3	0.0343	0.0481	4	4	18	0.0618	0.0777	3	3
4	0.0369	0.0527	3	3	19	0.0513	0.1008	5	5
5	0.0423	0.0666	4	5	20	0.0947	0.1478	4	4
6	0.0323	0.0561	4	4	21	0.0448	0.0614	4	3
7	0.0737	0.1418	5	5	22	0.0475	0.0932	4	6
8	0.0899	0.1431	5	5	23	0.086	0.1349	4	4
9	0.1134	0.1493	4	4	24	0.0587	0.0949	3	5
10	0.0787	0.1541	5	5	25	0.0632	0.0899	4	3
11	0.0692	0.1294	3	6	26	0.0507	0.0633	4	4
12	0.0565	0.0823	4	4	27	0.0807	0.1426	3	3
13	0.1083	0.1802	3	3	28	0.0372	0.0753	4	4
14	0.0497	0.1456	4	4	29	0.0317	0.0612	4	5
15	0.0783	0.1133	4	4	30	0.061	0.1204	4	5



er radial)

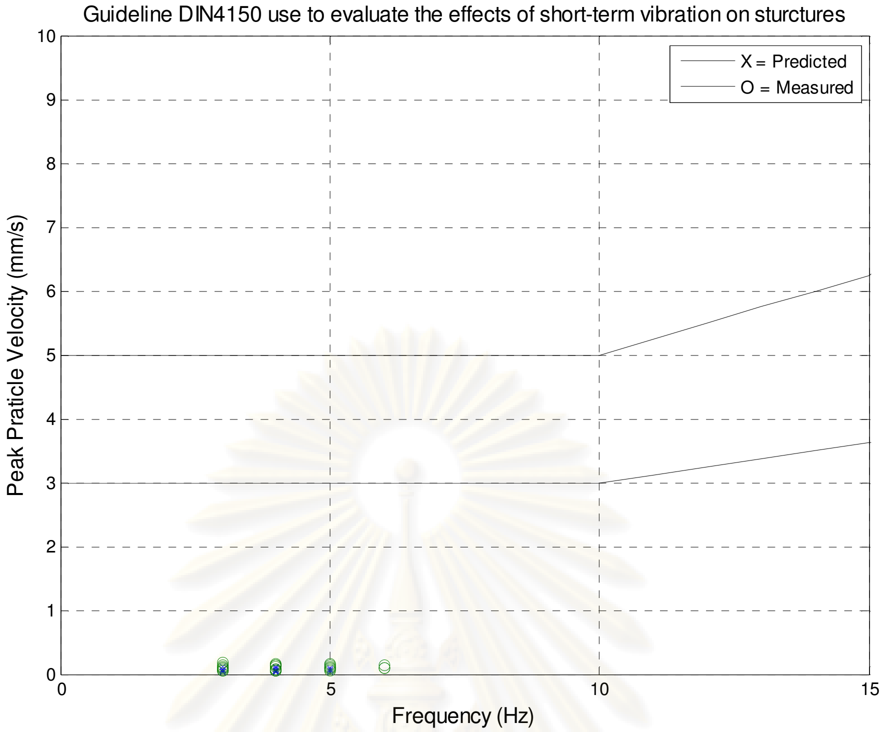


Figure 5-22 Plot of peak particle velocities versus the dominance frequency in DIN 4150 (Hammer radial)

5.5.2.3 Prediction in Transversal direction

Figure 5-23 is a typical predicted building response for two events followed by the Table 5-6 summarized all the predicted and measured of PPVs and the dominance frequency in vertical direction. All the 30 predicted events can be found in the appendix G. The predicted motion in this direction, Figure 5-24, shows the value of nearly twice under estimated with the coefficient of *y= 0.96x*. The consistency between the predicted and measured is in the moderate level (50% < R^2 = 64.96% < 69.99%). And the plot in DIN 4150, Figure 5-25, shows that the generated vibrations in this direction are in the safe level.

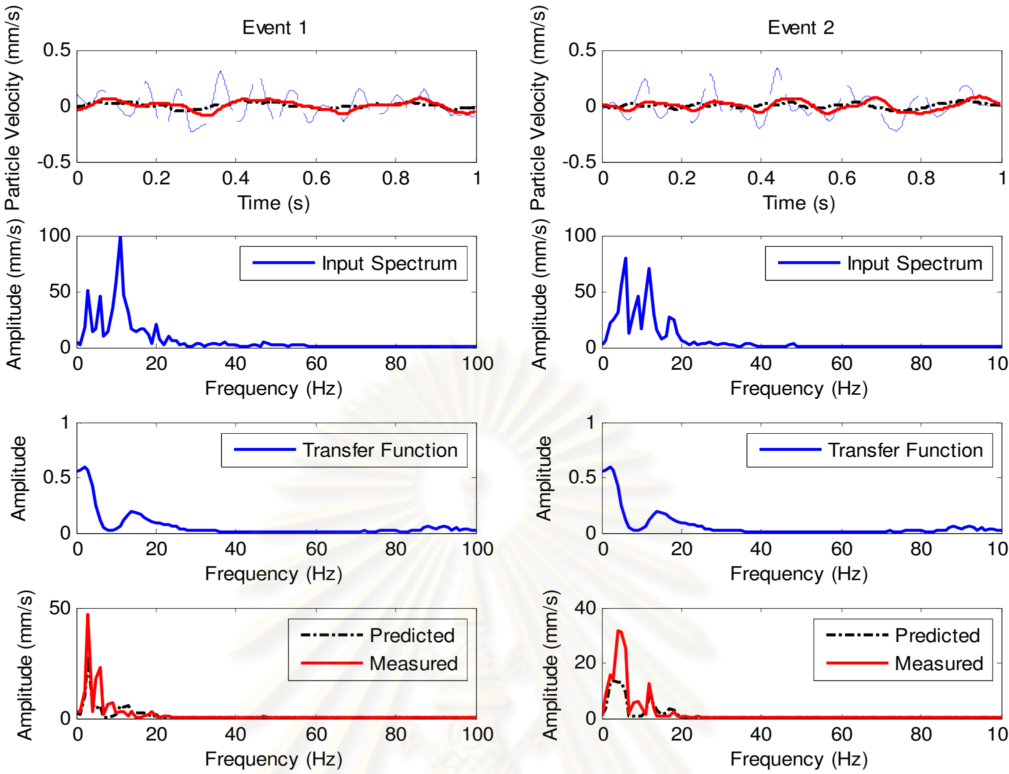
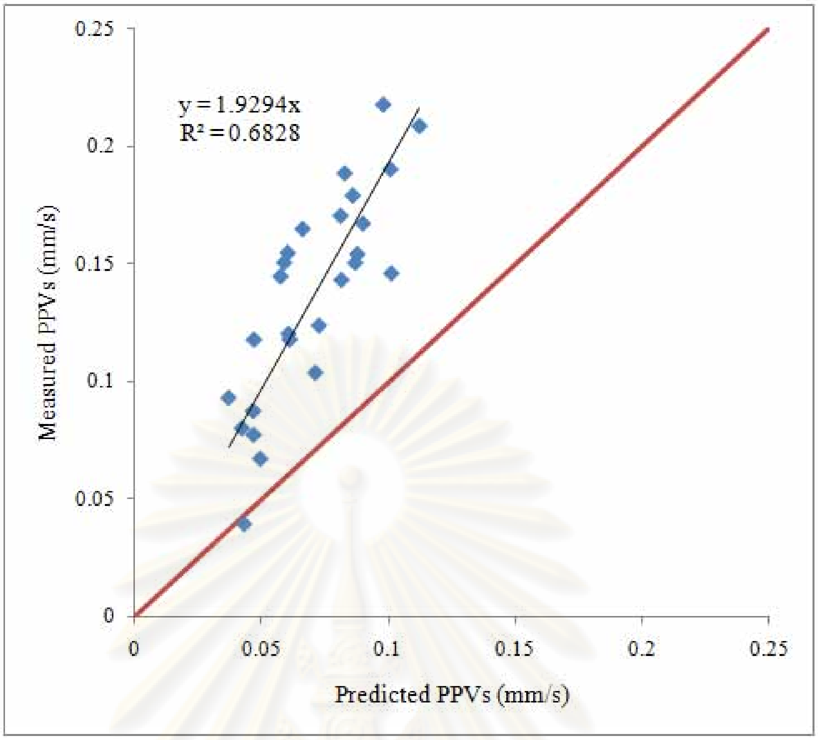


Figure 5-23 Particle velocity of input, predicted, and measured motions (top), input spectrum, transfer function, and the spectrum of predicted and measured motion (bottom) of event 1 and 2 (Hammer transversal).

Table 5-6 Summarized of the predicted and measured of PPVs and Dominance Frequency (Hammer transversal)

Events	PPVs		Dominance Frequency		Events	PPVs		Dominance Frequency	
	Predicted	Measured	Predicted	Measured		Predicted	Measured	Predicted	Measured
1	0.0496	0.067	4	4	14	0.0611	0.1178	4	4
2	0.0424	0.08	4	5	15	0.0576	0.1446	6	6
3	0.0877	0.1541	4	4	16	0.0827	0.1885	4	6
4	0.0662	0.1648	5	5	17	0.047	0.0772	4	7
5	0.0899	0.1671	4	4	18	0.0859	0.179	6	6
6	0.0811	0.1704	4	4	19	0.0869	0.1504	4	6
7	0.0607	0.1202	7	7	20	0.0372	0.0929	4	4
8	0.0712	0.1036	2	7	21	0.0604	0.1546	6	7
9	0.1007	0.1902	4	4	22	0.0814	0.1431	6	6
10	0.101	0.1459	4	4	23	0.1121	0.2086	4	4
11	0.0468	0.0873	5	6	24	0.0727	0.1237	4	4
12	0.0979	0.2177	4	4	25	0.059	0.1505	4	4
13	0.0433	0.0392	3	4	26	0.0472	0.1177	4	4



ransversal)

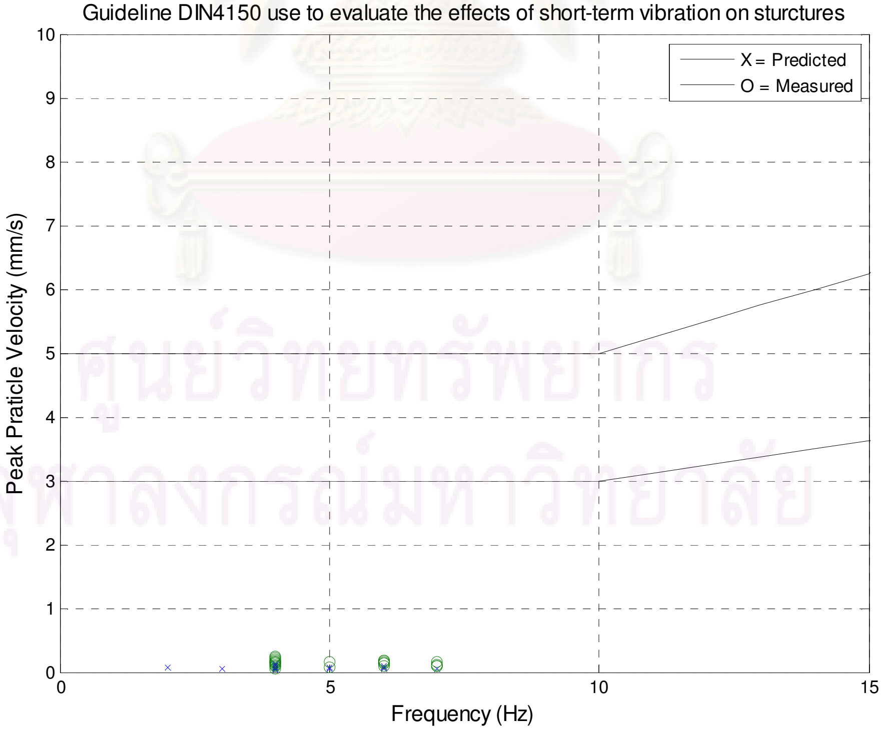


Figure 5-25 Plot of peak particle velocities versus the dominance frequency in DIN 4150 (Hammer transversal)

5.6 Result Discussion

The results in this study show that, both ambient vibration and hammer vibration can be used to predict the response of building from the construction sited. Here below are the comparisons of the results of the prediction getting from ambient vibration and hammer vibration.

Table 5-7 Summery of the predicted results getting from both ambient vibration and hammer vibration

Source	Ambient Vibration				Hammer Vibration			
Direction	Predicted equation	Coeff.	Level	Consistency	Predicted equation	Coeff.	Level	Consistency
Vertical	Y = 1.307 X	1.307	Under Estimated	High	Y = 3.075 X	3.077	Under Estimated	Moderate
Radial	Y = 0.964 X	0.964	Over Estimated	Moderate	Y = 1.66 X	1.66	Under Estimated	Moderate
Transversal.	Y = 0.892 X	0.892	Over Estimated	Moderate	Y = 1.929 X	1.929	Under Estimated	Moderate

From the Table 5-7, we can see that the prediction by making use of ambient vibration give the result of much close to the measured motion with coefficient close to 1 (0.892 to 1.307). On the other hand, the predictions by making use of hammer vibration give most of the results of much far away from the measured motion with the coefficient of at one and a half to three times less than the measured motions. These results shown that building vibrated in different mod shape and the different mode shape is the suspect source that lead to different prediction between the ambient vibration and hammer vibration.

CHAPTER VI
CONSCLUSION

This study tried to stimulate the response of buildings to ground vibration by transfer function. The transfer function can be defined as the ratio between output and input signal in frequency domain. To determine the transfer function of a building, 30 two-point measurements were carried out under each of ambient vibration and man-made vibration by weight dropping. Transfer functions obtained from the former and the later conditions were called the ambient transfer function and active transfer function, respectively.

To evaluate the fidelity of obtained transfer functions, field data were taken from the same site under vibration generated from a nearby building demolition. It was found the ambient transfer function gave better predictions than the active one. Since the frequency contents of the verification signal and those of the ambient vibration fell in a same range (0 – 10 Hz) and differed from these of the active condition, it was assumed that the building might vibrate in different modes of vibration under the active condition.

As the peak particle velocity and dominant frequency are key parameters for severity evaluation of building by many standards, comparisons were made between predicted and verification data. For the PPV, it was found that the ambient transfer function predicted the building response with a moderate degree of determination. Nonetheless, the measured PPVs were slightly underestimated by the function and it will have to be investigated further. Regarding the dominant frequency, the ambient transfer function gave the predicted dominance frequency with a moderate degree of determination in all directions; meanwhile the active transfer function gave the predicted dominance frequency with a low degree of determination in vertical direction and with a moderate degree of determination in other two directions.

In sum, the response of a building has been estimated with a certain degree of success by the proposed transfer function. However, there are still some areas needed to be investigated further. To achieve an accurate result under current finding, it is necessary to assess that the frequency contents of stimulating signal is approximately in the same range as those of ambient vibration.

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APPENDICES

APPENIX A
UNIT CONVERSION TABLE

Table A-1 Unit Conversion Use with Vibration Meter (Instruction Manual of SERVO Type Vibration Meter Model: VM - 5112

range	Input Voltage (mV)	Input Voltage (V)	Acceleration (cm/s^2)	Velocity (cm/s)	Displacement (m m^{p-p})	Degree (^{o})
1	**±2**	**±5**	**1**	**0.1**	**1**	**-**
3	±6	±5	3	0.3	3	-
10	±20	±5	10	1	10	-
30	±60	±5	30	3	30	-
100	±200	±5	100	10	100	-
300	±600	±5	300	30	300	-
1000	±2000	±5	1000	100	1000	-
TILT	±1	±5	-	-	-	±30
OFF	-	±0	-	-	-	-
CAL	-	+5	F.S	F.S	F.S	F.S
Auto(100)	±200	±5	100	10	100	-
Auto(500)	±1000	±5	500	50	-	-
Auto(1000)	±2000	±5	1000	100	-	-

Note: Displacement is P-P value.

Max. measurement range is determined by max. acceleration range 20/s^2 of pickup.

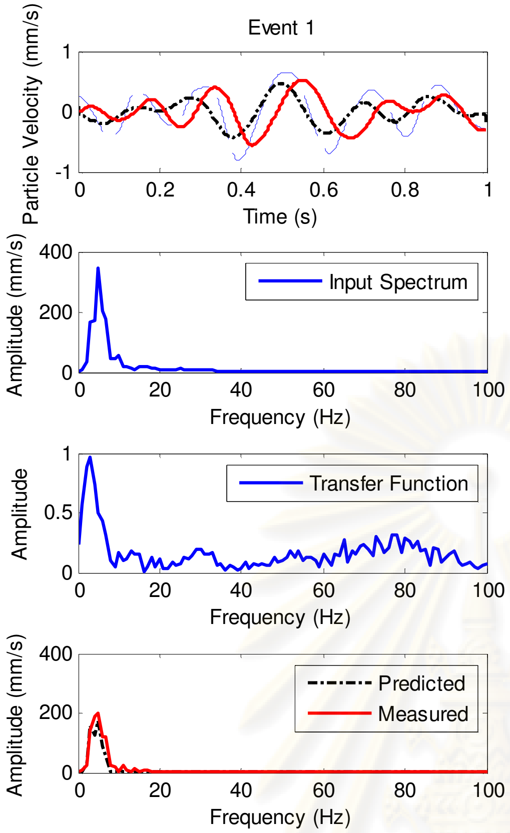
Calculation of vibration velocity

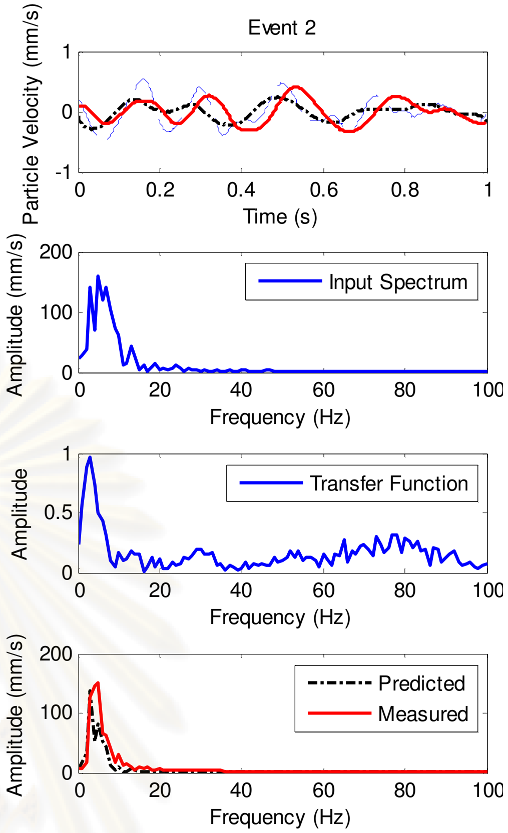
Selected range = X1 ⟶ conversion factor = 0.1cm/s = 1mm/s

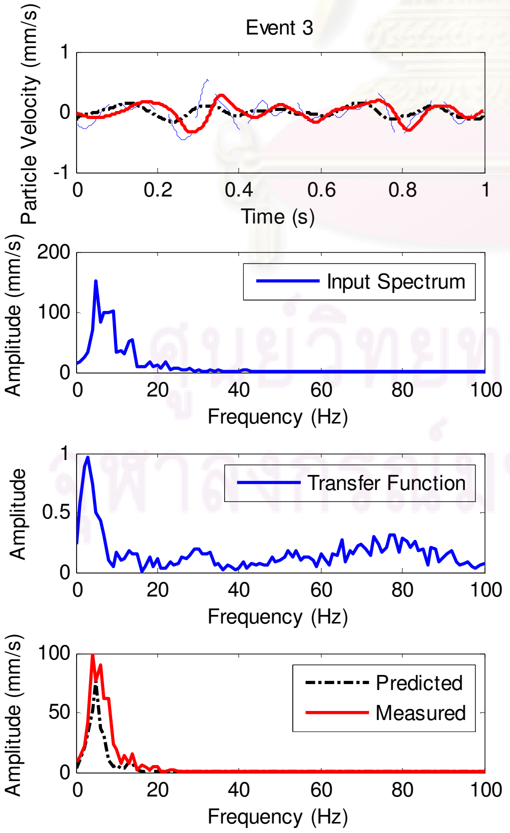
$$VibrationVelocity = \frac{MeasureVelocityVoltage\left(V\right)}{CalibrationVoltage\left(5V\right)} \times 0.1\left(cm/s\right)$$

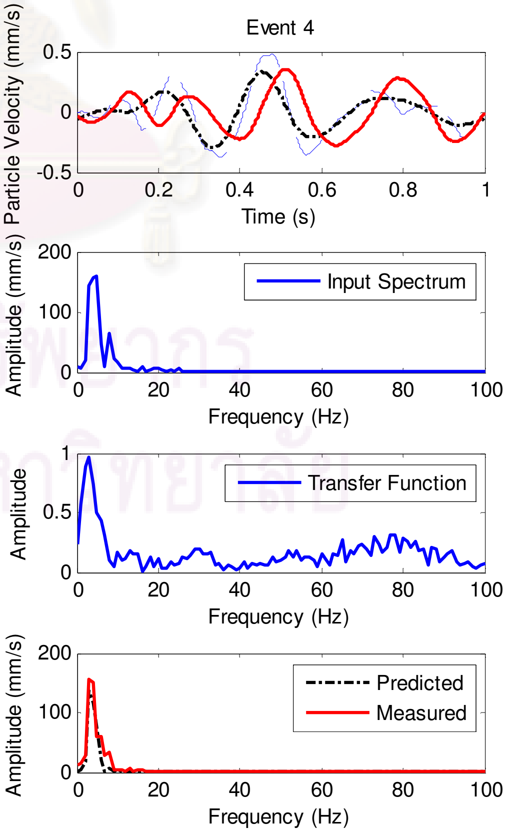
APPENDIX B

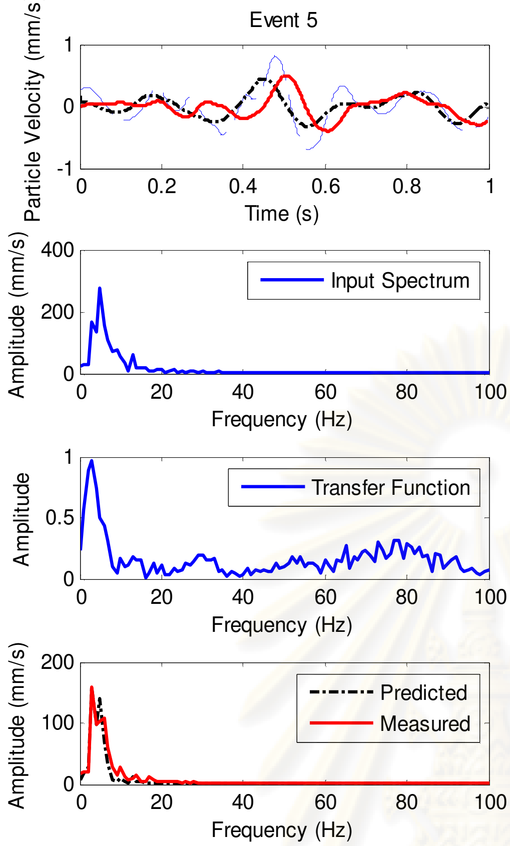
30 PREDICTED BUILDING RESPONSES IN VERTICAL DIRECTION USING TF OF AMBIENT VIBRATION

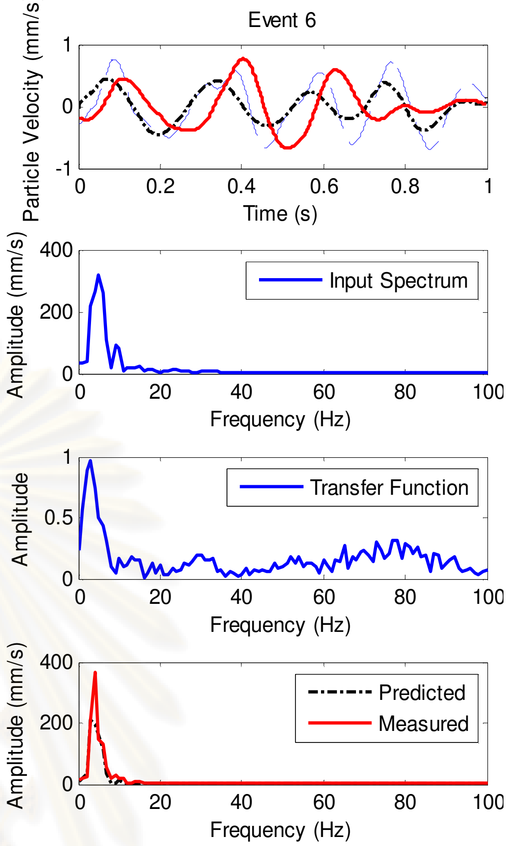

Event 1
Particle Velocity (mm/s)
Time (s)
Amplitude (mm/s)
Frequency (Hz)
Input Spectrum
Amplitude
Transfer Function
Predicted
Measured
1
0
-1
0.2
0.4
0.6
0.8
400
200
20
40
60
80
100
0.5

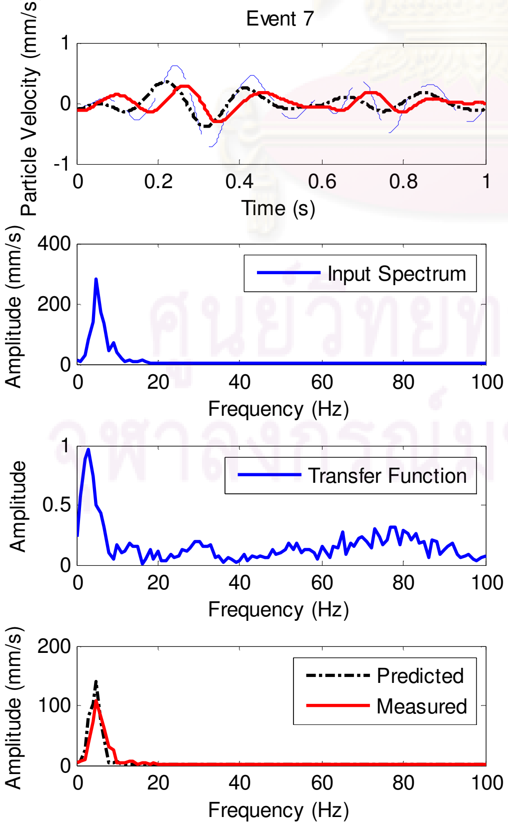

Event 2
Particle Velocity (mm/s)
Time (s)
Amplitude (mm/s)
Frequency (Hz)
Input Spectrum
Amplitude
Transfer Function
Predicted
Measured
1
0
-1
0.2
0.4
0.6
0.8
200
100
20
40
60
80
0.5

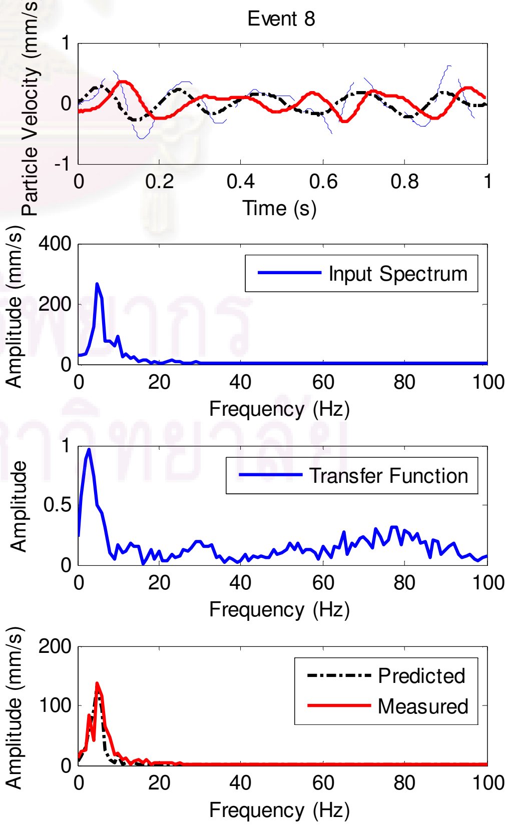

Event 3
Particle Velocity (mm/s)
Time (s)
Amplitude (mm/s)
Frequency (Hz)
Input Spectrum
Amplitude
Transfer Function
Predicted
Measured
1
0
-1
0.2
0.4
0.6
0.8
200
100
50
20
40
60
80
0.5

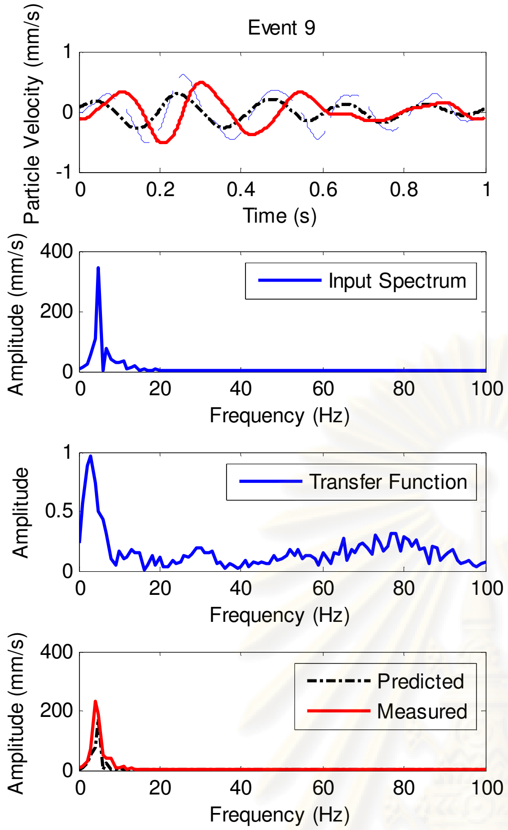

Event 4
Particle Velocity (mm/s)
Time (s)
Amplitude (mm/s)
Frequency (Hz)
Input Spectrum
Amplitude
Transfer Function
Predicted
Measured
0.5
0
-0.5
0.2
0.4
0.6
0.8
1
200
100
20
40
60
80

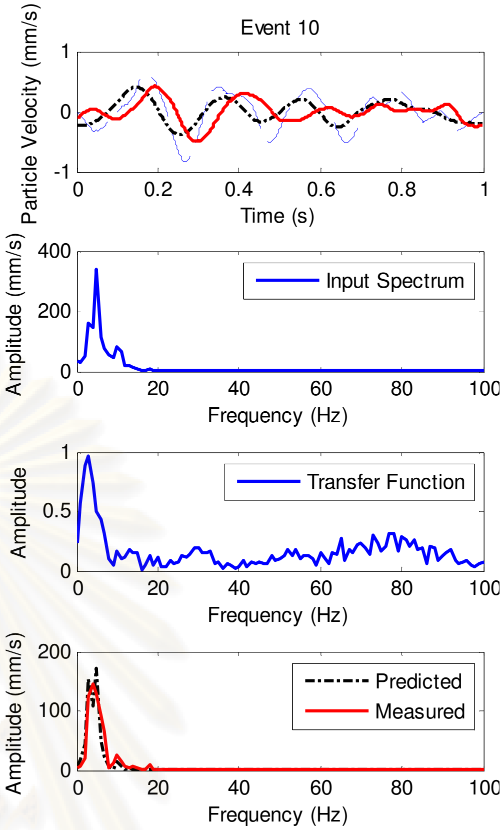

Event 5
Particle Velocity (mm/s)
1
0
-1
0
0.2
0.4
0.6
0.8
1
Time (s)
Amplitude (mm/s)
400
200
0
Input Spectrum
0
20
40
60
80
100
Frequency (Hz)
Amplitude
1
0.5
0
Transfer Function
Frequency (Hz)
Amplitude (mm/s)
200
100
0
Predicted
Measured
Frequency (Hz)

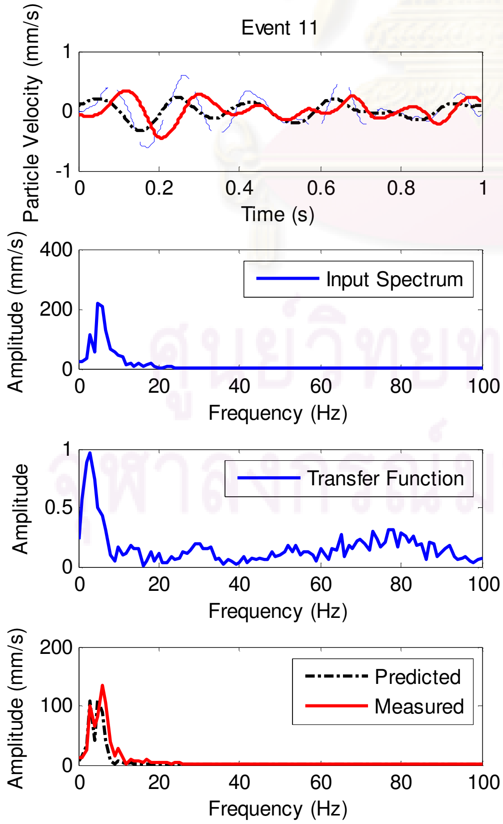

Event 6
Particle Velocity (mm/s)
1
0
-1
0
0.2
0.4
0.6
0.8
1
Time (s)
Amplitude (mm/s)
400
200
0
Input Spectrum
0
20
40
60
80
100
Frequency (Hz)
Amplitude
1
0.5
0
Transfer Function
Frequency (Hz)
Amplitude (mm/s)
400
200
0
Predicted
Measured
Frequency (Hz)

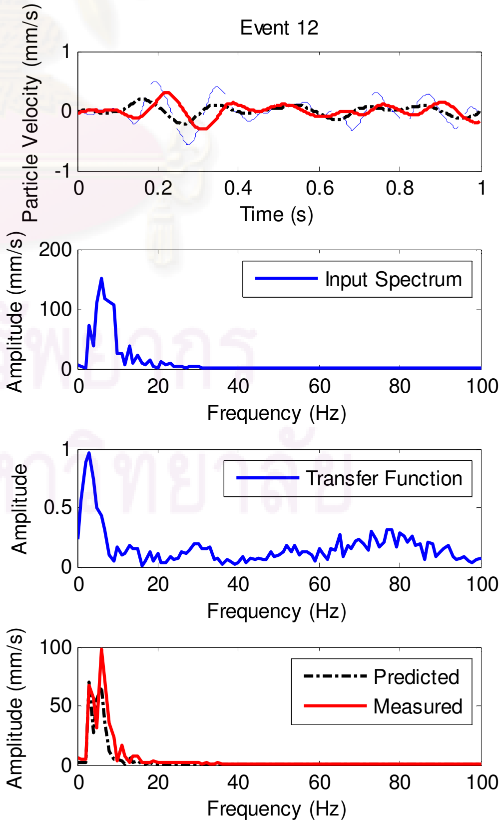

Event 7
Particle Velocity (mm/s)
1
0
-1
0
0.2
0.4
0.6
0.8
1
Time (s)
Amplitude (mm/s)
400
200
0
Input Spectrum
0
20
40
60
80
100
Frequency (Hz)
Amplitude
1
0.5
0
Transfer Function
Frequency (Hz)
Amplitude (mm/s)
200
100
0
Predicted
Measured
Frequency (Hz)

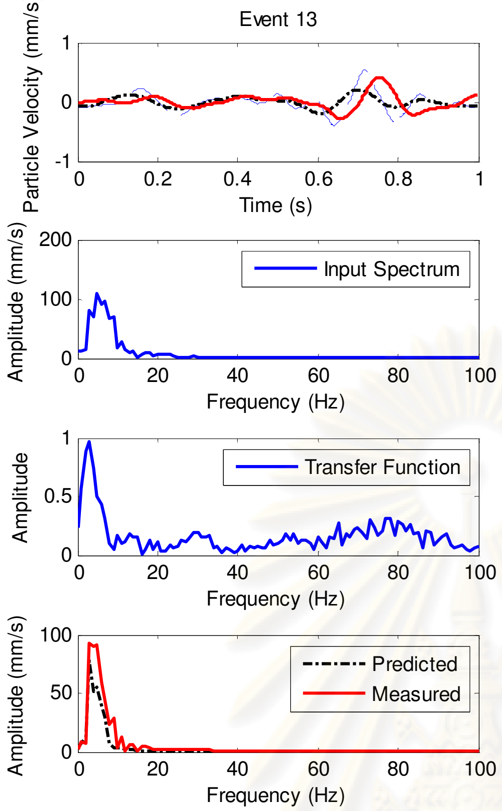

Event 8
Particle Velocity (mm/s)
1
0
-1
0
0.2
0.4
0.6
0.8
1
Time (s)
Amplitude (mm/s)
400
200
0
Input Spectrum
0
20
40
60
80
100
Frequency (Hz)
Amplitude
1
0.5
0
Transfer Function
Frequency (Hz)
Amplitude (mm/s)
200
100
0
Predicted
Measured
Frequency (Hz)

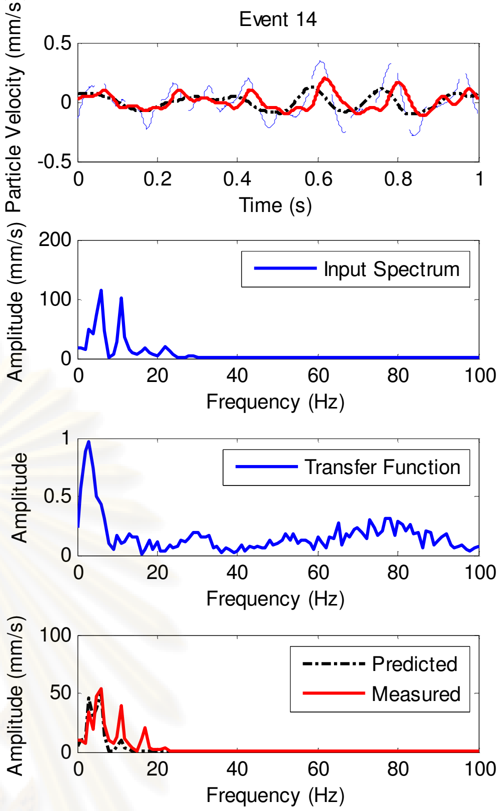

Event 9
Particle Velocity (mm/s)
1
0
-1
0
0.2
0.4
0.6
0.8
1
Time (s)
Amplitude (mm/s)
400
200
0
Input Spectrum
20
40
60
80
100
Frequency (Hz)
Amplitude
0.5
Transfer Function
Predicted
Measured

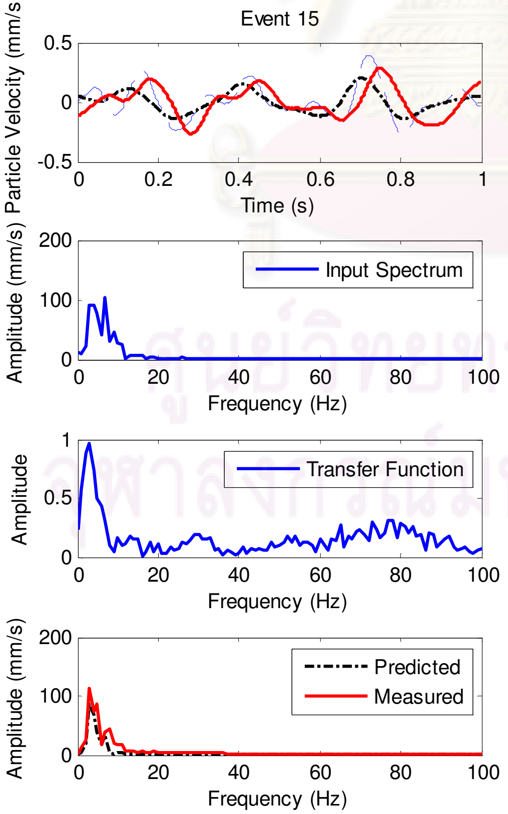

Event 10
Particle Velocity (mm/s)
1
0
-1
0
0.2
0.4
0.6
0.8
1
Time (s)
Amplitude (mm/s)
400
200
0
Input Spectrum
20
40
60
80
100
Frequency (Hz)
Amplitude
0.5
Transfer Function
200
100
Predicted
Measured

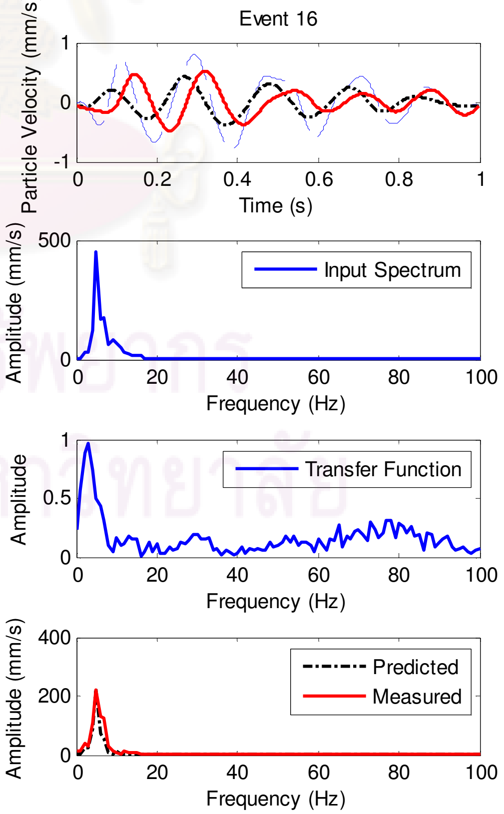

Event 11
Particle Velocity (mm/s)
1
0
-1
0
0.2
0.4
0.6
0.8
1
Time (s)
Amplitude (mm/s)
400
200
0
Input Spectrum
20
40
60
80
100
Frequency (Hz)
Amplitude
0.5
Transfer Function
200
100
Predicted
Measured

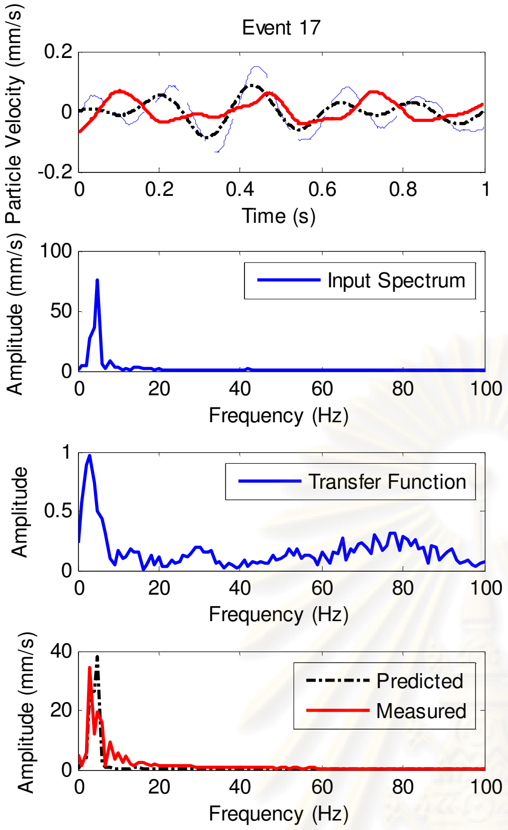

Event 12
Particle Velocity (mm/s)
1
0
-1
0
0.2
0.4
0.6
0.8
1
Time (s)
Amplitude (mm/s)
200
100
0
Input Spectrum
20
40
60
80
100
Frequency (Hz)
Amplitude
0.5
Transfer Function
100
50
Predicted
Measured

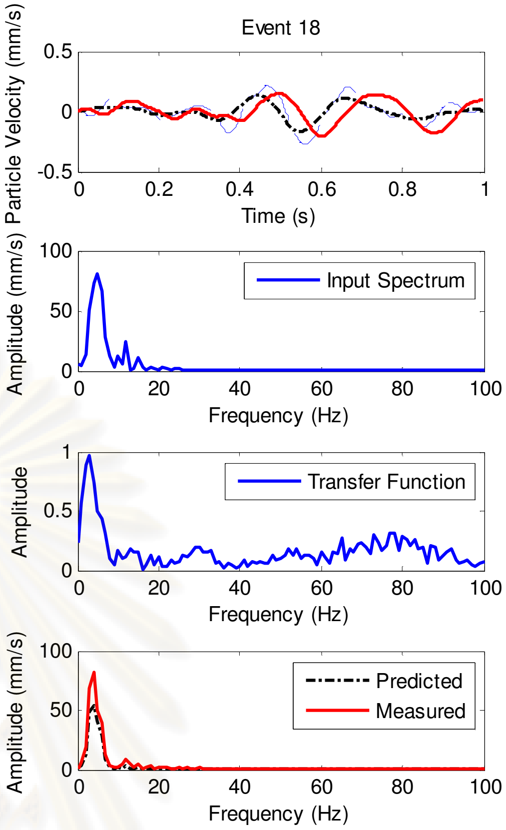

Event 13
Particle Velocity (mm/s)
Time (s)
Amplitude (mm/s)
Frequency (Hz)
Input Spectrum
Amplitude
Transfer Function
Predicted
Measured

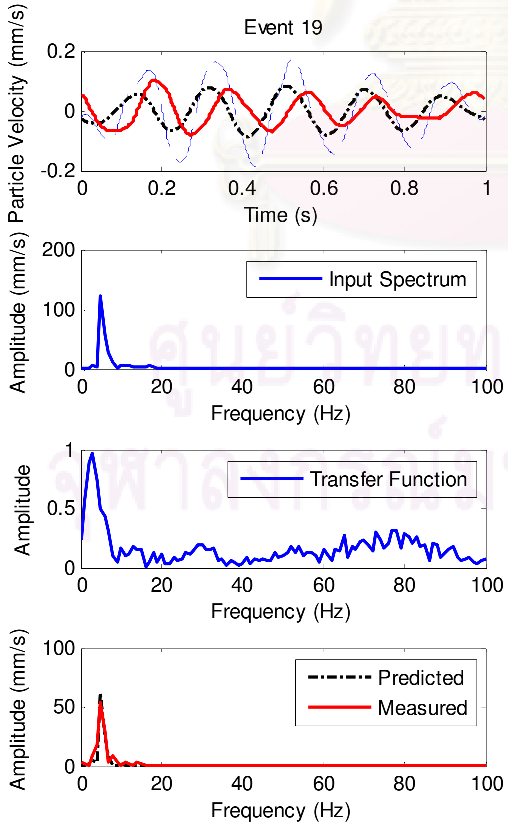

Event 14
Particle Velocity (mm/s)
Time (s)
Amplitude (mm/s)
Frequency (Hz)
Input Spectrum
Amplitude
Transfer Function
Predicted
Measured

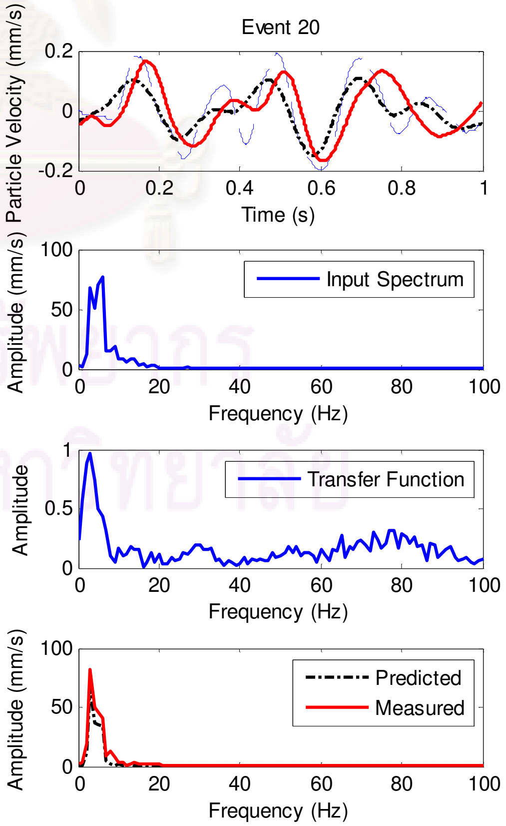

Event 15
Particle Velocity (mm/s)
Time (s)
Amplitude (mm/s)
Frequency (Hz)
Input Spectrum
Amplitude
Transfer Function
Predicted
Measured

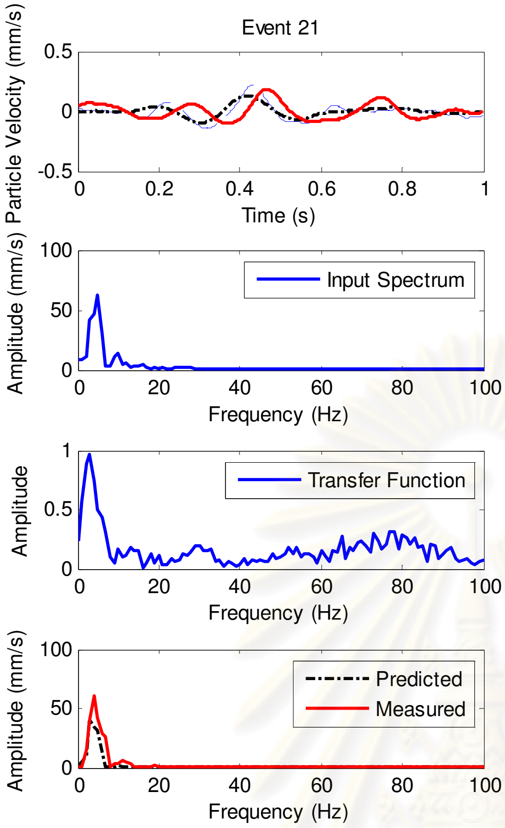

Event 16
Particle Velocity (mm/s)
Time (s)
Amplitude (mm/s)
Frequency (Hz)
Input Spectrum
Amplitude
Transfer Function
Predicted
Measured

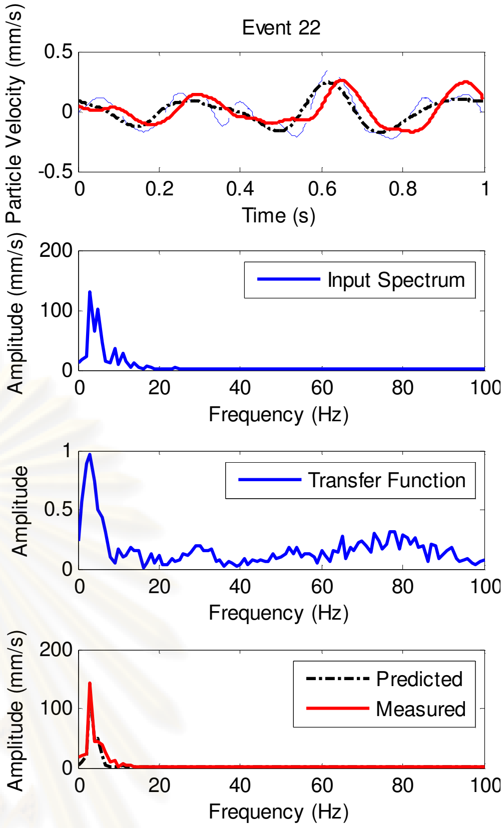

Event 17
Particle Velocity (mm/s)
0.2
0
-0.2
0
0.2
0.4
0.6
0.8
1
Time (s)
Amplitude (mm/s)
100
50
0
Input Spectrum
0
20
40
60
80
100
Frequency (Hz)
Amplitude
1
0.5
0
Transfer Function
Frequency (Hz)
Amplitude (mm/s)
40
20
0
Predicted
Measured
Frequency (Hz)

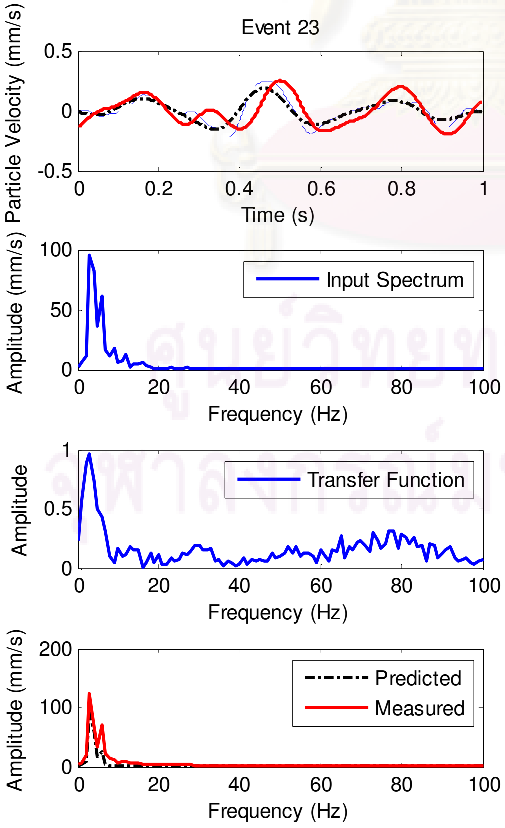

Event 18
Particle Velocity (mm/s)
0.5
0
-0.5
0
0.2
0.4
0.6
0.8
1
Time (s)
Amplitude (mm/s)
100
50
0
Input Spectrum
0
20
40
60
80
100
Frequency (Hz)
Amplitude
1
0.5
0
Transfer Function
Frequency (Hz)
Amplitude (mm/s)
100
50
0
Predicted
Measured
Frequency (Hz)

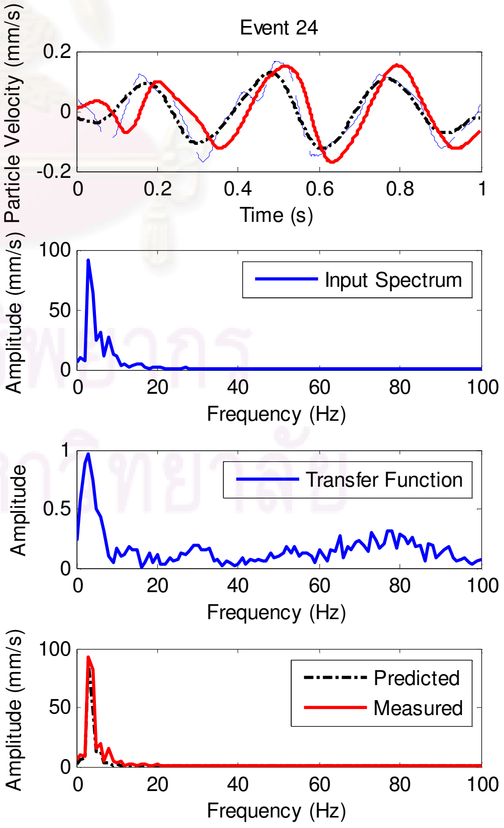

Event 19
Particle Velocity (mm/s)
0.2
0
-0.2
0
0.2
0.4
0.6
0.8
1
Time (s)
Amplitude (mm/s)
200
100
0
Input Spectrum
0
20
40
60
80
100
Frequency (Hz)
Amplitude
1
0.5
0
Transfer Function
Frequency (Hz)
Amplitude (mm/s)
100
50
0
Predicted
Measured
Frequency (Hz)

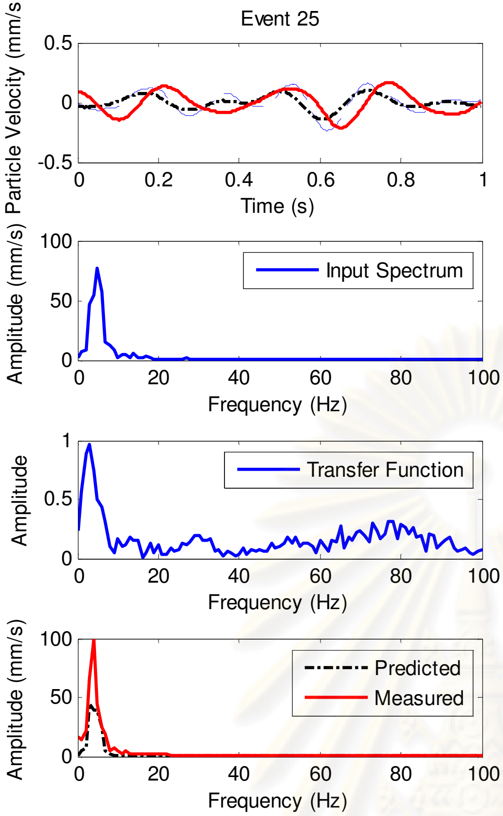

Event 20
Particle Velocity (mm/s)
0.2
0
-0.2
0
0.2
0.4
0.6
0.8
1
Time (s)
Amplitude (mm/s)
100
50
0
Input Spectrum
0
20
40
60
80
100
Frequency (Hz)
Amplitude
1
0.5
0
Transfer Function
Frequency (Hz)
Amplitude (mm/s)
100
50
0
Predicted
Measured
Frequency (Hz)

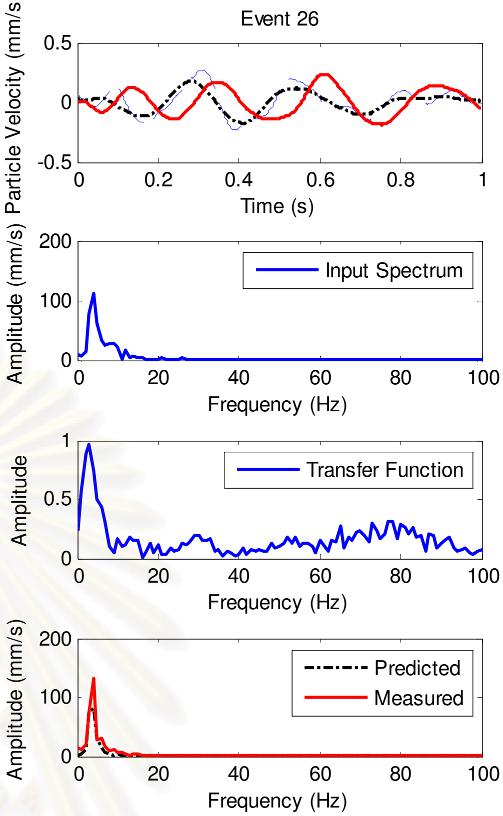

Event 21
Particle Velocity (mm/s)
0.5
0
-0.5
0
0.2
0.4
0.6
0.8
1
Time (s)
Amplitude (mm/s)
100
50
0
Input Spectrum
20
40
60
80
100
Frequency (Hz)
Amplitude
0.5
Transfer Function
Predicted
Measured

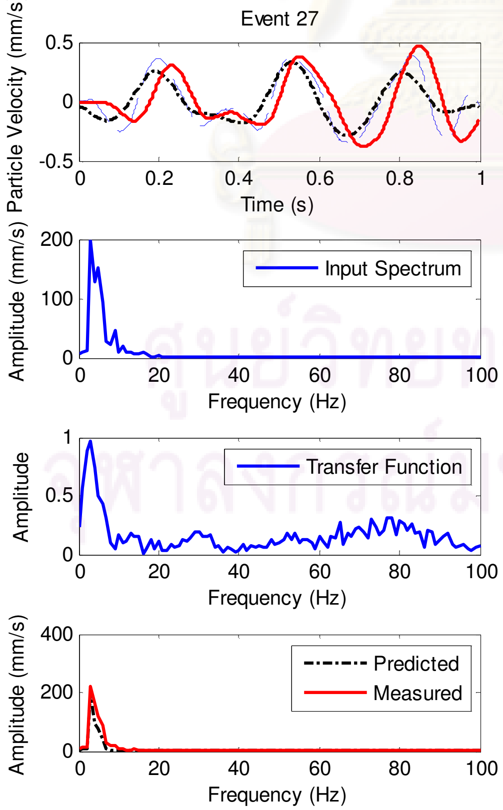

Event 22
Particle Velocity (mm/s)
0.5
0
-0.5
0
0.2
0.4
0.6
0.8
1
Time (s)
Amplitude (mm/s)
200
100
0
Input Spectrum
20
40
60
80
100
Frequency (Hz)
Amplitude
0.5
Transfer Function
Predicted
Measured

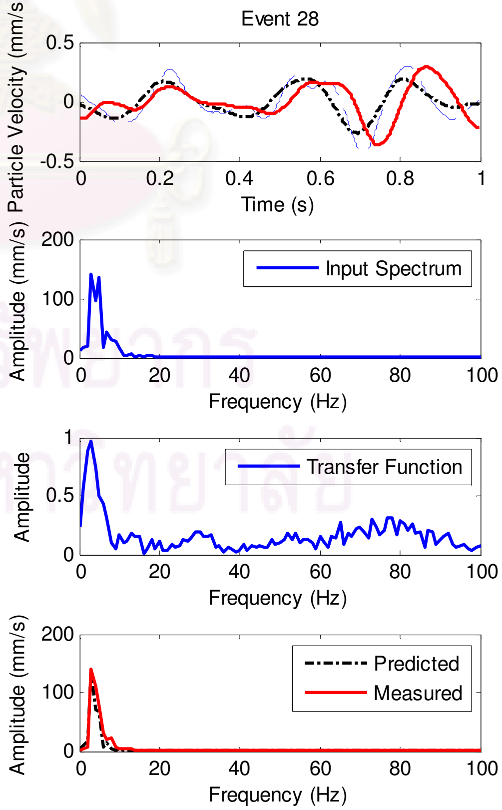

Event 23
Particle Velocity (mm/s)
0.5
0
-0.5
0
0.2
0.4
0.6
0.8
1
Time (s)
Amplitude (mm/s)
100
50
0
Input Spectrum
20
40
60
80
100
Frequency (Hz)
Amplitude
0.5
Transfer Function
200
Predicted
Measured

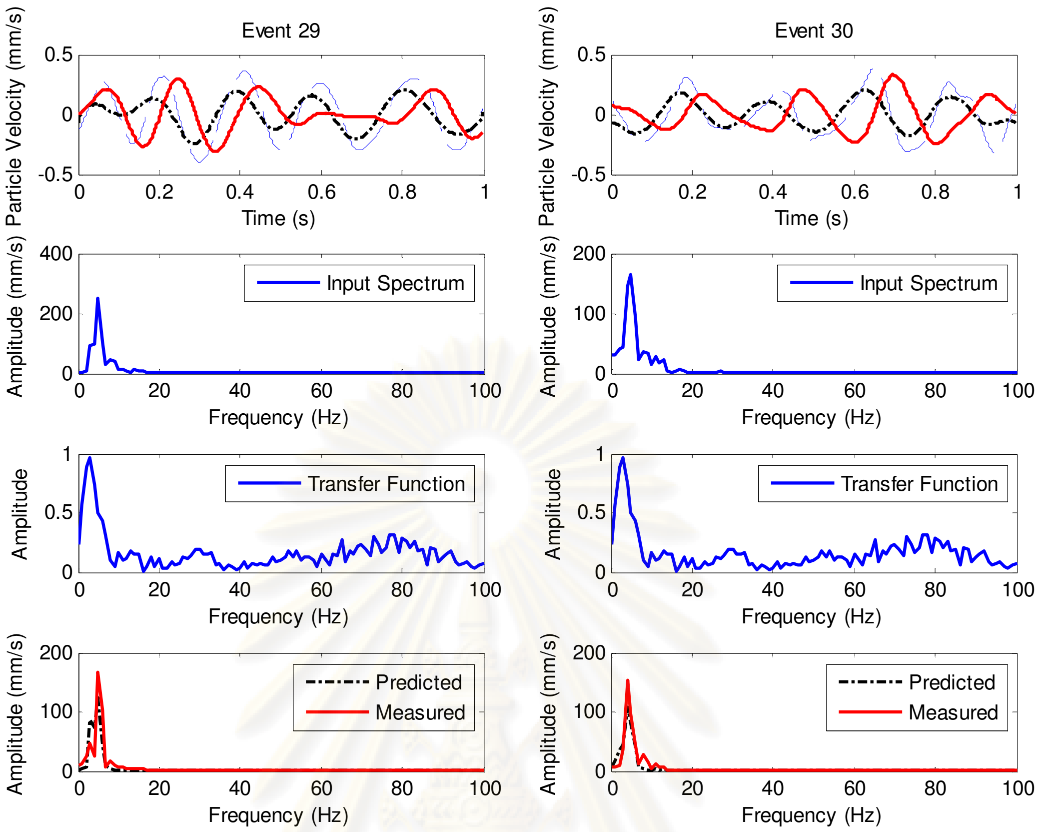

Event 24
Particle Velocity (mm/s)
0.2
0
-0.2
0
0.2
0.4
0.6
0.8
1
Time (s)
Amplitude (mm/s)
100
50
0
Input Spectrum
20
40
60
80
100
Frequency (Hz)
Amplitude
0.5
Transfer Function
Predicted
Measured


Event 25
Particle Velocity (mm/s)
0.5
0
-0.5
0
0.2
0.4
0.6
0.8
1
Time (s)
Amplitude (mm/s)
100
50
0
Input Spectrum
0
20
40
60
80
100
Frequency (Hz)
Amplitude
1
0.5
0
Transfer Function
Frequency (Hz)
Amplitude (mm/s)
100
50
0
Predicted
Measured
Frequency (Hz)


Event 26
Particle Velocity (mm/s)
0.5
0
-0.5
0
0.2
0.4
0.6
0.8
1
Time (s)
Amplitude (mm/s)
200
100
0
Input Spectrum
0
20
40
60
80
100
Frequency (Hz)
Amplitude
1
0.5
0
Transfer Function
Frequency (Hz)
Amplitude (mm/s)
200
100
0
Predicted
Measured
Frequency (Hz)

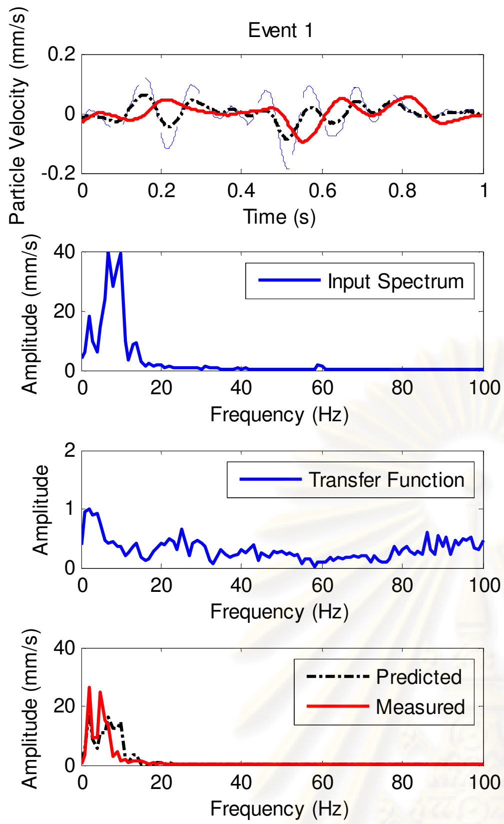

Event 27
Particle Velocity (mm/s)
0.5
0
-0.5
0
0.2
0.4
0.6
0.8
1
Time (s)
Amplitude (mm/s)
200
100
0
Input Spectrum
0
20
40
60
80
100
Frequency (Hz)
Amplitude
1
0.5
0
Transfer Function
Frequency (Hz)
Amplitude (mm/s)
400
200
0
Predicted
Measured
Frequency (Hz)

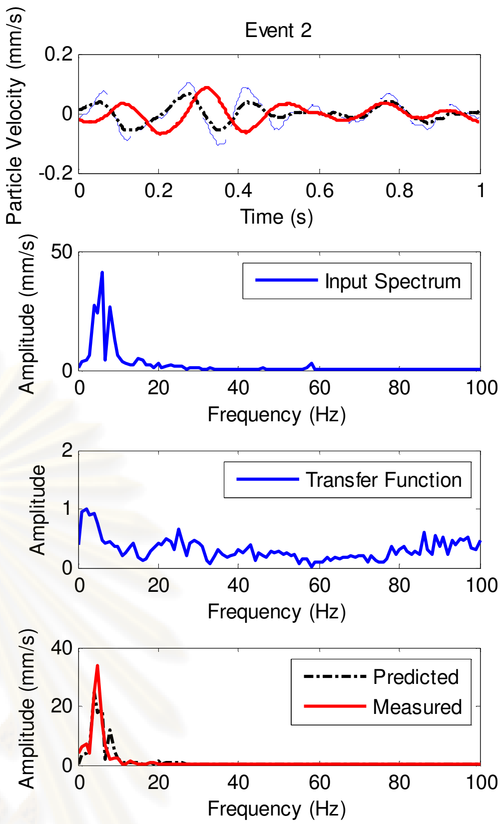

Event 28
Particle Velocity (mm/s)
0.5
0
-0.5
0
0.2
0.4
0.6
0.8
1
Time (s)
Amplitude (mm/s)
200
100
0
Input Spectrum
0
20
40
60
80
100
Frequency (Hz)
Amplitude
1
0.5
0
Transfer Function
Frequency (Hz)
Amplitude (mm/s)
200
100
0
Predicted
Measured
Frequency (Hz)

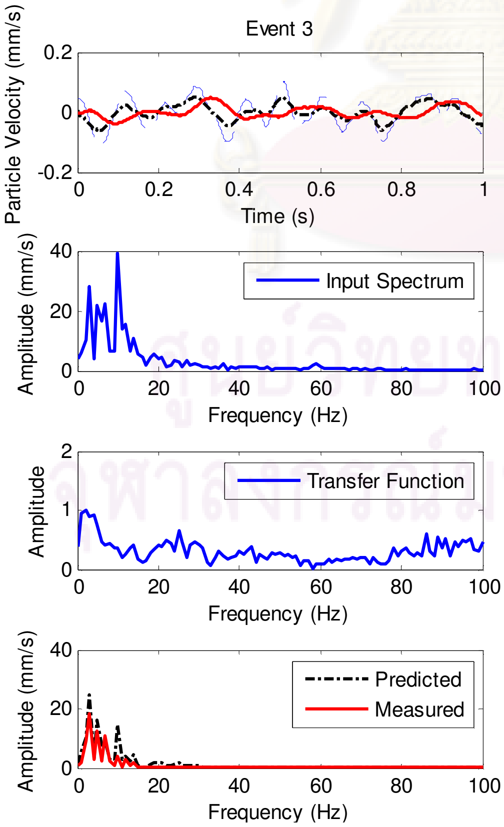

Event 29
Event 30
Particle Velocity (mm/s)
0.5
0
-0.5
0
0.2
0.4
0.6
0.8
1
Time (s)
Amplitude (mm/s)
400
200
100
0
20
40
60
80
100
Frequency (Hz)
Input Spectrum
Amplitude
1
0.5
Transfer Function
Predicted
Measured

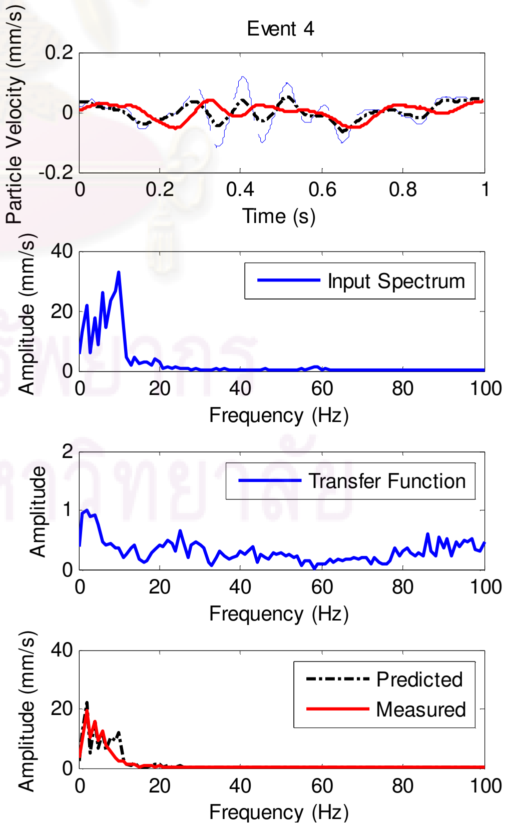
APPENDIX C

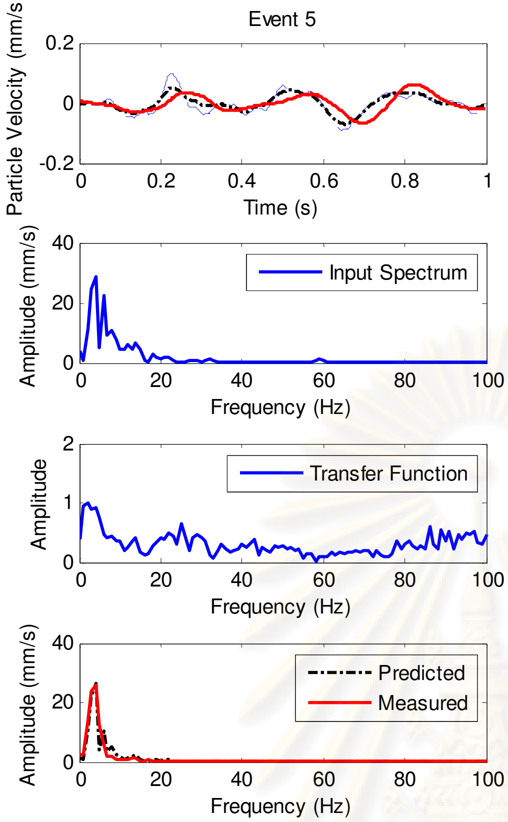
30 PREDICTED BUILDING RESPONSES IN RADIAL DIRECTION USING TF OF AMBIENT VIBRATION

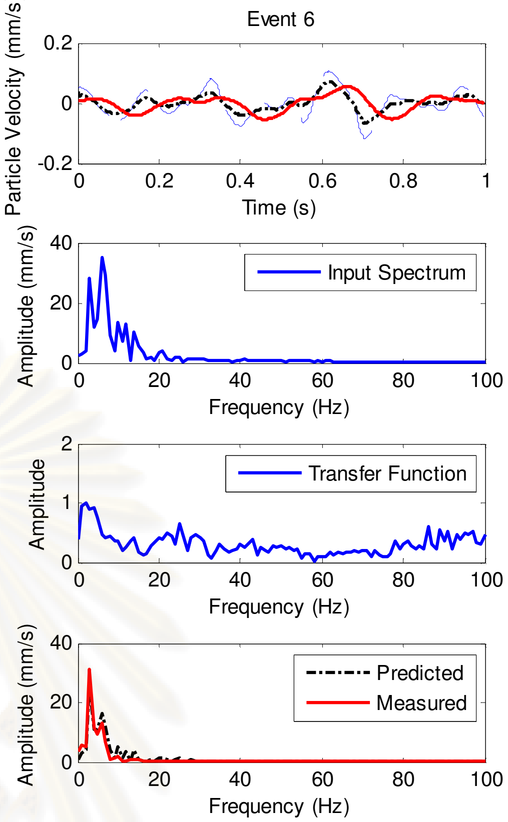

Event 1
Particle Velocity (mm/s)
0.2
0
-0.2
0
0.2
0.4
0.6
0.8
1
Time (s)
Amplitude (mm/s)
40
20
0
Input Spectrum
0
20
40
60
80
100
Frequency (Hz)
Amplitude
2
1
0
Transfer Function
Frequency (Hz)
Amplitude (mm/s)
40
20
0
Predicted
Measured
Frequency (Hz)

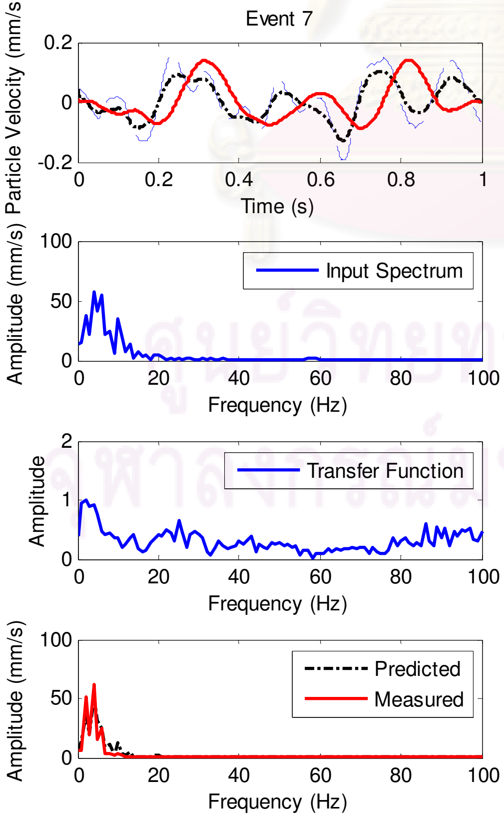

Event 2
Particle Velocity (mm/s)
0.2
0
-0.2
0
0.2
0.4
0.6
0.8
1
Time (s)
Amplitude (mm/s)
50
0
Input Spectrum
0
20
40
60
80
100
Frequency (Hz)
Amplitude
2
1
0
Transfer Function
Frequency (Hz)
Amplitude (mm/s)
40
20
0
Predicted
Measured
Frequency (Hz)

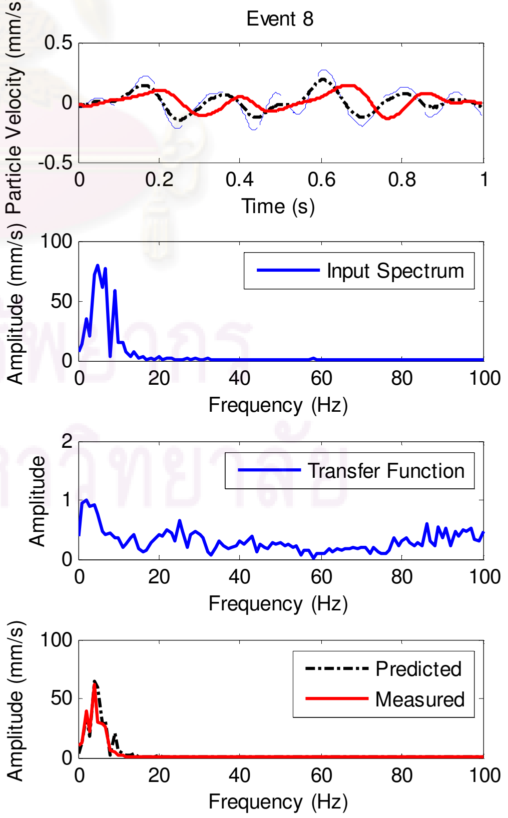

Event 3
Particle Velocity (mm/s)
0.2
0
-0.2
0
0.2
0.4
0.6
0.8
1
Time (s)
Amplitude (mm/s)
40
20
0
Input Spectrum
0
20
40
60
80
100
Frequency (Hz)
Amplitude
2
1
0
Transfer Function
Frequency (Hz)
Amplitude (mm/s)
40
20
0
Predicted
Measured
Frequency (Hz)

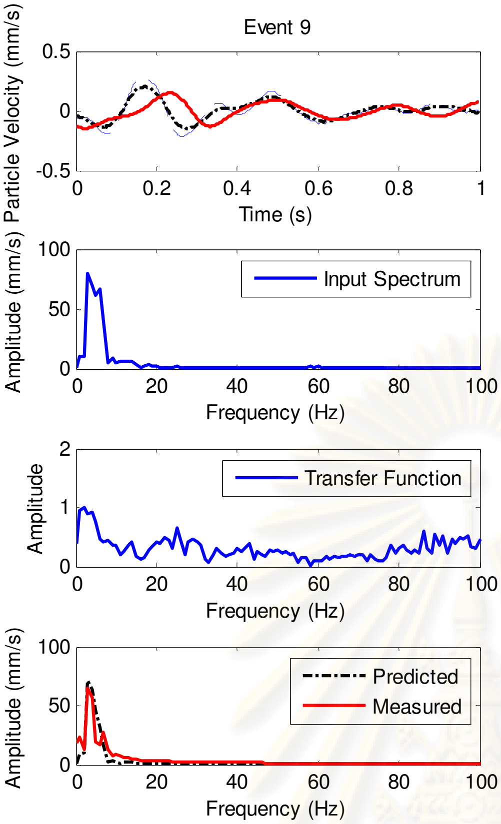

Event 4
Particle Velocity (mm/s)
0.2
0
-0.2
0
0.2
0.4
0.6
0.8
1
Time (s)
Amplitude (mm/s)
40
20
0
Input Spectrum
0
20
40
60
80
100
Frequency (Hz)
Amplitude
2
1
0
Transfer Function
Frequency (Hz)
Amplitude (mm/s)
40
20
0
Predicted
Measured
Frequency (Hz)

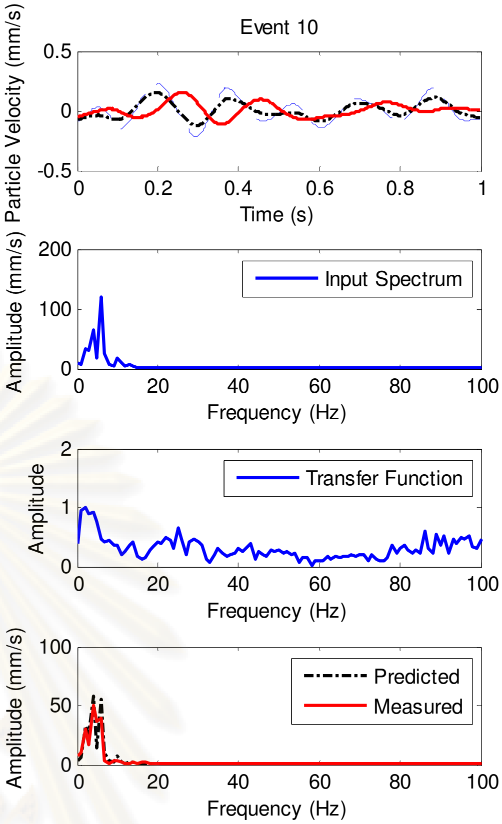

Event 5
Particle Velocity (mm/s)
0.2
0
-0.2
0
0.2
0.4
0.6
0.8
1
Time (s)
Amplitude (mm/s)
40
20
0
Input Spectrum
0
20
40
60
80
100
Frequency (Hz)
Amplitude
2
1
0
Transfer Function
Frequency (Hz)
Amplitude (mm/s)
40
20
0
Predicted
Measured
Frequency (Hz)

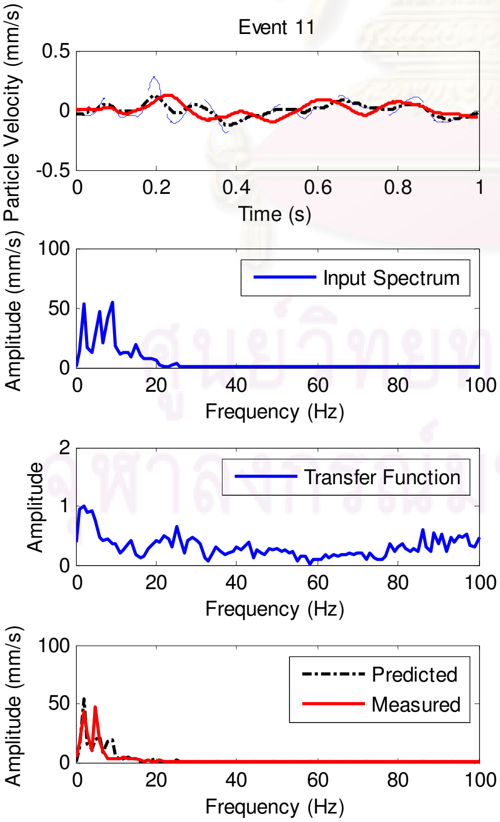

Event 6
Particle Velocity (mm/s)
0.2
0
-0.2
0
0.2
0.4
0.6
0.8
1
Time (s)
Amplitude (mm/s)
40
20
0
Input Spectrum
0
20
40
60
80
100
Frequency (Hz)
Amplitude
2
1
0
Transfer Function
Frequency (Hz)
Amplitude (mm/s)
40
20
0
Predicted
Measured
Frequency (Hz)

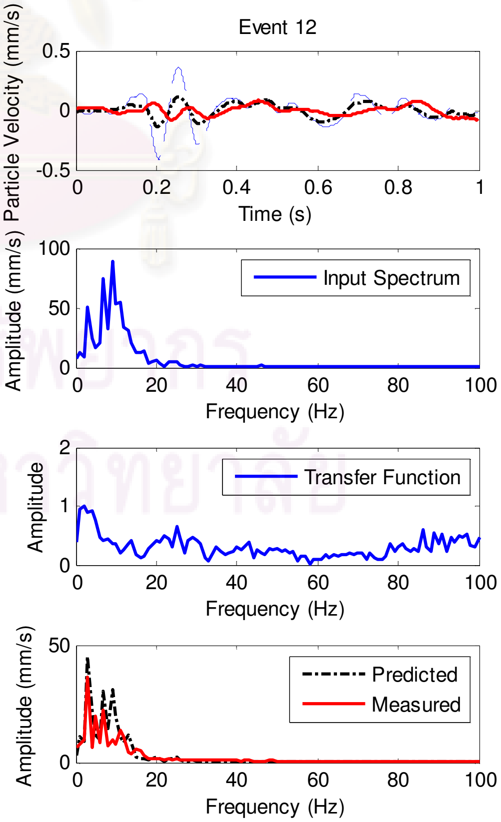

Event 7
Particle Velocity (mm/s)
0.2
0
-0.2
0
0.2
0.4
0.6
0.8
1
Time (s)
Amplitude (mm/s)
100
50
0
Input Spectrum
0
20
40
60
80
100
Frequency (Hz)
Amplitude
2
1
0
Transfer Function
Frequency (Hz)
Amplitude (mm/s)
100
50
0
Predicted
Measured
Frequency (Hz)

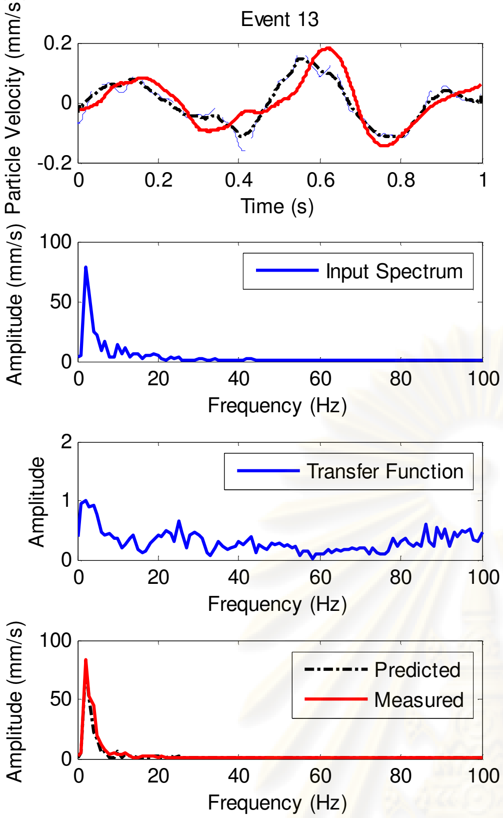

Event 8
Particle Velocity (mm/s)
0.5
0
-0.5
0
0.2
0.4
0.6
0.8
1
Time (s)
Amplitude (mm/s)
100
50
0
Input Spectrum
0
20
40
60
80
100
Frequency (Hz)
Amplitude
2
1
0
Transfer Function
Frequency (Hz)
Amplitude (mm/s)
100
50
0
Predicted
Measured
Frequency (Hz)

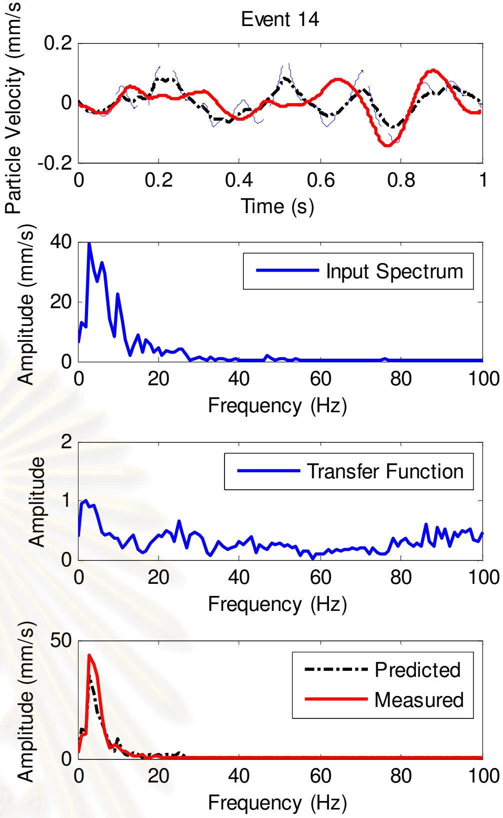

Event 9
Particle Velocity (mm/s)
0.5
0
-0.5
0
0.2
0.4
0.6
0.8
1
Time (s)
Amplitude (mm/s)
100
50
0
Input Spectrum
0
20
40
60
80
100
Frequency (Hz)
Amplitude
2
1
0
Transfer Function
Frequency (Hz)
Amplitude (mm/s)
100
50
0
Predicted
Measured
Frequency (Hz)

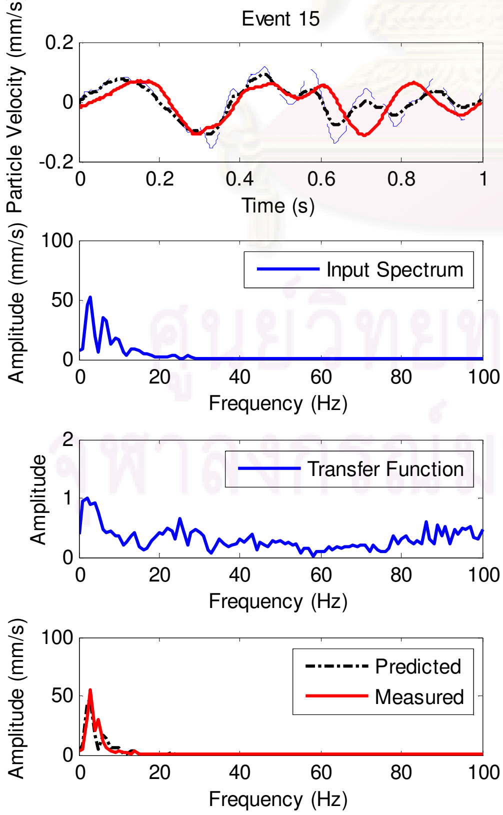

Event 10
Particle Velocity (mm/s)
0.5
0
-0.5
0
0.2
0.4
0.6
0.8
1
Time (s)
Amplitude (mm/s)
200
100
0
Input Spectrum
0
20
40
60
80
100
Frequency (Hz)
Amplitude
2
1
0
Transfer Function
Frequency (Hz)
Amplitude (mm/s)
100
50
0
Predicted
Measured
Frequency (Hz)

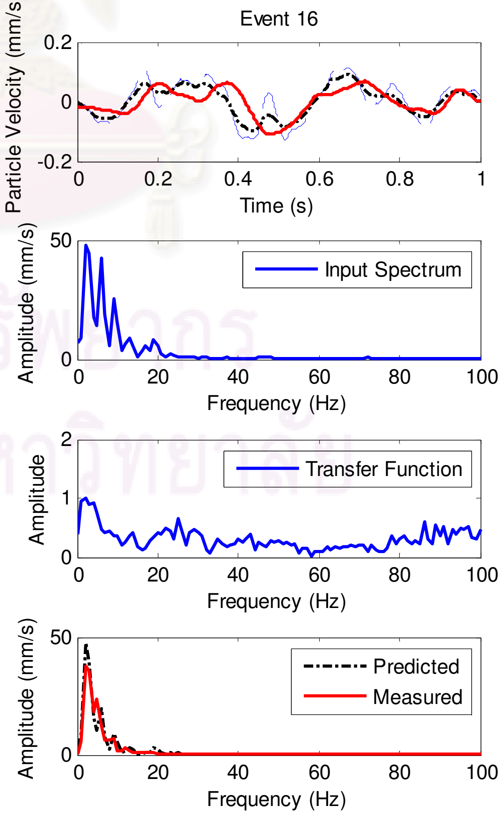

Event 11
Particle Velocity (mm/s)
0.5
0
-0.5
0
0.2
0.4
0.6
0.8
1
Time (s)
Amplitude (mm/s)
100
50
0
Input Spectrum
0
20
40
60
80
100
Frequency (Hz)
Amplitude
2
1
0
Transfer Function
Frequency (Hz)
Amplitude (mm/s)
100
50
0
Predicted
Measured
Frequency (Hz)

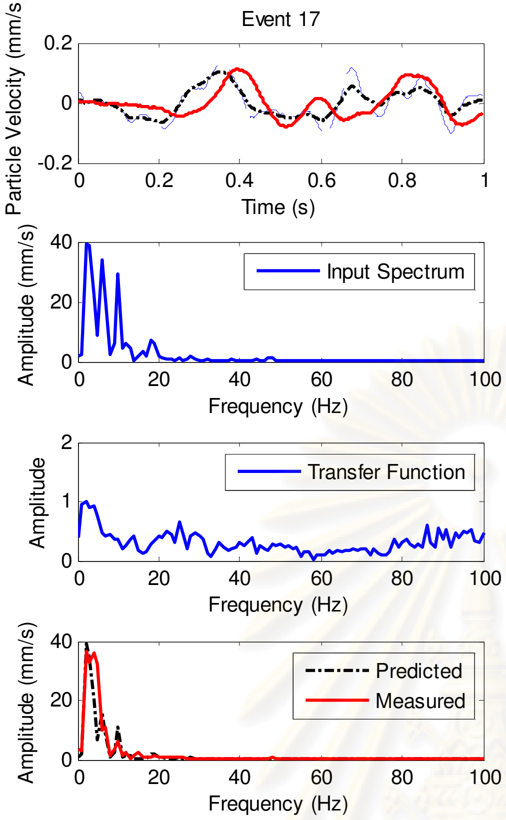

Event 12
Particle Velocity (mm/s)
0.5
0
-0.5
0
0.2
0.4
0.6
0.8
1
Time (s)
Amplitude (mm/s)
100
50
0
Input Spectrum
0
20
40
60
80
100
Frequency (Hz)
Amplitude
2
1
0
Transfer Function
Frequency (Hz)
Amplitude (mm/s)
50
0
Predicted
Measured
Frequency (Hz)

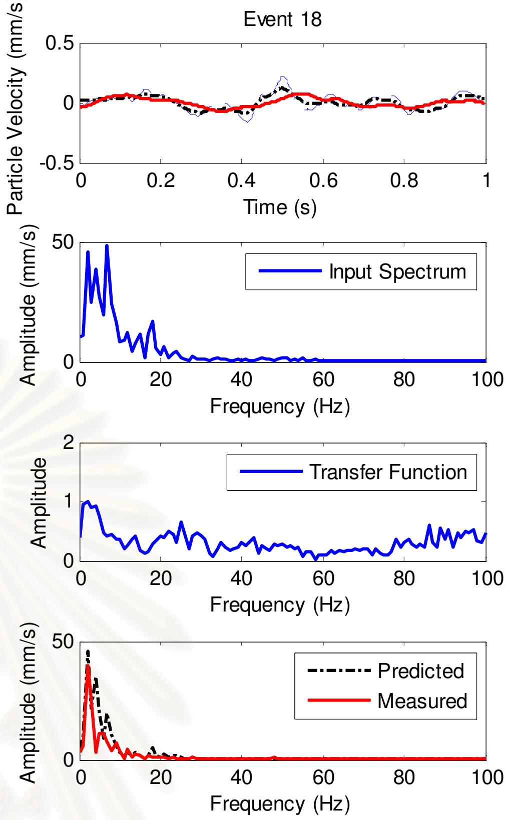

Event 13
Particle Velocity (mm/s)
Time (s)
Amplitude (mm/s)
Frequency (Hz)
Input Spectrum
Amplitude
Transfer Function
Predicted
Measured

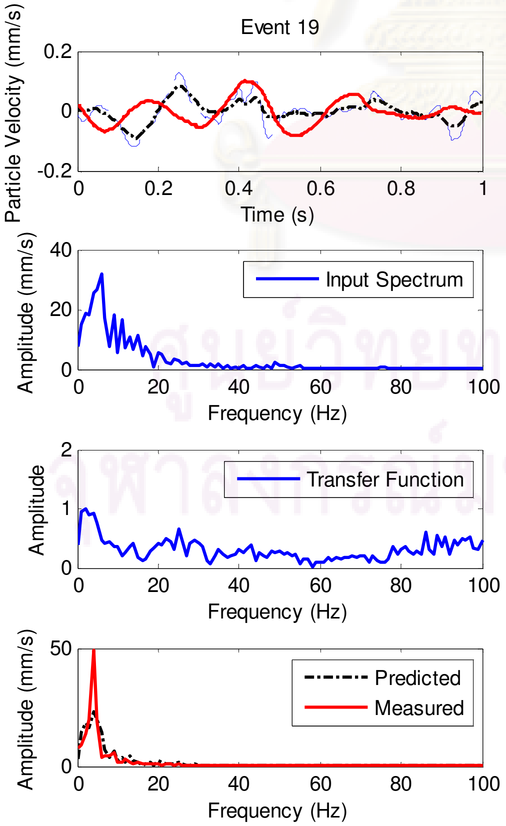

Event 14
Particle Velocity (mm/s)
Time (s)
Amplitude (mm/s)
Frequency (Hz)
Input Spectrum
Amplitude
Transfer Function
Predicted
Measured

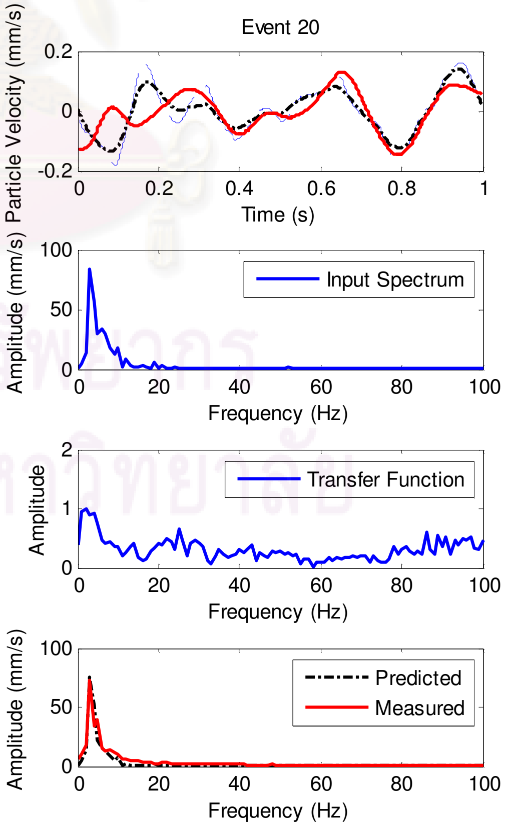

Event 15
Particle Velocity (mm/s)
Time (s)
Amplitude (mm/s)
Frequency (Hz)
Input Spectrum
Amplitude
Transfer Function
Predicted
Measured

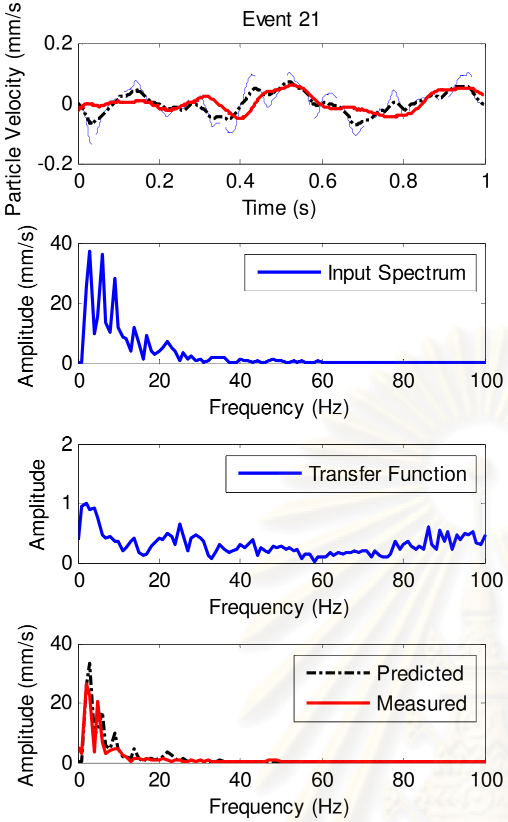

Event 16
Particle Velocity (mm/s)
Time (s)
Amplitude (mm/s)
Frequency (Hz)
Input Spectrum
Amplitude
Transfer Function
Predicted
Measured

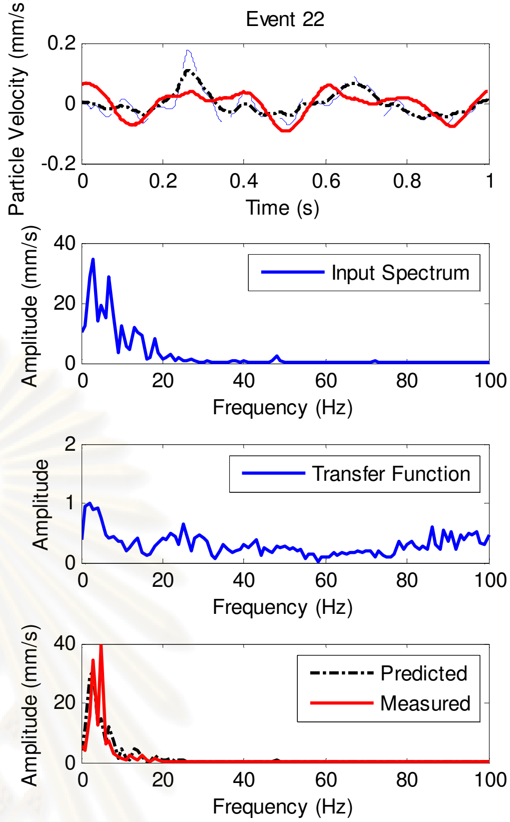

Event 17
Particle Velocity (mm/s)
Time (s)
Amplitude (mm/s)
Frequency (Hz)
Input Spectrum
Amplitude
Transfer Function
Predicted
Measured

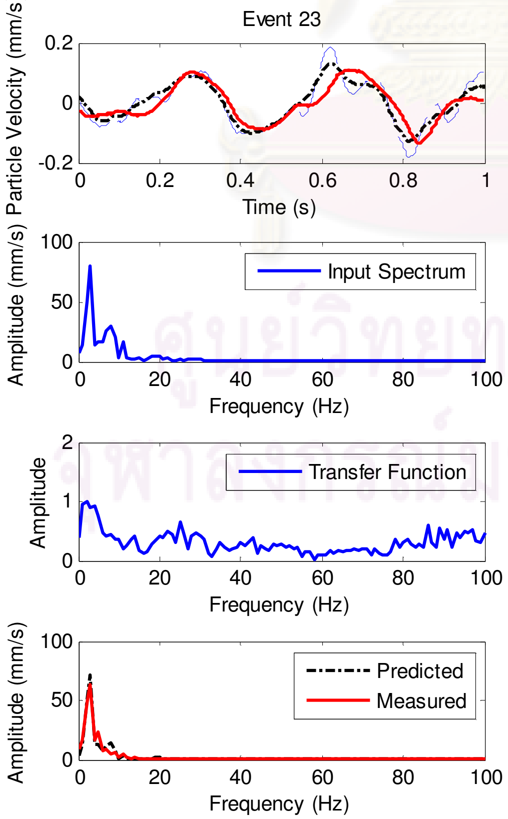

Event 18
Particle Velocity (mm/s)
Time (s)
Amplitude (mm/s)
Frequency (Hz)
Input Spectrum
Amplitude
Transfer Function
Predicted
Measured

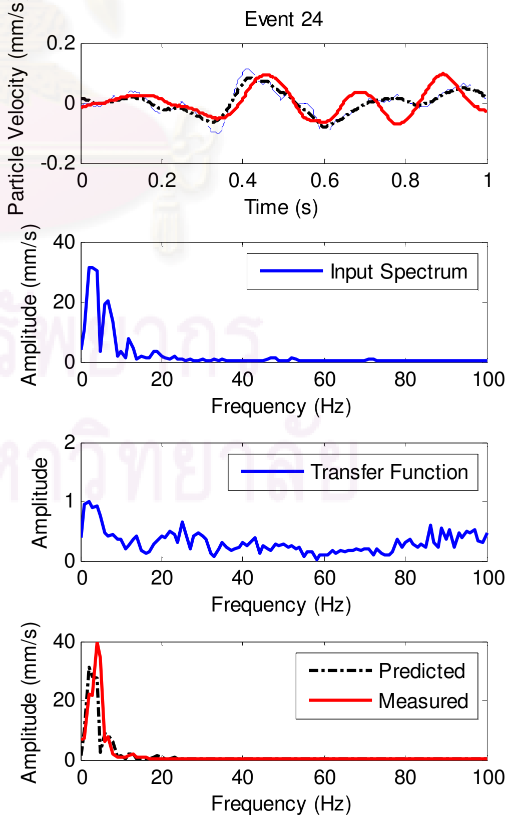

Event 19
Particle Velocity (mm/s)
Time (s)
Amplitude (mm/s)
Frequency (Hz)
Input Spectrum
Amplitude
Transfer Function
Predicted
Measured

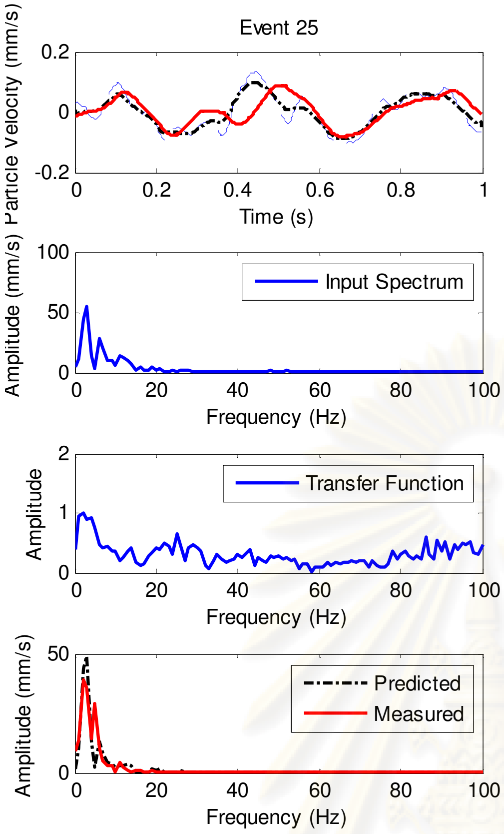

Event 20
Particle Velocity (mm/s)
Time (s)
Amplitude (mm/s)
Frequency (Hz)
Input Spectrum
Amplitude
Transfer Function
Predicted
Measured

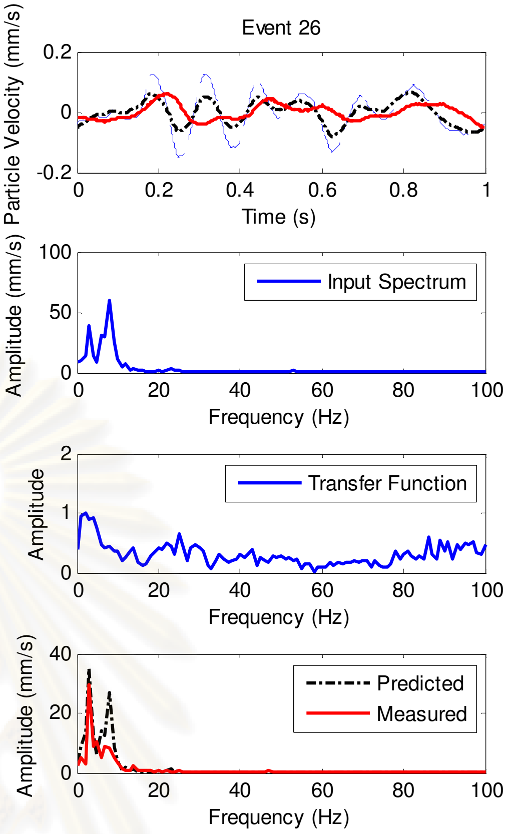

Event 21
Particle Velocity (mm/s)
0.2
0
-0.2
0
0.2
0.4
0.6
0.8
1
Time (s)
Amplitude (mm/s)
40
20
0
Input Spectrum
0
20
40
60
80
100
Frequency (Hz)
Amplitude
2
1
0
Transfer Function
Frequency (Hz)
Amplitude (mm/s)
Predicted
Measured
Frequency (Hz)

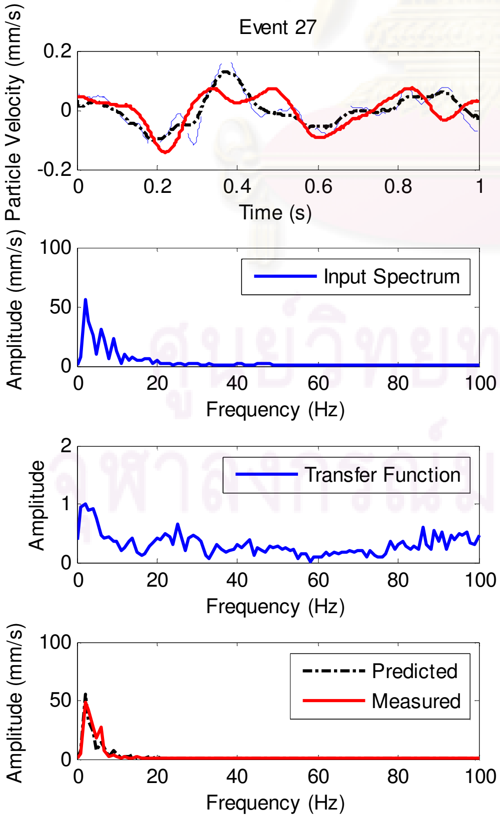

Event 22
Particle Velocity (mm/s)
0.2
0
-0.2
0
0.2
0.4
0.6
0.8
1
Time (s)
Amplitude (mm/s)
40
20
0
Input Spectrum
0
20
40
60
80
100
Frequency (Hz)
Amplitude
2
1
0
Transfer Function
Frequency (Hz)
Amplitude (mm/s)
Predicted
Measured
Frequency (Hz)

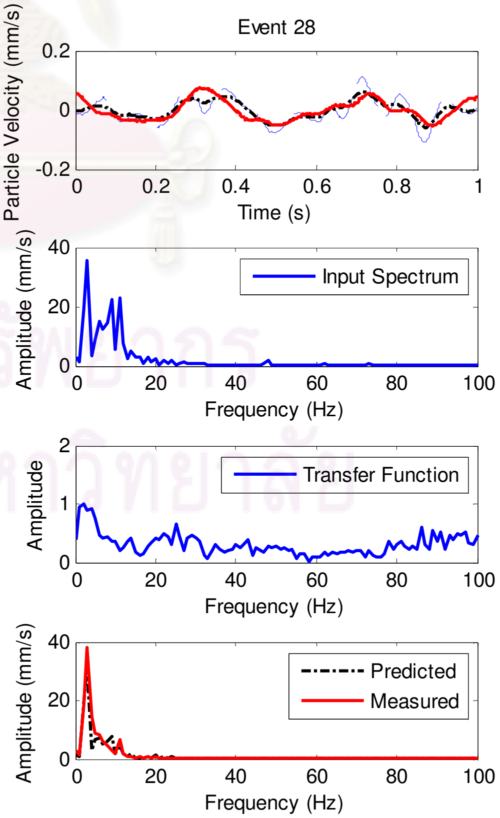

Event 23
Particle Velocity (mm/s)
0.2
0
-0.2
0
0.2
0.4
0.6
0.8
1
Time (s)
Amplitude (mm/s)
100
50
0
Input Spectrum
0
20
40
60
80
100
Frequency (Hz)
Amplitude
2
1
0
Transfer Function
Frequency (Hz)
Amplitude (mm/s)
Predicted
Measured
Frequency (Hz)

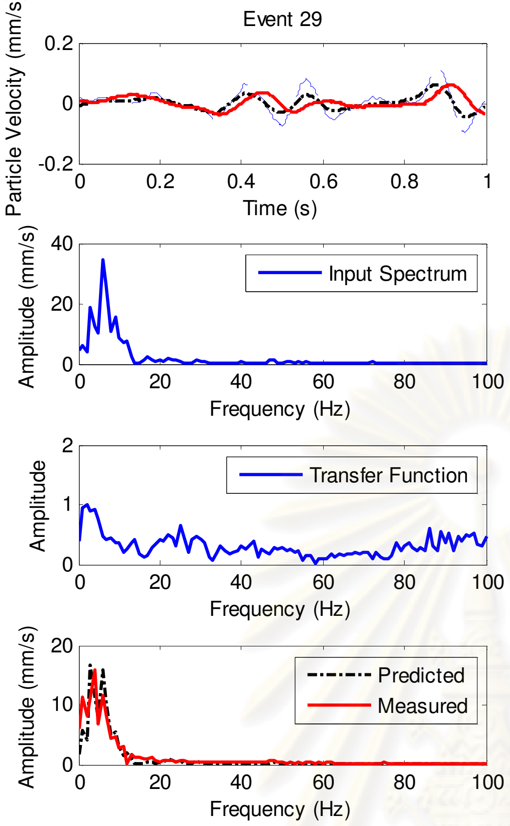

Event 24
Particle Velocity (mm/s)
0.2
0
-0.2
0
0.2
0.4
0.6
0.8
1
Time (s)
Amplitude (mm/s)
40
20
0
Input Spectrum
0
20
40
60
80
100
Frequency (Hz)
Amplitude
2
1
0
Transfer Function
Frequency (Hz)
Amplitude (mm/s)
Predicted
Measured
Frequency (Hz)

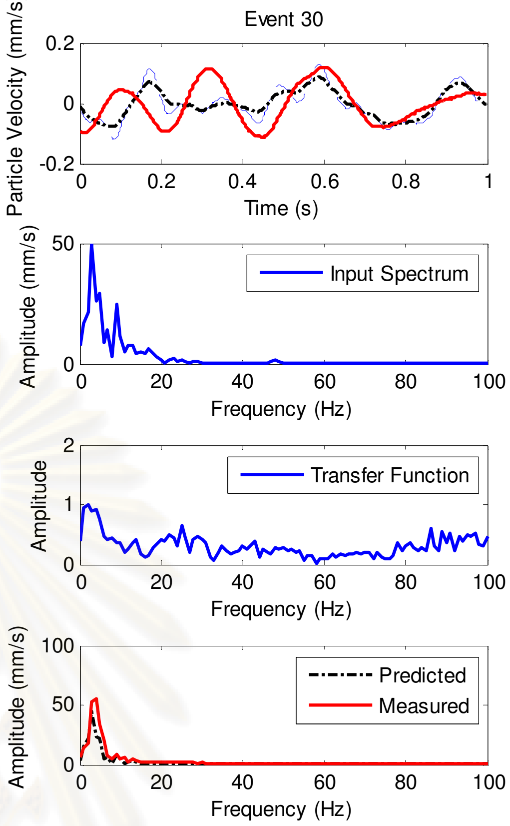

Event 25
Particle Velocity (mm/s)
0.2
0
-0.2
0
0.2
0.4
0.6
0.8
1
Time (s)
Amplitude (mm/s)
100
50
0
Input Spectrum
0
20
40
60
80
100
Frequency (Hz)
Amplitude
2
1
0
Transfer Function
0
20
40
60
80
100
Frequency (Hz)
Amplitude (mm/s)
50
0
Predicted
Measured
0
20
40
60
80
100
Frequency (Hz)


Event 26
Particle Velocity (mm/s)
0.2
0
-0.2
0
0.2
0.4
0.6
0.8
1
Time (s)
Amplitude (mm/s)
100
50
0
Input Spectrum
0
20
40
60
80
100
Frequency (Hz)
Amplitude
2
1
0
Transfer Function
0
20
40
60
80
100
Frequency (Hz)
Amplitude (mm/s)
40
20
0
Predicted
Measured
0
20
40
60
80
100
Frequency (Hz)


Event 27
Particle Velocity (mm/s)
0.2
0
-0.2
0
0.2
0.4
0.6
0.8
1
Time (s)
Amplitude (mm/s)
100
50
0
Input Spectrum
0
20
40
60
80
100
Frequency (Hz)
Amplitude
2
1
0
Transfer Function
0
20
40
60
80
100
Frequency (Hz)
Amplitude (mm/s)
100
50
0
Predicted
Measured
0
20
40
60
80
100
Frequency (Hz)

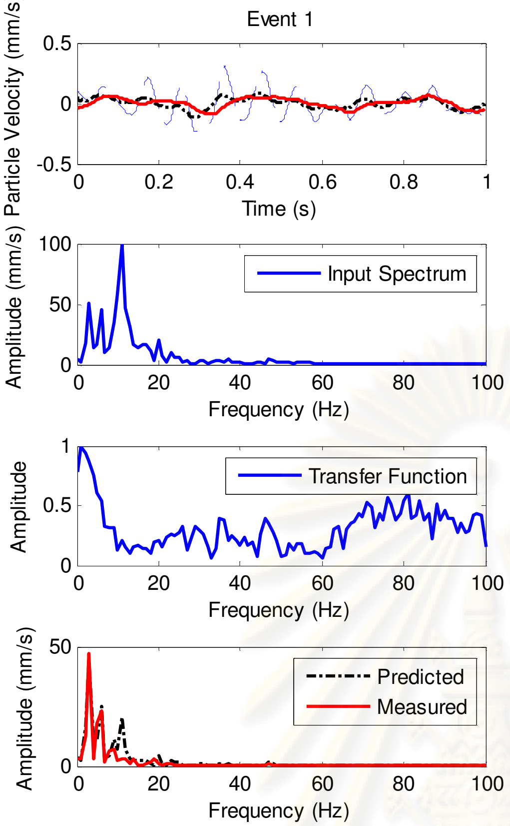

Event 28
Particle Velocity (mm/s)
0.2
0
-0.2
0
0.2
0.4
0.6
0.8
1
Time (s)
Amplitude (mm/s)
40
20
0
Input Spectrum
0
20
40
60
80
100
Frequency (Hz)
Amplitude
2
1
0
Transfer Function
0
20
40
60
80
100
Frequency (Hz)
Amplitude (mm/s)
40
20
0
Predicted
Measured
0
20
40
60
80
100
Frequency (Hz)

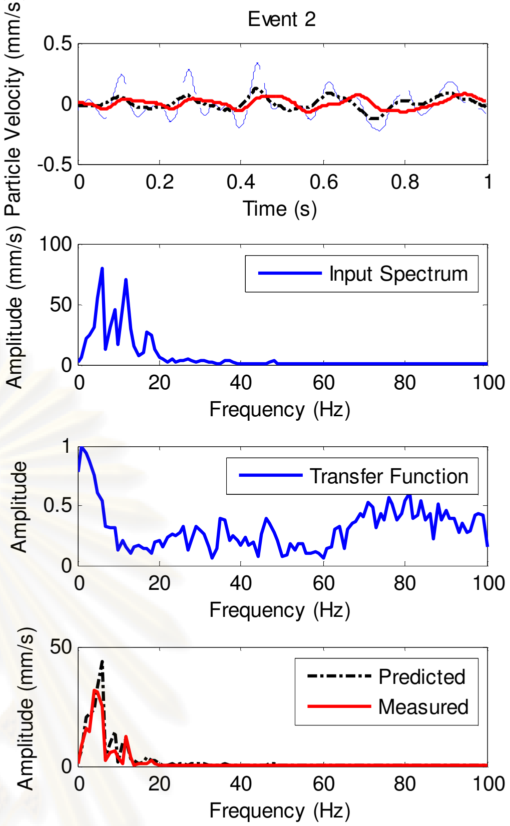

Event 29
Particle Velocity (mm/s)
0.2
0
-0.2
0
0.2
0.4
0.6
0.8
1
Time (s)
Amplitude (mm/s)
40
20
0
Input Spectrum
Frequency (Hz)
Amplitude
2
1
0
Transfer Function
Frequency (Hz)
Amplitude (mm/s)
20
10
0
Predicted
Measured
20
40
60
80
100
Frequency (Hz)

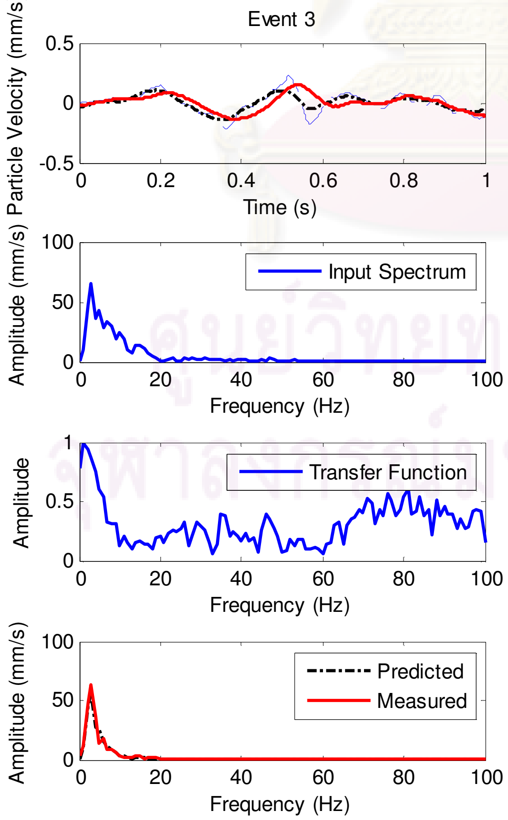

Event 30
Particle Velocity (mm/s)
0.2
0
-0.2
0
0.2
0.4
0.6
0.8
1
Time (s)
Amplitude (mm/s)
50
0
Input Spectrum
Frequency (Hz)
Amplitude
2
1
0
Transfer Function
Frequency (Hz)
Amplitude (mm/s)
100
50
0
Predicted
Measured
20
40
60
80
100
Frequency (Hz)

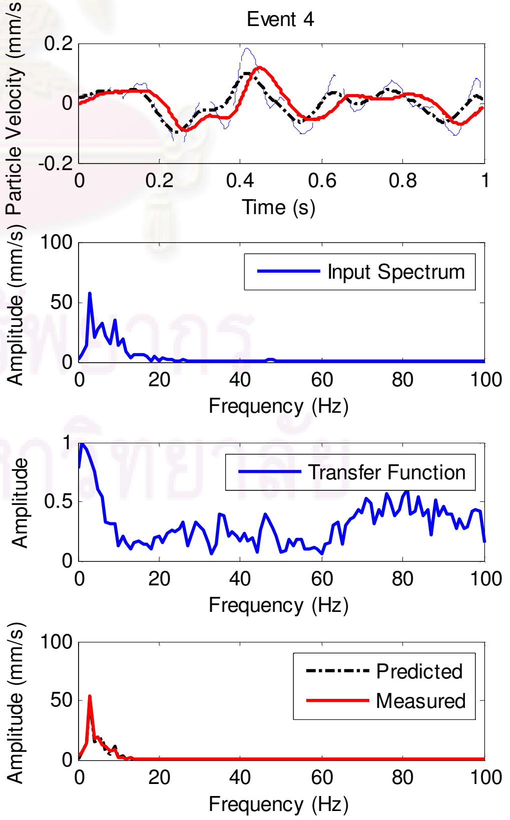
APPENDIX D

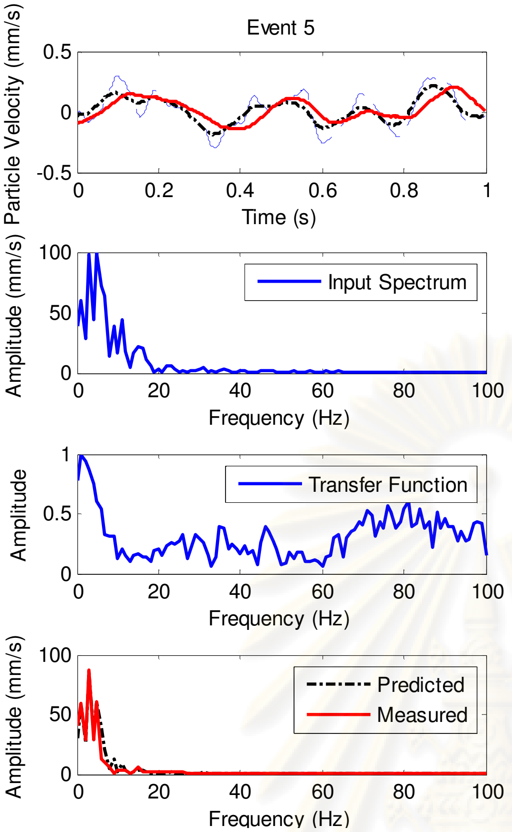
26 PREDICTED BUILDING RESPONSES IN TRANSVERSAL DIRECTION USING TF OF AMBIENT VIBRATION

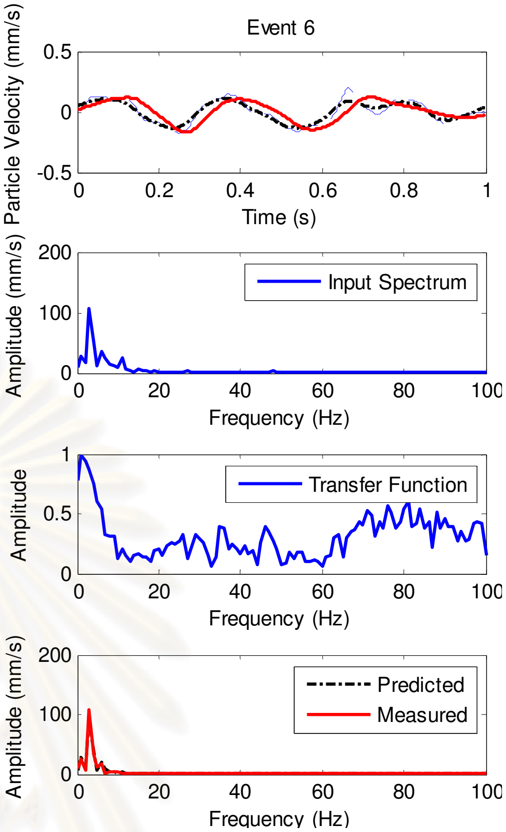

Event 1

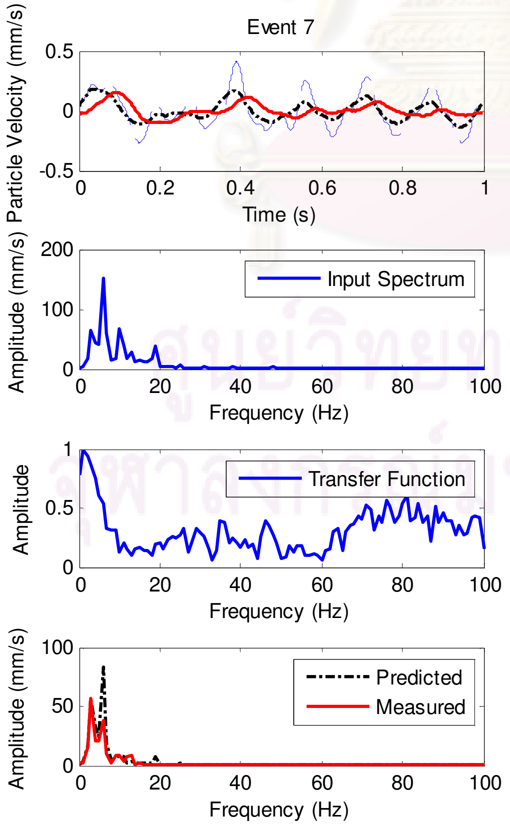

Event 2

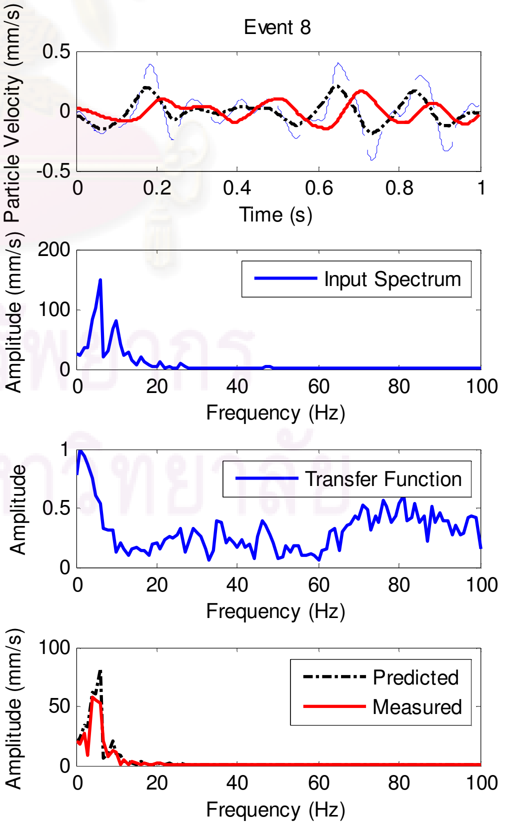

Event 3

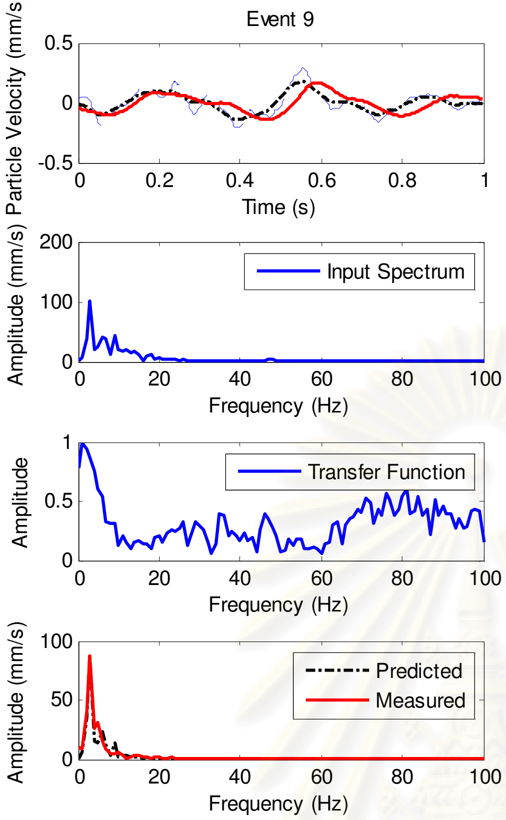

Event 4

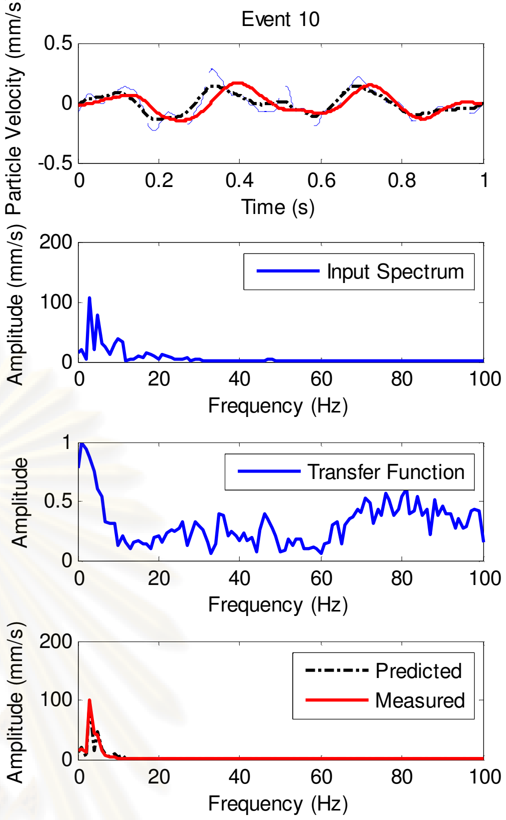

Event 5
Particle Velocity (mm/s)
0.5
0
-0.5
0
0.2
0.4
0.6
0.8
1
Time (s)
Amplitude (mm/s)
100
50
0
Input Spectrum
Amplitude
1
0.5
0
Transfer Function
Amplitude (mm/s)
100
50
0
Predicted
Measured
0
20
40
60
80
100
Frequency (Hz)

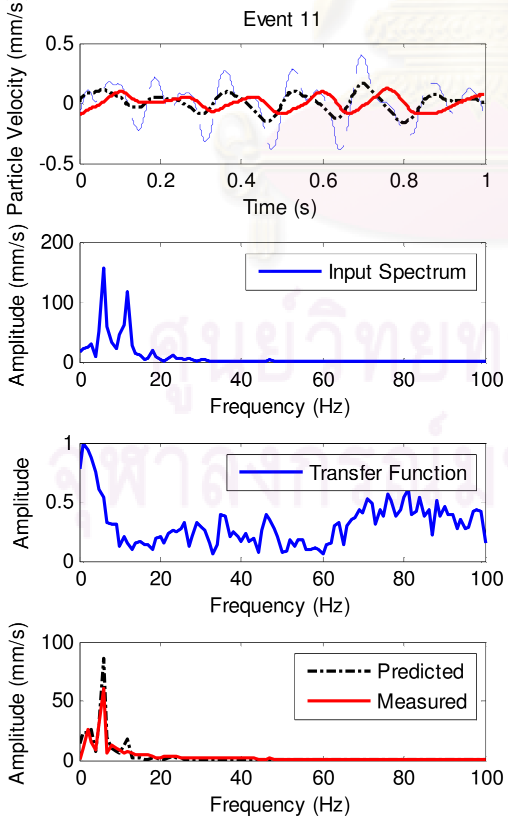

Event 6
Particle Velocity (mm/s)
0.5
0
-0.5
0
0.2
0.4
0.6
0.8
1
Time (s)
Amplitude (mm/s)
200
100
0
Input Spectrum
Amplitude
1
0.5
0
Transfer Function
Amplitude (mm/s)
200
100
0
Predicted
Measured
0
20
40
60
80
100
Frequency (Hz)

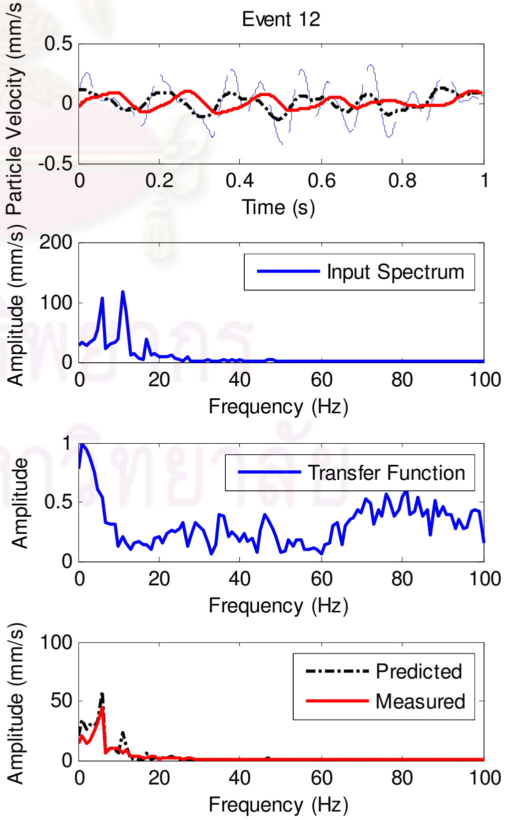

Event 7
Particle Velocity (mm/s)
0.5
0
-0.5
0
0.2
0.4
0.6
0.8
1
Time (s)
Amplitude (mm/s)
200
100
0
Input Spectrum
Amplitude
1
0.5
0
Transfer Function
Amplitude (mm/s)
100
50
0
Predicted
Measured
0
20
40
60
80
100
Frequency (Hz)

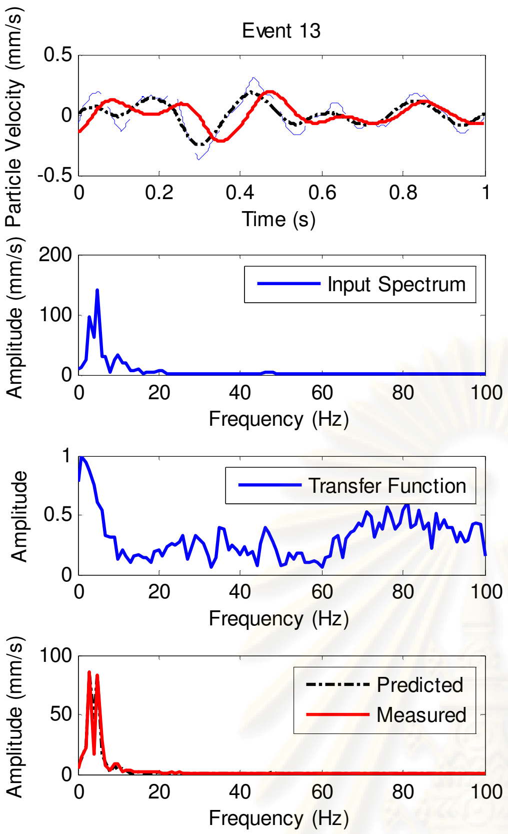

Event 8
Particle Velocity (mm/s)
0.5
0
-0.5
0
0.2
0.4
0.6
0.8
1
Time (s)
Amplitude (mm/s)
200
100
0
Input Spectrum
Amplitude
1
0.5
0
Transfer Function
Amplitude (mm/s)
100
50
0
Predicted
Measured
0
20
40
60
80
100
Frequency (Hz)

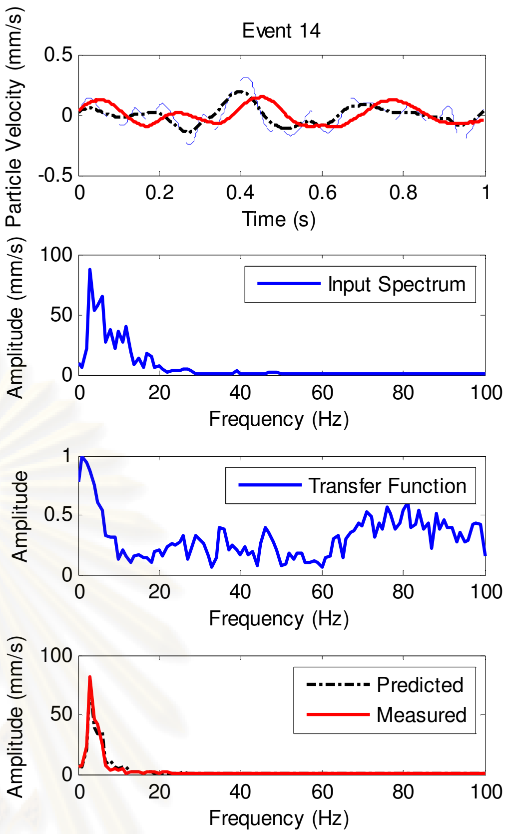

Event 9
Particle Velocity (mm/s)
0.5
0
-0.5
0
0.2
0.4
0.6
0.8
1
Time (s)
Amplitude (mm/s)
200
100
0
Input Spectrum
0
20
40
60
80
100
Frequency (Hz)
Amplitude
1
0.5
0
Transfer Function
Frequency (Hz)
Amplitude (mm/s)
100
50
0
Predicted
Measured
Frequency (Hz)

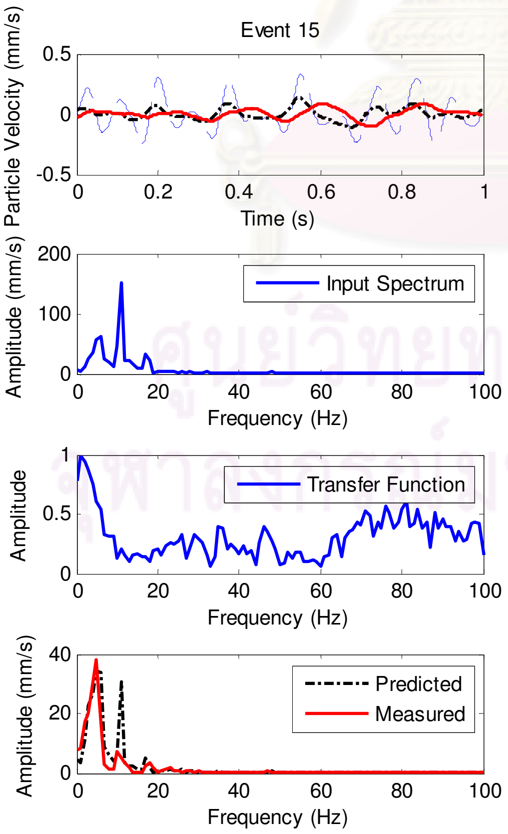

Event 10
Particle Velocity (mm/s)
0.5
0
-0.5
0
0.2
0.4
0.6
0.8
1
Time (s)
Amplitude (mm/s)
200
100
0
Input Spectrum
0
20
40
60
80
100
Frequency (Hz)
Amplitude
1
0.5
0
Transfer Function
Frequency (Hz)
Amplitude (mm/s)
200
100
0
Predicted
Measured
Frequency (Hz)

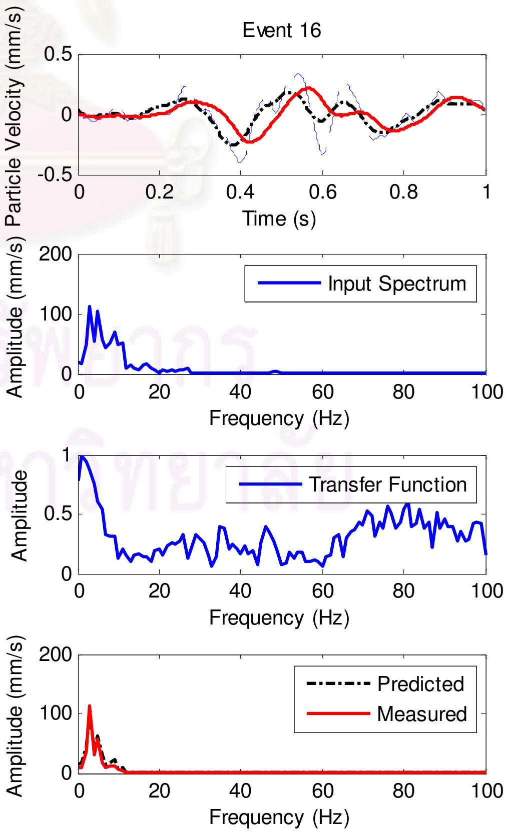

Event 11
Particle Velocity (mm/s)
0.5
0
-0.5
0
0.2
0.4
0.6
0.8
1
Time (s)
Amplitude (mm/s)
200
100
0
Input Spectrum
0
20
40
60
80
100
Frequency (Hz)
Amplitude
1
0.5
0
Transfer Function
Frequency (Hz)
Amplitude (mm/s)
100
50
0
Predicted
Measured
Frequency (Hz)

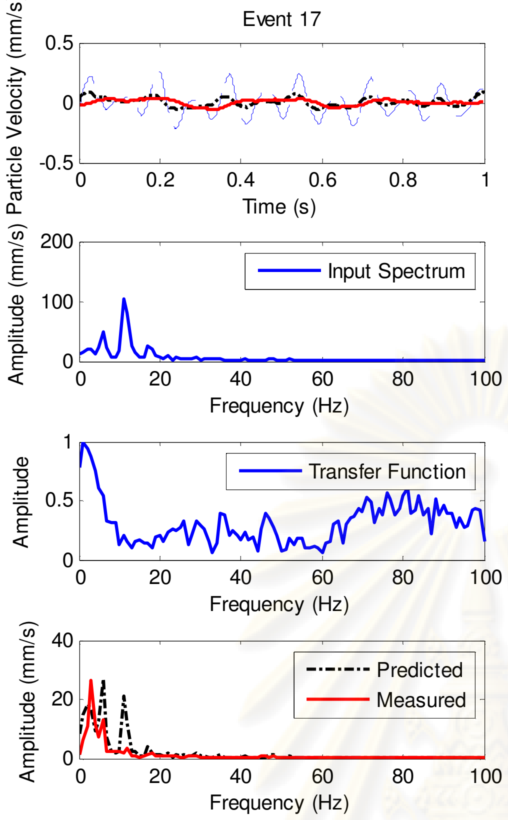

Event 12
Particle Velocity (mm/s)
0.5
0
-0.5
0
0.2
0.4
0.6
0.8
1
Time (s)
Amplitude (mm/s)
200
100
0
Input Spectrum
0
20
40
60
80
100
Frequency (Hz)
Amplitude
1
0.5
0
Transfer Function
Frequency (Hz)
Amplitude (mm/s)
100
50
0
Predicted
Measured
Frequency (Hz)

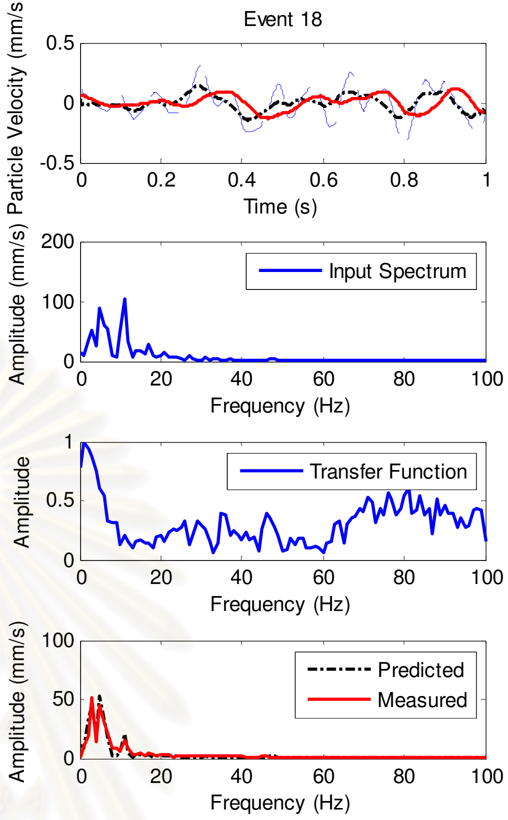

Event 13
Particle Velocity (mm/s)
0.5
0
-0.5
0
0.2
0.4
0.6
0.8
1
Time (s)
Amplitude (mm/s)
200
100
0
Input Spectrum
0
20
40
60
80
100
Frequency (Hz)
Amplitude
1
0.5
0
Transfer Function
Frequency (Hz)
Amplitude (mm/s)
100
50
0
Predicted
Measured
Frequency (Hz)

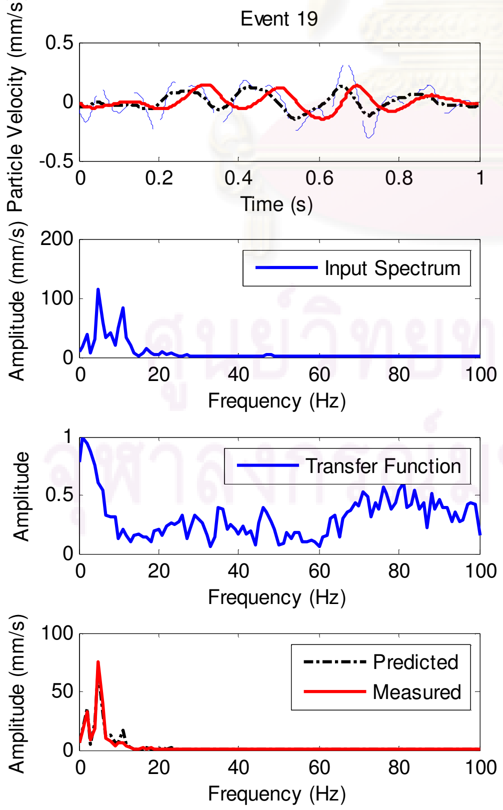

Event 14
Particle Velocity (mm/s)
0.5
0
-0.5
0
0.2
0.4
0.6
0.8
1
Time (s)
Amplitude (mm/s)
100
50
0
Input Spectrum
0
20
40
60
80
100
Frequency (Hz)
Amplitude
1
0.5
0
Transfer Function
Frequency (Hz)
Amplitude (mm/s)
100
50
0
Predicted
Measured
Frequency (Hz)

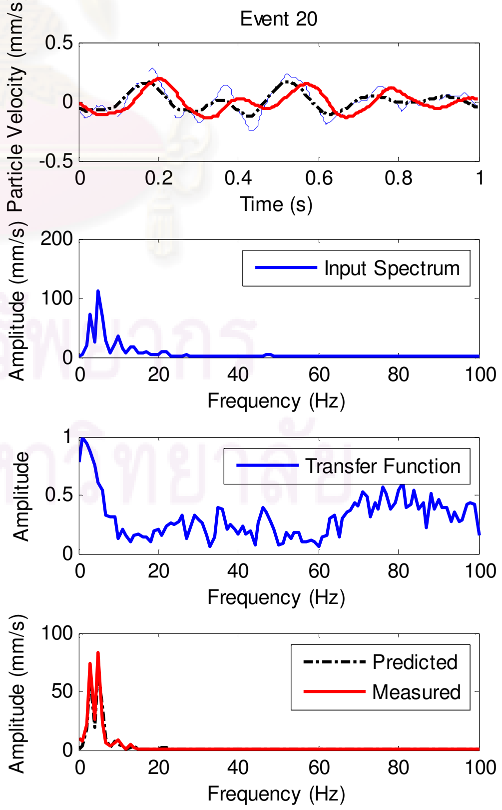

Event 15
Particle Velocity (mm/s)
0.5
0
-0.5
0
0.2
0.4
0.6
0.8
1
Time (s)
Amplitude (mm/s)
200
100
0
Input Spectrum
0
20
40
60
80
100
Frequency (Hz)
Amplitude
1
0.5
0
Transfer Function
Frequency (Hz)
Amplitude (mm/s)
40
20
0
Predicted
Measured
Frequency (Hz)

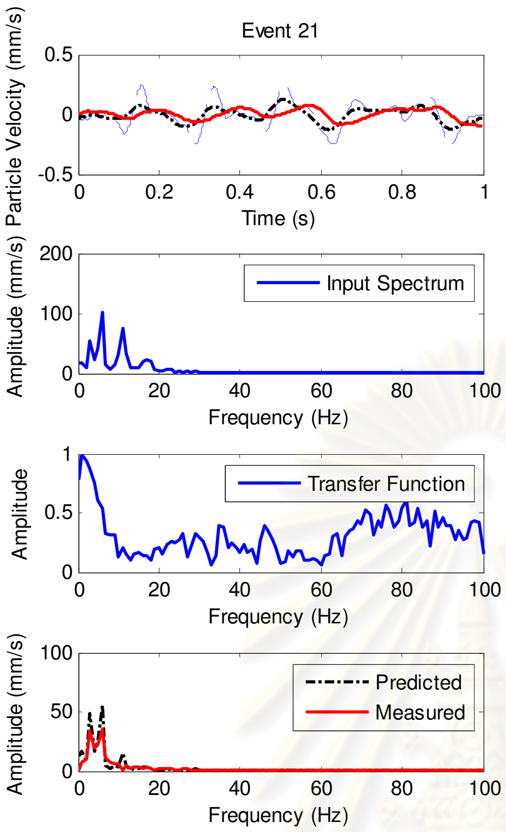

Event 16
Particle Velocity (mm/s)
0.5
0
-0.5
0
0.2
0.4
0.6
0.8
1
Time (s)
Amplitude (mm/s)
200
100
0
Input Spectrum
0
20
40
60
80
100
Frequency (Hz)
Amplitude
1
0.5
0
Transfer Function
Frequency (Hz)
Amplitude (mm/s)
200
100
0
Predicted
Measured
Frequency (Hz)

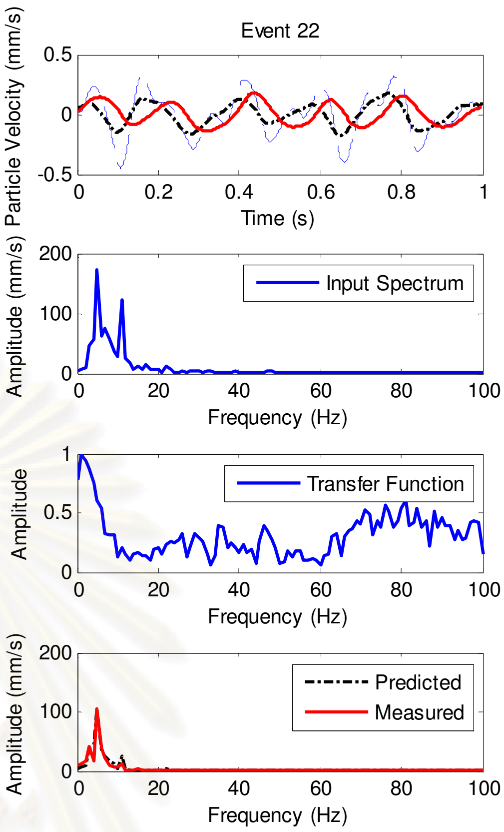

Event 17
Particle Velocity (mm/s)
0.5
0
-0.5
0
0.2
0.4
0.6
0.8
1
Time (s)
Amplitude (mm/s)
200
100
0
Input Spectrum
0
20
40
60
80
100
Frequency (Hz)
Amplitude
1
0.5
0
Transfer Function
Frequency (Hz)
Amplitude (mm/s)
40
20
0
Predicted
Measured
Frequency (Hz)

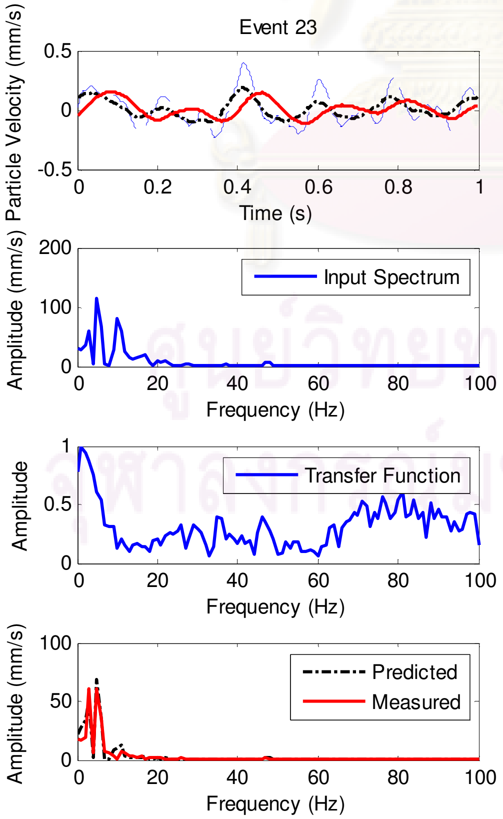

Event 18
Particle Velocity (mm/s)
0.5
0
-0.5
0
0.2
0.4
0.6
0.8
1
Time (s)
Amplitude (mm/s)
200
100
0
Input Spectrum
0
20
40
60
80
100
Frequency (Hz)
Amplitude
1
0.5
0
Transfer Function
Frequency (Hz)
Amplitude (mm/s)
100
50
0
Predicted
Measured
Frequency (Hz)

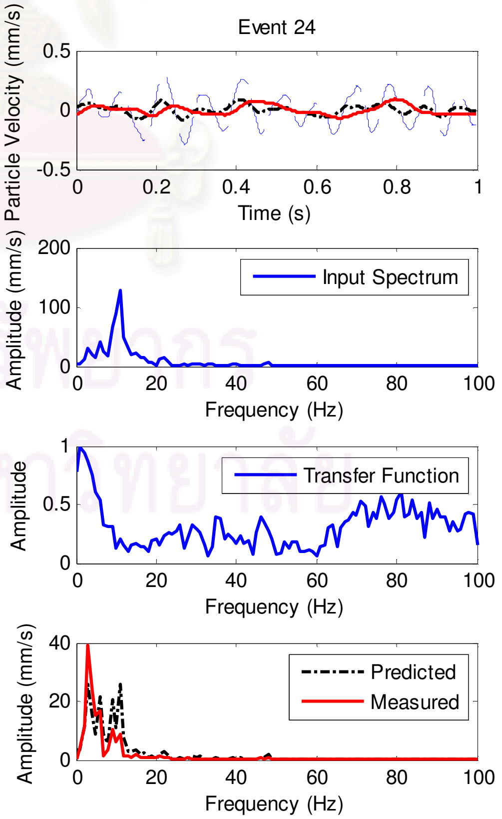

Event 19
Particle Velocity (mm/s)
0.5
0
-0.5
0
0.2
0.4
0.6
0.8
1
Time (s)
Amplitude (mm/s)
200
100
0
Input Spectrum
0
20
40
60
80
100
Frequency (Hz)
Amplitude
1
0.5
0
Transfer Function
Frequency (Hz)
Amplitude (mm/s)
100
50
0
Predicted
Measured
Frequency (Hz)

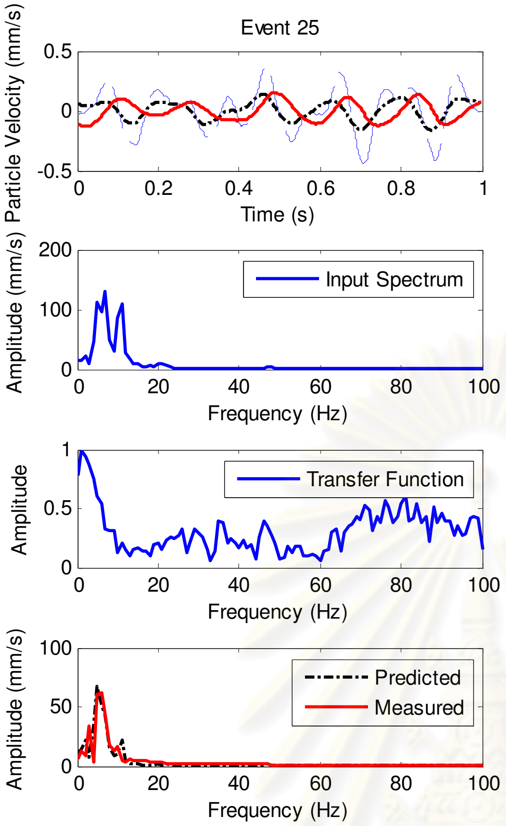

Event 20
Particle Velocity (mm/s)
0.5
0
-0.5
0
0.2
0.4
0.6
0.8
1
Time (s)
Amplitude (mm/s)
200
100
0
Input Spectrum
0
20
40
60
80
100
Frequency (Hz)
Amplitude
1
0.5
0
Transfer Function
Frequency (Hz)
Amplitude (mm/s)
100
50
0
Predicted
Measured
Frequency (Hz)

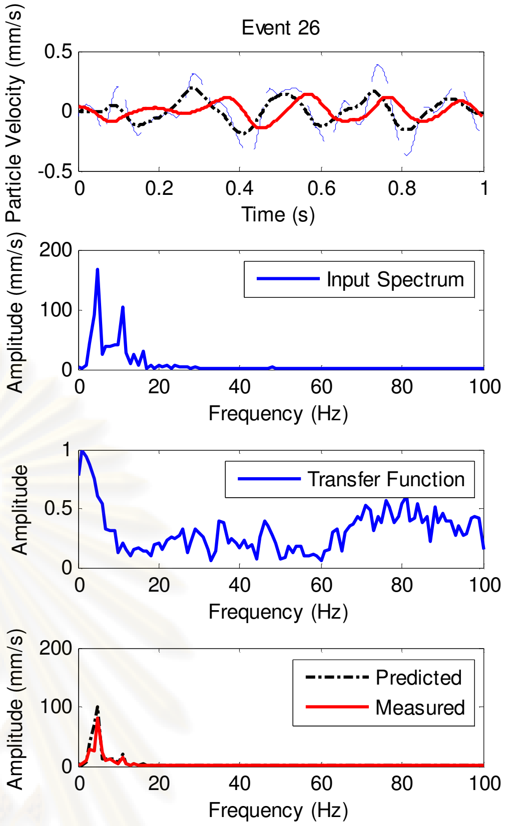

Event 21
Particle Velocity (mm/s)
0.5
0
-0.5
0
0.2
0.4
0.6
0.8
1
Time (s)
Amplitude (mm/s)
200
100
0
Input Spectrum
0
20
40
60
80
100
Frequency (Hz)
Amplitude
1
0.5
0
Transfer Function
Frequency (Hz)
Amplitude (mm/s)
100
50
0
Predicted
Measured
Frequency (Hz)


Event 22
Particle Velocity (mm/s)
0.5
0
-0.5
0
0.2
0.4
0.6
0.8
1
Time (s)
Amplitude (mm/s)
200
100
0
Input Spectrum
0
20
40
60
80
100
Frequency (Hz)
Amplitude
1
0.5
0
Transfer Function
Frequency (Hz)
Amplitude (mm/s)
200
100
0
Predicted
Measured
Frequency (Hz)


Event 23
Particle Velocity (mm/s)
0.5
0
-0.5
0
0.2
0.4
0.6
0.8
1
Time (s)
Amplitude (mm/s)
200
100
0
Input Spectrum
0
20
40
60
80
100
Frequency (Hz)
Amplitude
1
0.5
0
Transfer Function
Frequency (Hz)
Amplitude (mm/s)
100
50
0
Predicted
Measured
Frequency (Hz)

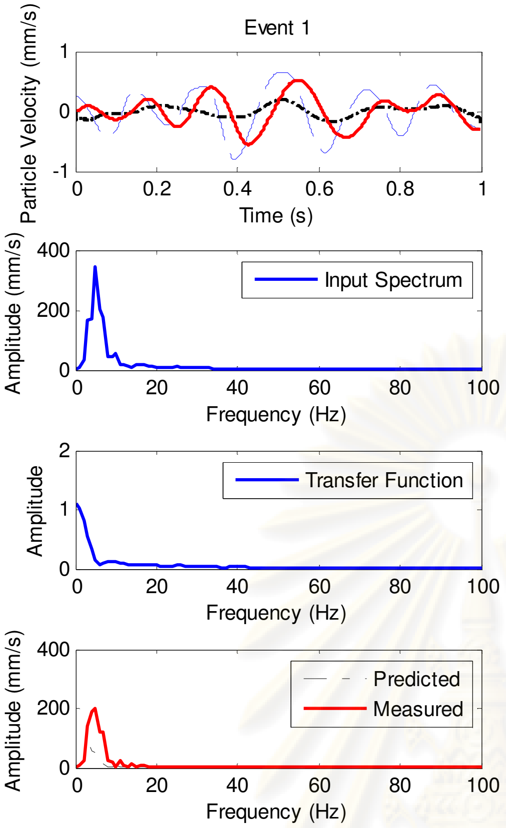

Event 24
Particle Velocity (mm/s)
0.5
0
-0.5
0
0.2
0.4
0.6
0.8
1
Time (s)
Amplitude (mm/s)
200
100
0
Input Spectrum
0
20
40
60
80
100
Frequency (Hz)
Amplitude
1
0.5
0
Transfer Function
Frequency (Hz)
Amplitude (mm/s)
40
20
0
Predicted
Measured
Frequency (Hz)

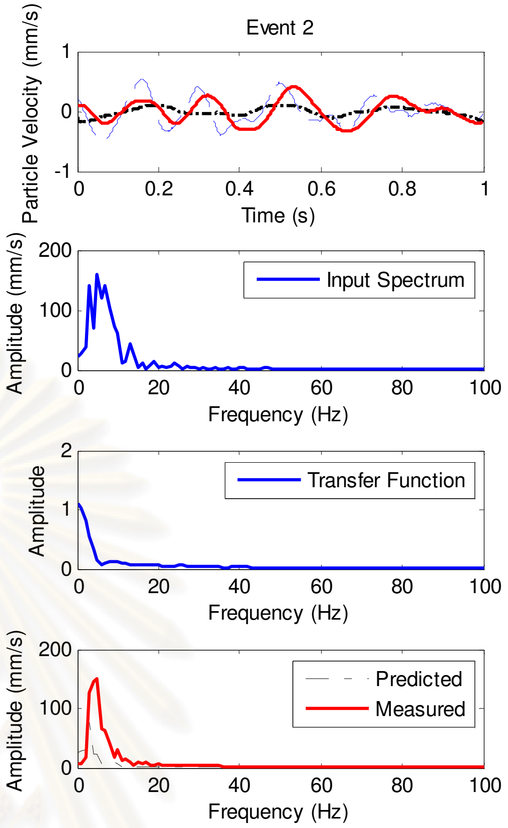

Event 25
Particle Velocity (mm/s)
0.5
0
-0.5
0
0.2
0.4
0.6
0.8
1
Time (s)
Amplitude (mm/s)
200
100
0
Input Spectrum
0
20
40
60
80
100
Frequency (Hz)
Amplitude
1
0.5
0
Transfer Function
Frequency (Hz)
Amplitude (mm/s)
100
50
0
Predicted
Measured
Frequency (Hz)

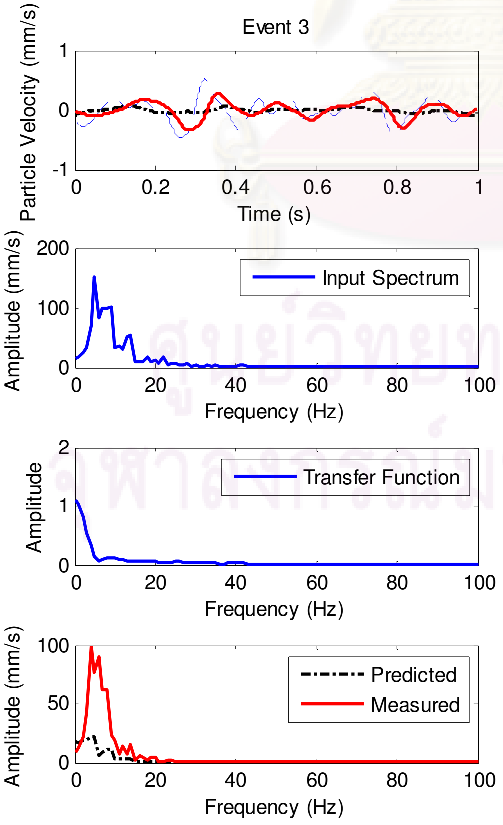

Event 26
Particle Velocity (mm/s)
0.5
0
-0.5
0
0.2
0.4
0.6
0.8
1
Time (s)
Amplitude (mm/s)
200
100
0
Input Spectrum
0
20
40
60
80
100
Frequency (Hz)
Amplitude
1
0.5
0
Transfer Function
Frequency (Hz)
Amplitude (mm/s)
200
100
0
Predicted
Measured
Frequency (Hz)

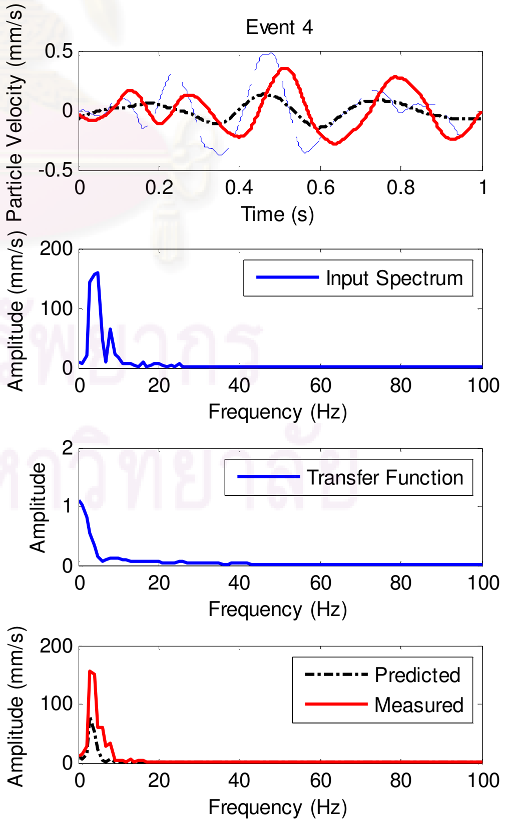
APPENDIX E

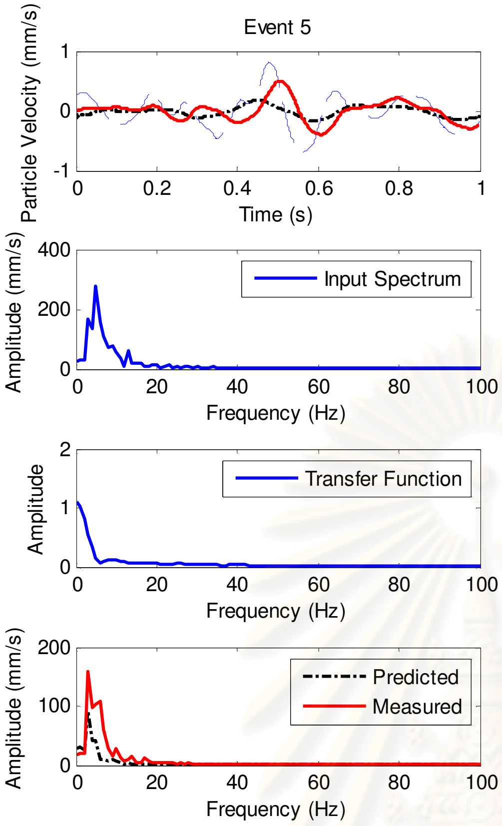
30 PREDICTED BUILDING RESPONSES IN VERTICAL DIRECTION USING TF OF HAMMER VIBRATION

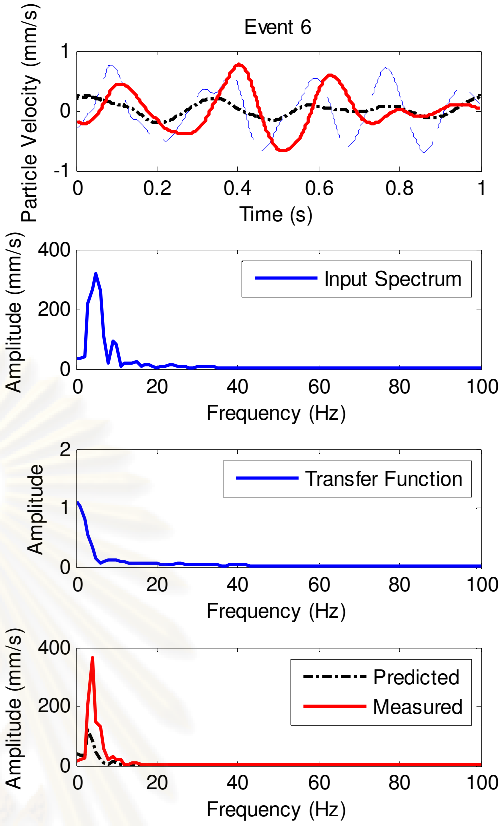

Event 1
Particle Velocity (mm/s)
1
0
-1
0
0.2
0.4
0.6
0.8
1
Time (s)
Amplitude (mm/s)
400
200
0
Input Spectrum
0
20
40
60
80
100
Frequency (Hz)
Amplitude
2
1
0
Transfer Function
Frequency (Hz)
Amplitude (mm/s)
400
200
0
Predicted
Measured
Frequency (Hz)

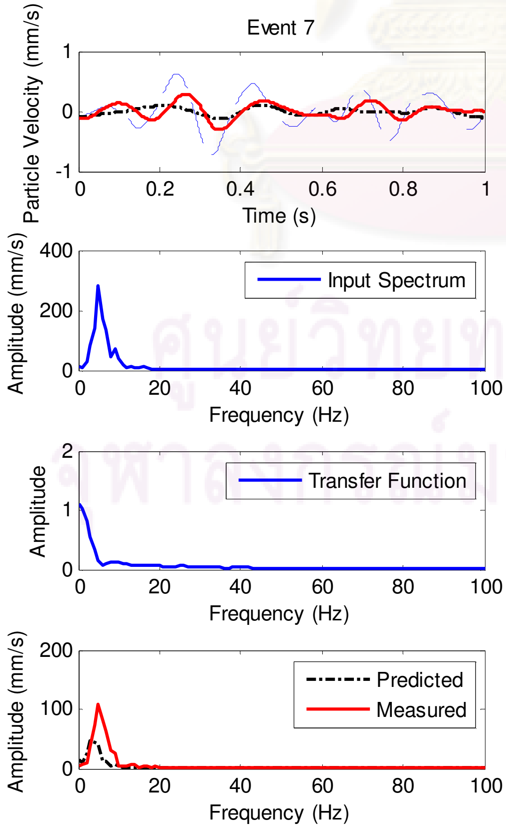

Event 2
Particle Velocity (mm/s)
1
0
-1
0
0.2
0.4
0.6
0.8
1
Time (s)
Amplitude (mm/s)
200
100
0
Input Spectrum
0
20
40
60
80
100
Frequency (Hz)
Amplitude
2
1
0
Transfer Function
Frequency (Hz)
Amplitude (mm/s)
200
100
0
Predicted
Measured
Frequency (Hz)

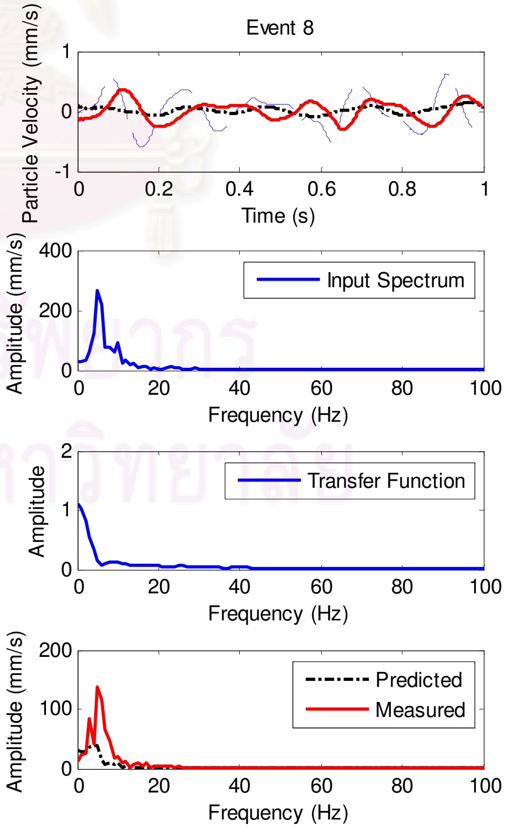

Event 3
Particle Velocity (mm/s)
1
0
-1
0
0.2
0.4
0.6
0.8
1
Time (s)
Amplitude (mm/s)
200
100
0
Input Spectrum
0
20
40
60
80
100
Frequency (Hz)
Amplitude
2
1
0
Transfer Function
Frequency (Hz)
Amplitude (mm/s)
100
50
0
Predicted
Measured
Frequency (Hz)

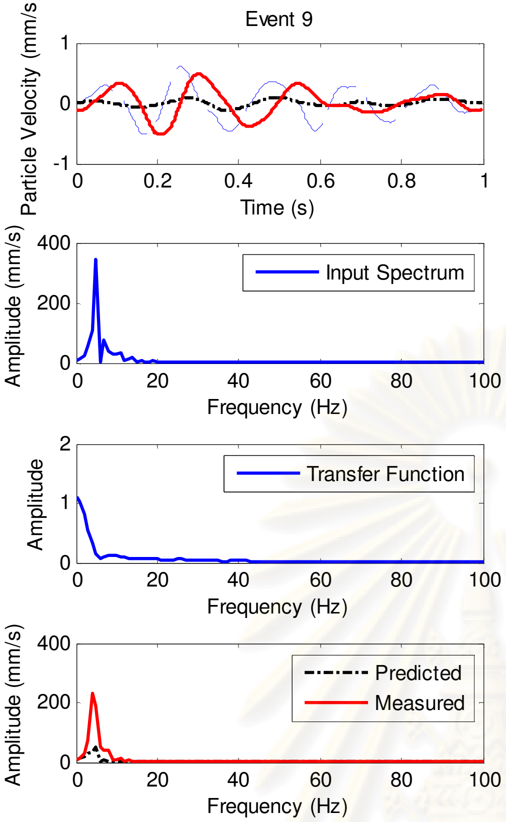

Event 4
Particle Velocity (mm/s)
0.5
0
-0.5
0
0.2
0.4
0.6
0.8
1
Time (s)
Amplitude (mm/s)
200
100
0
Input Spectrum
0
20
40
60
80
100
Frequency (Hz)
Amplitude
2
1
0
Transfer Function
Frequency (Hz)
Amplitude (mm/s)
200
100
0
Predicted
Measured
Frequency (Hz)

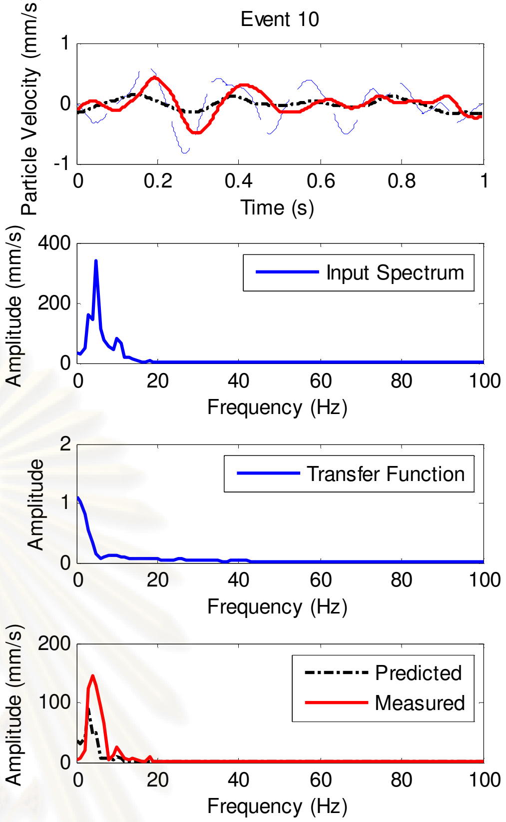

Event 5
Particle Velocity (mm/s)
1
0
-1
0
0.2
0.4
0.6
0.8
1
Time (s)
Amplitude (mm/s)
400
200
0
Input Spectrum
0
20
40
60
80
100
Frequency (Hz)
Amplitude
2
1
0
Transfer Function
Frequency (Hz)
Amplitude (mm/s)
200
100
0
Predicted
Measured
Frequency (Hz)

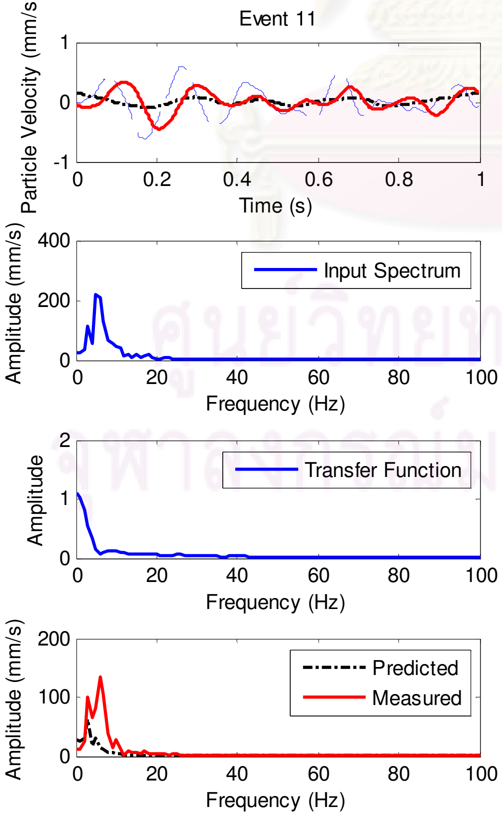

Event 6
Particle Velocity (mm/s)
1
0
-1
0
0.2
0.4
0.6
0.8
1
Time (s)
Amplitude (mm/s)
400
200
0
Input Spectrum
0
20
40
60
80
100
Frequency (Hz)
Amplitude
2
1
0
Transfer Function
Frequency (Hz)
Amplitude (mm/s)
400
200
0
Predicted
Measured
Frequency (Hz)

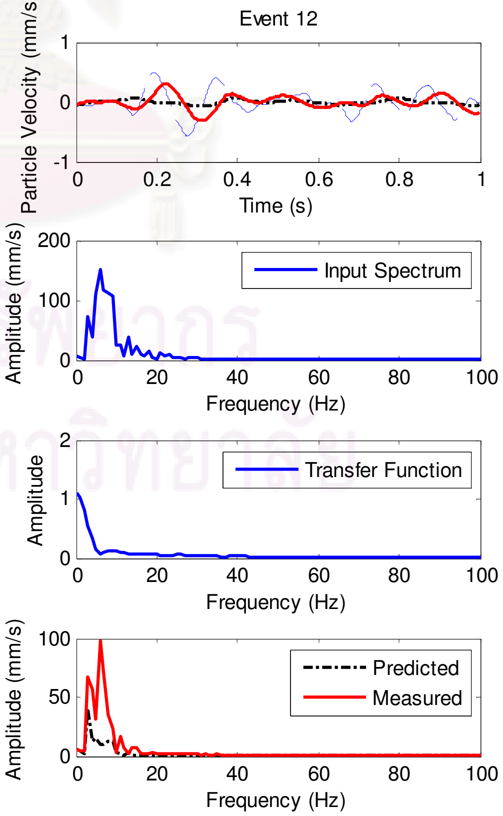

Event 7
Particle Velocity (mm/s)
1
0
-1
0
0.2
0.4
0.6
0.8
1
Time (s)
Amplitude (mm/s)
400
200
0
Input Spectrum
0
20
40
60
80
100
Frequency (Hz)
Amplitude
2
1
0
Transfer Function
Frequency (Hz)
Amplitude (mm/s)
200
100
0
Predicted
Measured
Frequency (Hz)

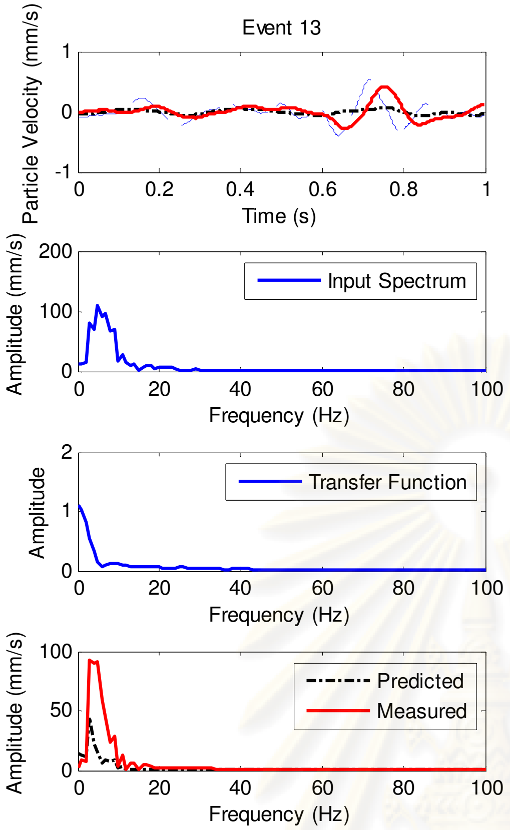

Event 8
Particle Velocity (mm/s)
1
0
-1
0
0.2
0.4
0.6
0.8
1
Time (s)
Amplitude (mm/s)
400
200
0
Input Spectrum
0
20
40
60
80
100
Frequency (Hz)
Amplitude
2
1
0
Transfer Function
Frequency (Hz)
Amplitude (mm/s)
200
100
0
Predicted
Measured
Frequency (Hz)

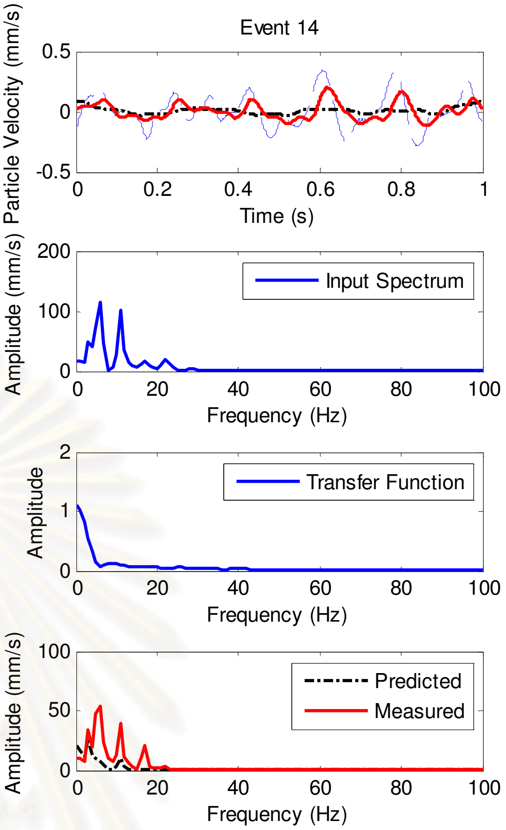

Event 9
Particle Velocity (mm/s)
Time (s)
Amplitude (mm/s)
Input Spectrum
Frequency (Hz)
Amplitude
Transfer Function
Frequency (Hz)
Amplitude (mm/s)
Predicted
Measured
Frequency (Hz)

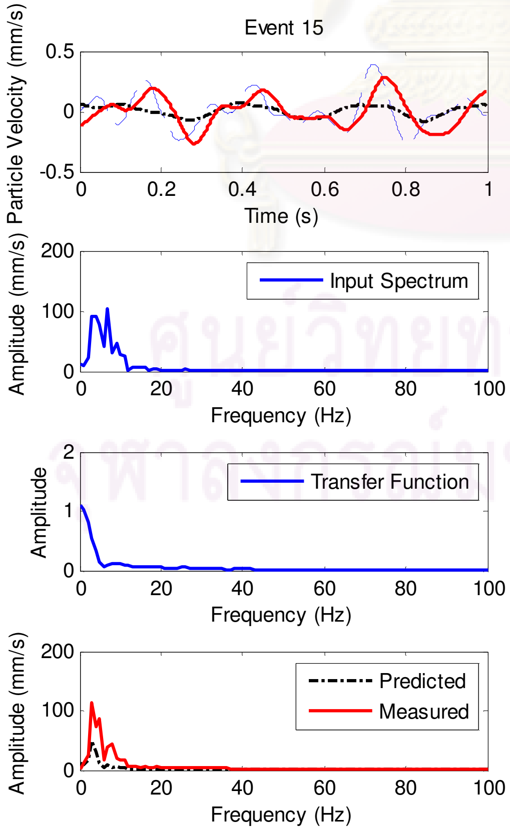

Event 10
Particle Velocity (mm/s)
Time (s)
Amplitude (mm/s)
Input Spectrum
Frequency (Hz)
Amplitude
Transfer Function
Frequency (Hz)
Amplitude (mm/s)
Predicted
Measured
Frequency (Hz)

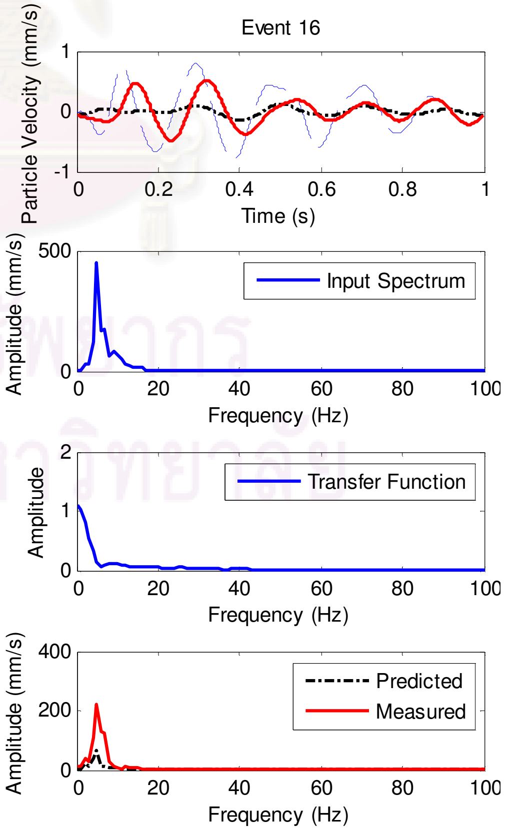

Event 11
Particle Velocity (mm/s)
Time (s)
Amplitude (mm/s)
Input Spectrum
Frequency (Hz)
Amplitude
Transfer Function
Frequency (Hz)
Amplitude (mm/s)
Predicted
Measured
Frequency (Hz)

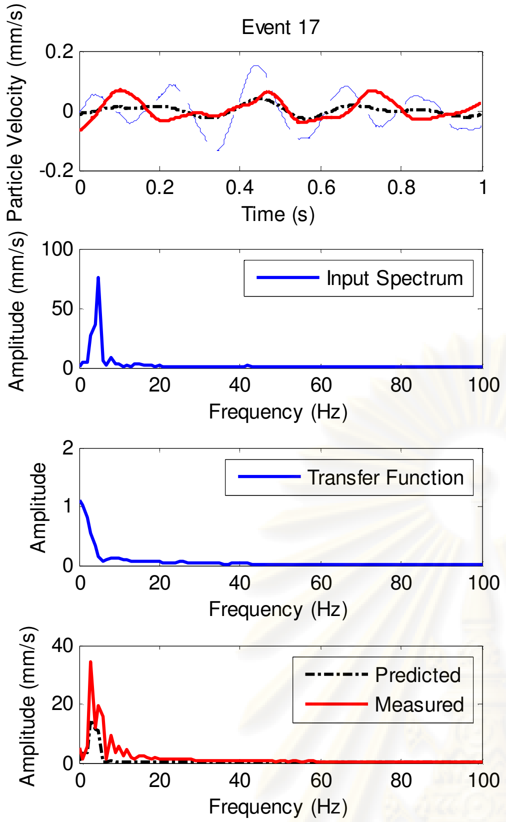

Event 12
Particle Velocity (mm/s)
Time (s)
Amplitude (mm/s)
Input Spectrum
Frequency (Hz)
Amplitude
Transfer Function
Frequency (Hz)
Amplitude (mm/s)
Predicted
Measured
Frequency (Hz)

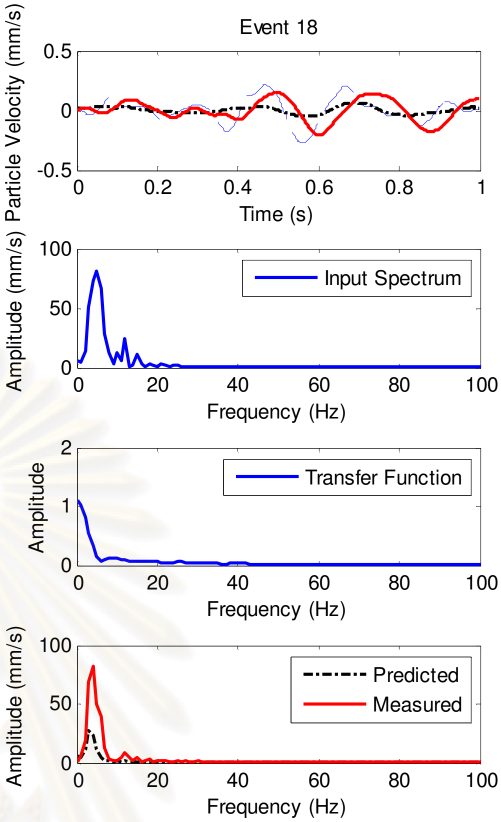

Event 13
Particle Velocity (mm/s)
1
0
-1
0
0.2
0.4
0.6
0.8
1
Time (s)
Amplitude (mm/s)
200
100
0
Input Spectrum
0
20
40
60
80
100
Frequency (Hz)
Amplitude
2
1
0
Transfer Function
0
20
40
60
80
100
Frequency (Hz)
Amplitude (mm/s)
100
50
0
Predicted
Measured
0
20
40
60
80
100
Frequency (Hz)

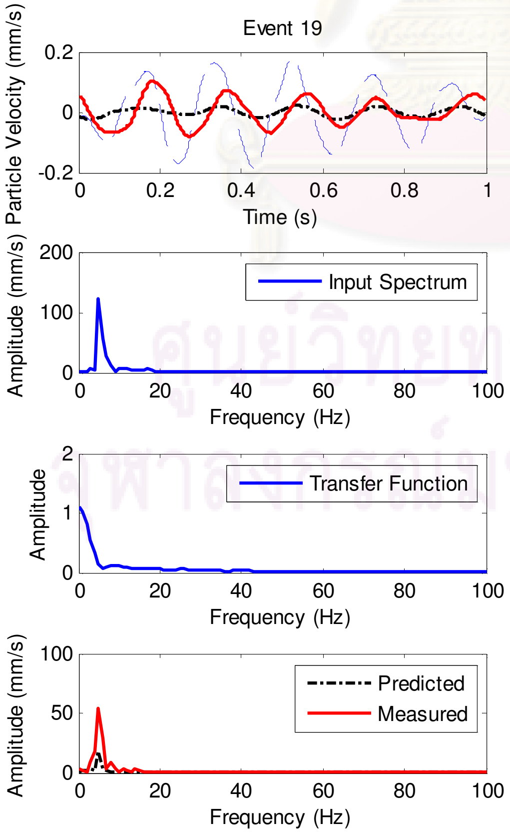

Event 14
Particle Velocity (mm/s)
0.5
0
-0.5
0
0.2
0.4
0.6
0.8
1
Time (s)
Amplitude (mm/s)
200
100
0
Input Spectrum
0
20
40
60
80
100
Frequency (Hz)
Amplitude
2
1
0
Transfer Function
0
20
40
60
80
100
Frequency (Hz)
Amplitude (mm/s)
100
50
0
Predicted
Measured
0
20
40
60
80
100
Frequency (Hz)

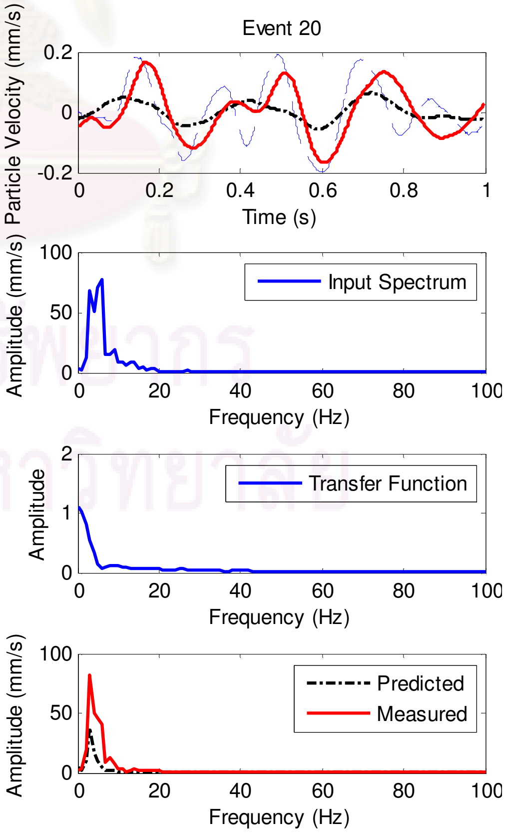

Event 15
Particle Velocity (mm/s)
0.5
0
-0.5
0
0.2
0.4
0.6
0.8
1
Time (s)
Amplitude (mm/s)
200
100
0
Input Spectrum
0
20
40
60
80
100
Frequency (Hz)
Amplitude
2
1
0
Transfer Function
0
20
40
60
80
100
Frequency (Hz)
Amplitude (mm/s)
200
100
0
Predicted
Measured
0
20
40
60
80
100
Frequency (Hz)

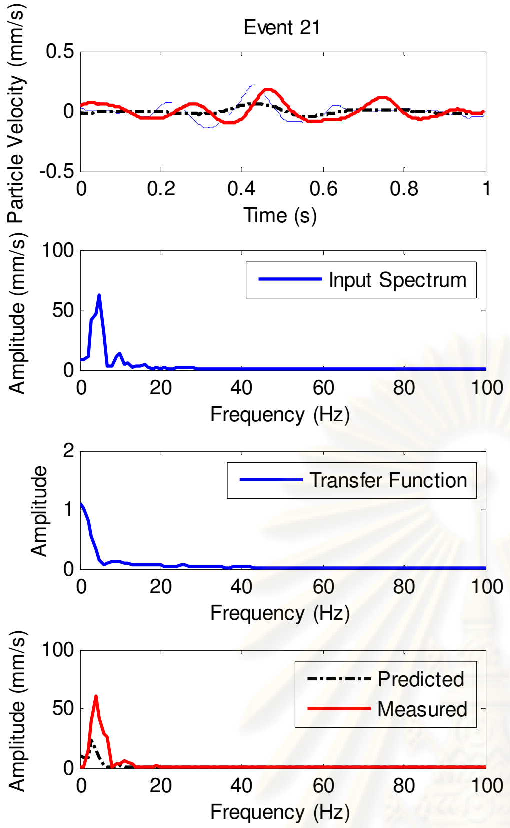

Event 16
Particle Velocity (mm/s)
1
0
-1
0
0.2
0.4
0.6
0.8
1
Time (s)
Amplitude (mm/s)
500
0
Input Spectrum
0
20
40
60
80
100
Frequency (Hz)
Amplitude
2
1
0
Transfer Function
0
20
40
60
80
100
Frequency (Hz)
Amplitude (mm/s)
400
200
0
Predicted
Measured
0
20
40
60
80
100
Frequency (Hz)

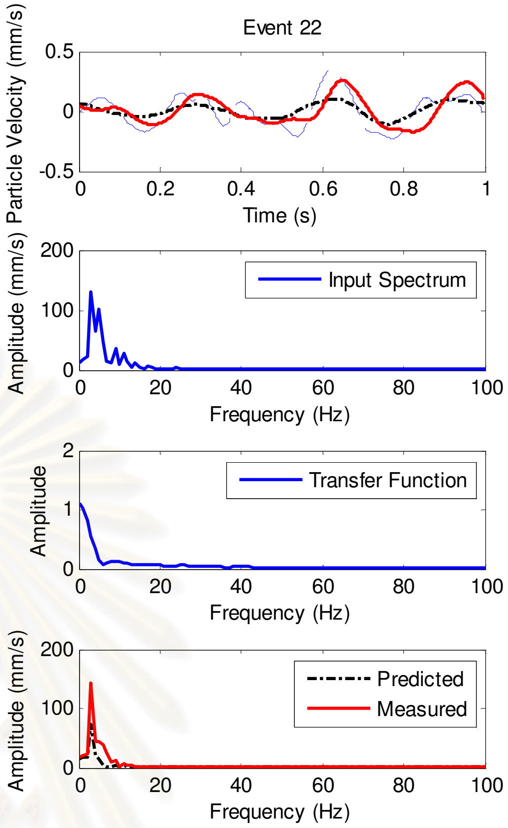

Event 17
Particle Velocity (mm/s)
0.2
0
-0.2
0
0.2
0.4
0.6
0.8
1
Time (s)
Amplitude (mm/s)
100
50
0
Input Spectrum
0
20
40
60
80
100
Frequency (Hz)
Amplitude
2
1
0
Transfer Function
Frequency (Hz)
Amplitude (mm/s)
40
20
0
Predicted
Measured
Frequency (Hz)

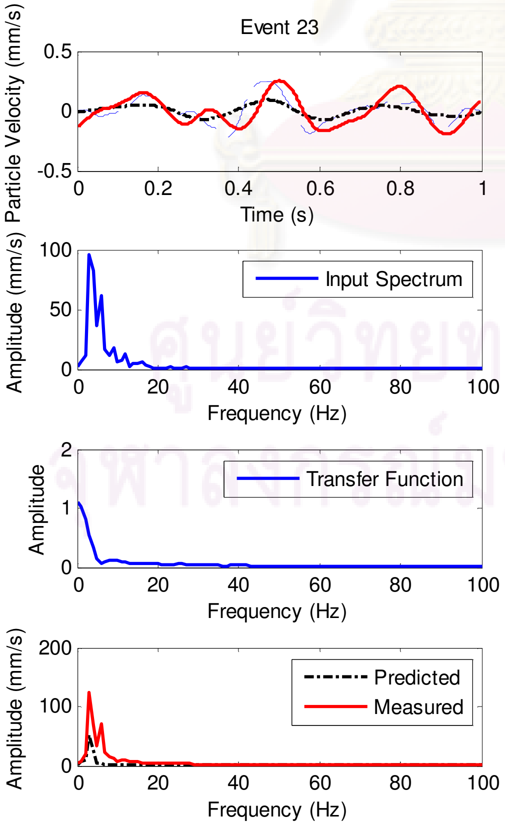

Event 18
Particle Velocity (mm/s)
0.5
0
-0.5
0
0.2
0.4
0.6
0.8
1
Time (s)
Amplitude (mm/s)
100
50
0
Input Spectrum
0
20
40
60
80
100
Frequency (Hz)
Amplitude
2
1
0
Transfer Function
Frequency (Hz)
Amplitude (mm/s)
100
50
0
Predicted
Measured
Frequency (Hz)

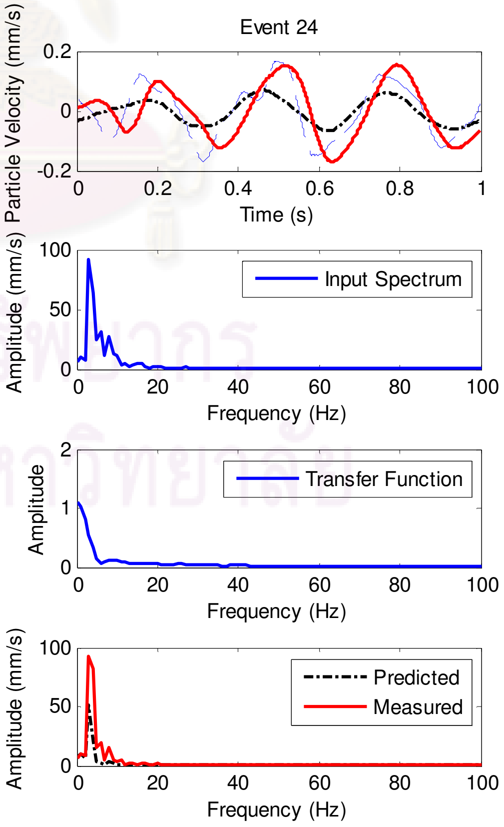

Event 19
Particle Velocity (mm/s)
0.2
0
-0.2
0
0.2
0.4
0.6
0.8
1
Time (s)
Amplitude (mm/s)
200
100
0
Input Spectrum
0
20
40
60
80
100
Frequency (Hz)
Amplitude
2
1
0
Transfer Function
Frequency (Hz)
Amplitude (mm/s)
100
50
0
Predicted
Measured
Frequency (Hz)

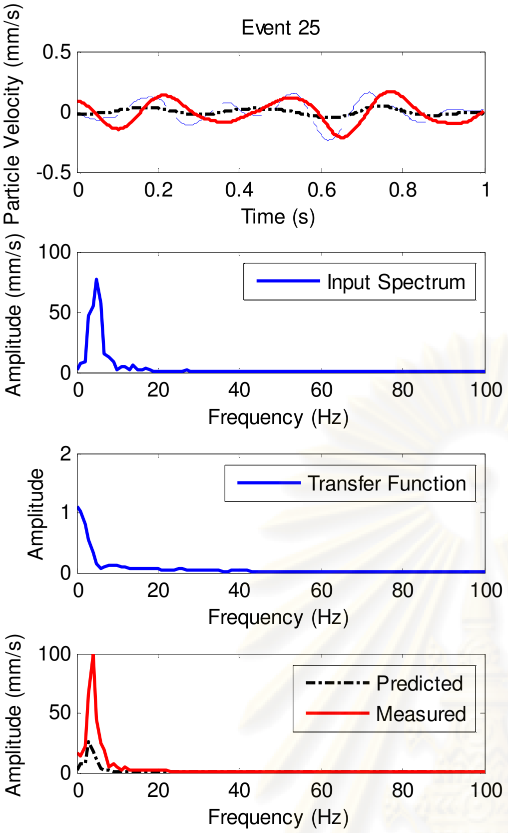

Event 20
Particle Velocity (mm/s)
0.2
0
-0.2
0
0.2
0.4
0.6
0.8
1
Time (s)
Amplitude (mm/s)
100
50
0
Input Spectrum
0
20
40
60
80
100
Frequency (Hz)
Amplitude
2
1
0
Transfer Function
Frequency (Hz)
Amplitude (mm/s)
100
50
0
Predicted
Measured
Frequency (Hz)

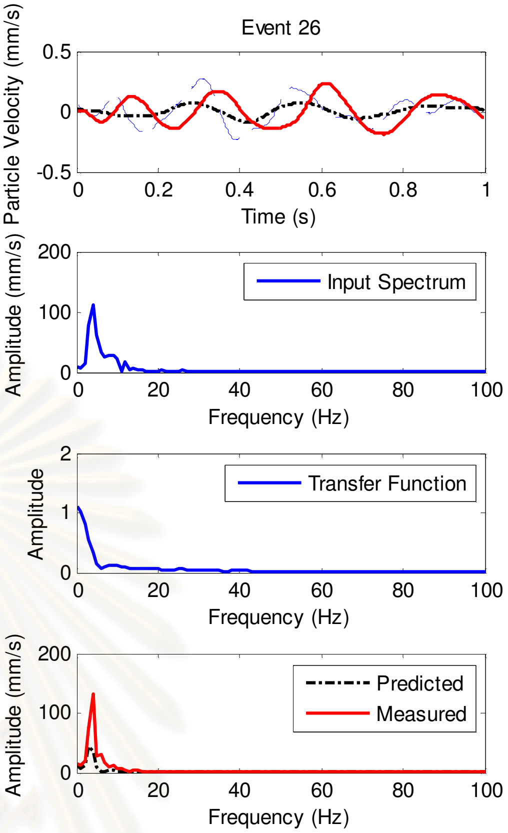

Event 21
Particle Velocity (mm/s)
0.5
0
-0.5
0
0.2
0.4
0.6
0.8
1
Time (s)
Amplitude (mm/s)
100
50
0
Input Spectrum
0
20
40
60
80
100
Frequency (Hz)
Amplitude
2
1
0
Transfer Function
Frequency (Hz)
Amplitude (mm/s)
100
50
0
Predicted
Measured
Frequency (Hz)

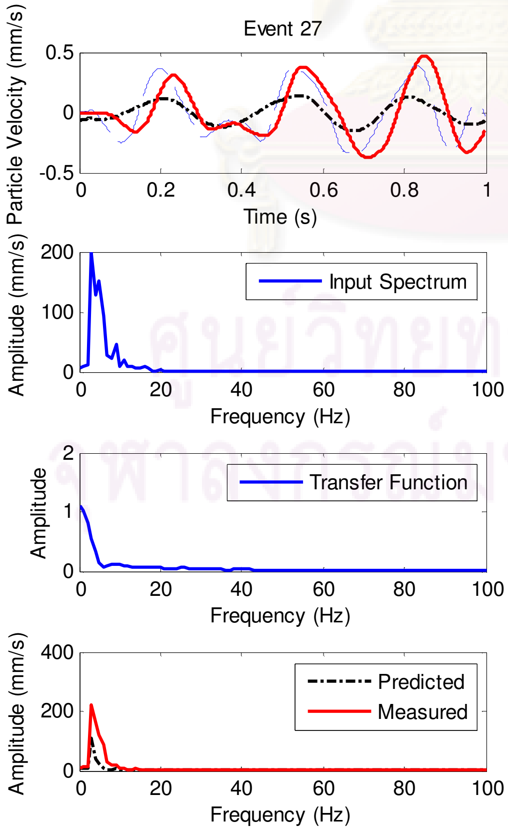

Event 22
Particle Velocity (mm/s)
0.5
0
-0.5
0
0.2
0.4
0.6
0.8
1
Time (s)
Amplitude (mm/s)
200
100
0
Input Spectrum
0
20
40
60
80
100
Frequency (Hz)
Amplitude
2
1
0
Transfer Function
Frequency (Hz)
Amplitude (mm/s)
200
100
0
Predicted
Measured
Frequency (Hz)

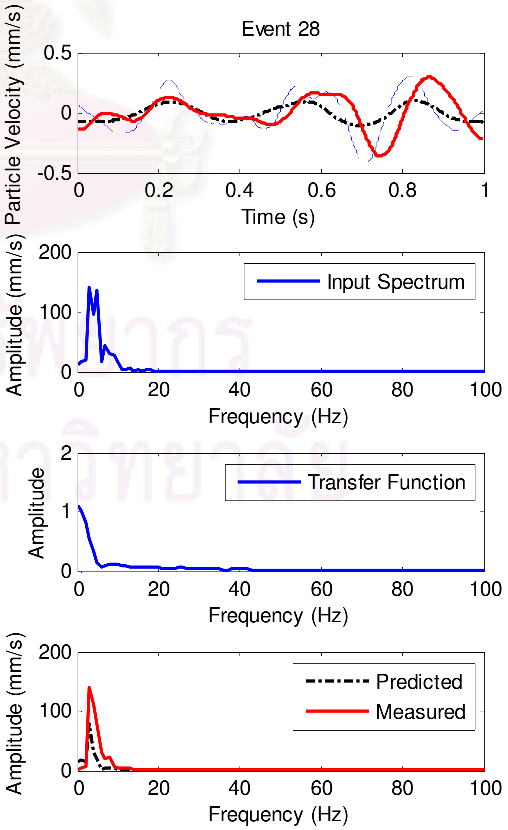

Event 23
Particle Velocity (mm/s)
0.5
0
-0.5
0
0.2
0.4
0.6
0.8
1
Time (s)
Amplitude (mm/s)
100
50
0
Input Spectrum
0
20
40
60
80
100
Frequency (Hz)
Amplitude
2
1
0
Transfer Function
Frequency (Hz)
Amplitude (mm/s)
200
100
0
Predicted
Measured
Frequency (Hz)

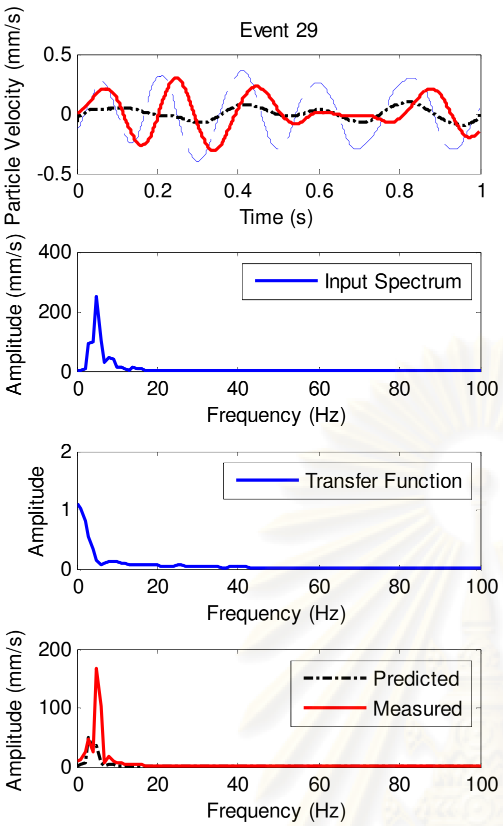

Event 24
Particle Velocity (mm/s)
0.2
0
-0.2
0
0.2
0.4
0.6
0.8
1
Time (s)
Amplitude (mm/s)
100
50
0
Input Spectrum
0
20
40
60
80
100
Frequency (Hz)
Amplitude
2
1
0
Transfer Function
Frequency (Hz)
Amplitude (mm/s)
100
50
0
Predicted
Measured
Frequency (Hz)

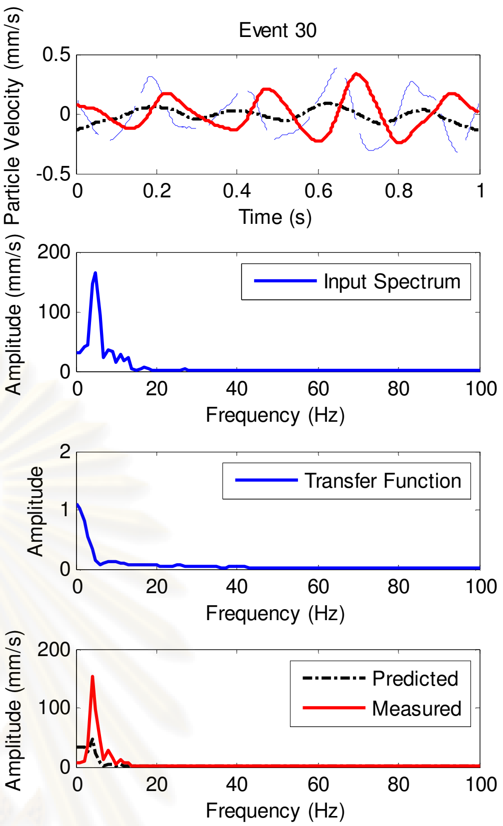

Event 25
Particle Velocity (mm/s)
0.5
0
-0.5
0
0.2
0.4
0.6
0.8
1
Time (s)
Amplitude (mm/s)
100
50
0
Input Spectrum
0
20
40
60
80
100
Frequency (Hz)
Amplitude
2
1
0
Transfer Function
Frequency (Hz)
Amplitude (mm/s)
100
50
0
Predicted
Measured
Frequency (Hz)


Event 26
Particle Velocity (mm/s)
0.5
0
-0.5
0
0.2
0.4
0.6
0.8
1
Time (s)
Amplitude (mm/s)
200
100
0
Input Spectrum
0
20
40
60
80
100
Frequency (Hz)
Amplitude
2
1
0
Transfer Function
Frequency (Hz)
Amplitude (mm/s)
200
100
0
Predicted
Measured
Frequency (Hz)


Event 27
Particle Velocity (mm/s)
0.5
0
-0.5
0
0.2
0.4
0.6
0.8
1
Time (s)
Amplitude (mm/s)
200
100
0
Input Spectrum
0
20
40
60
80
100
Frequency (Hz)
Amplitude
2
1
0
Transfer Function
Frequency (Hz)
Amplitude (mm/s)
400
200
0
Predicted
Measured
Frequency (Hz)

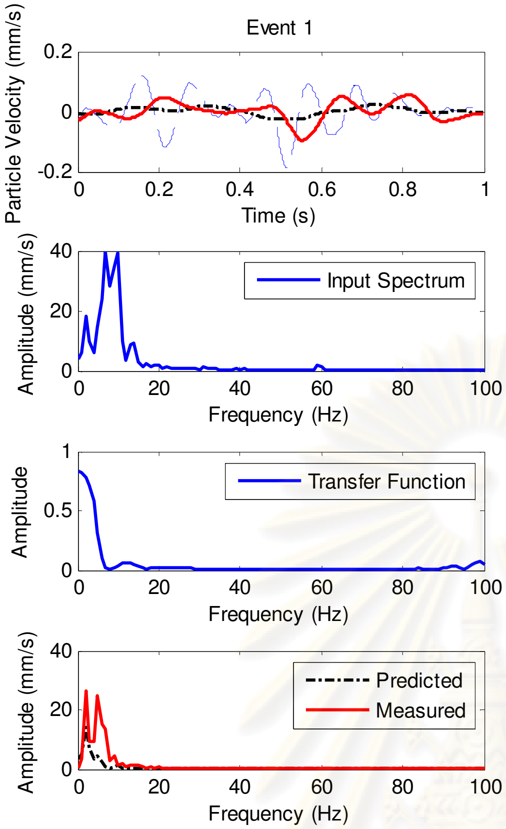

Event 28
Particle Velocity (mm/s)
0.5
0
-0.5
0
0.2
0.4
0.6
0.8
1
Time (s)
Amplitude (mm/s)
200
100
0
Input Spectrum
0
20
40
60
80
100
Frequency (Hz)
Amplitude
2
1
0
Transfer Function
Frequency (Hz)
Amplitude (mm/s)
200
100
0
Predicted
Measured
Frequency (Hz)

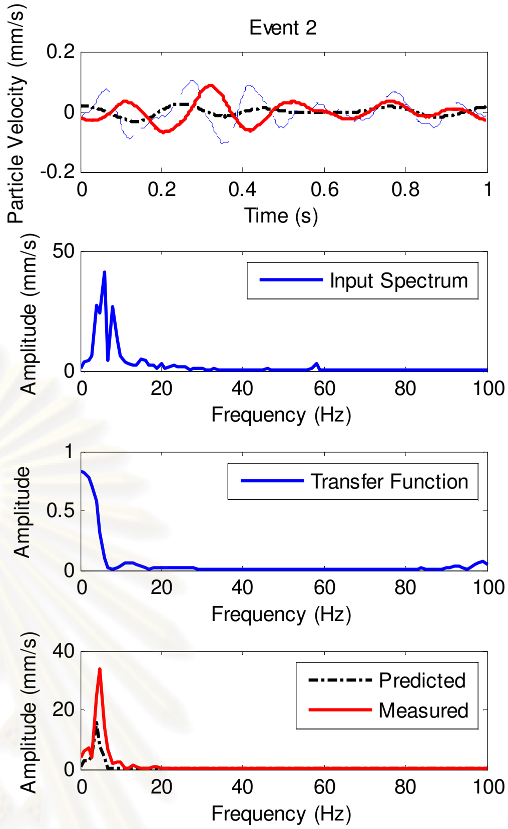

Event 29
Particle Velocity (mm/s)
0.5
0
-0.5
0
0.2
0.4
0.6
0.8
1
Time (s)
Amplitude (mm/s)
400
200
0
Input Spectrum
0
20
40
60
80
100
Frequency (Hz)
Amplitude
2
1
0
Transfer Function
0
20
40
60
80
100
Frequency (Hz)
Amplitude (mm/s)
200
100
0
Predicted
Measured
0
20
40
60
80
100
Frequency (Hz)

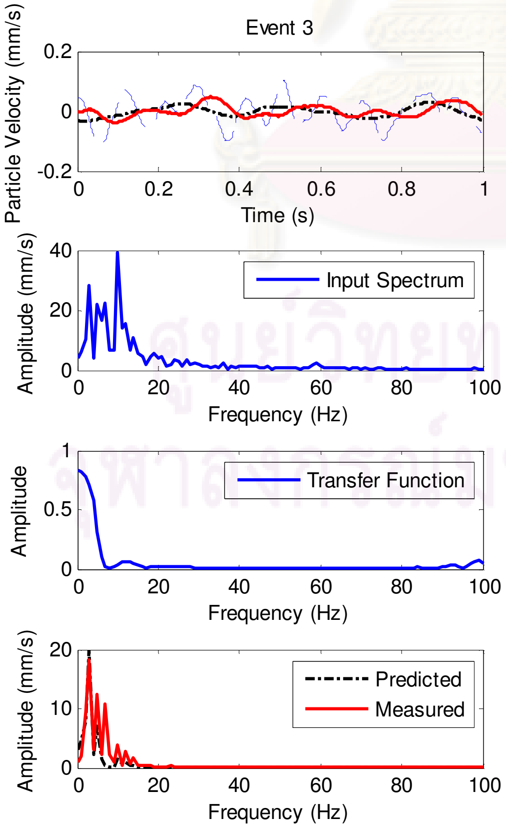

Event 30
Particle Velocity (mm/s)
0.5
0
-0.5
0
0.2
0.4
0.6
0.8
1
Time (s)
Amplitude (mm/s)
200
100
0
Input Spectrum
0
20
40
60
80
100
Frequency (Hz)
Amplitude
2
1
0
Transfer Function
0
20
40
60
80
100
Frequency (Hz)
Amplitude (mm/s)
200
100
0
Predicted
Measured
0
20
40
60
80
100
Frequency (Hz)

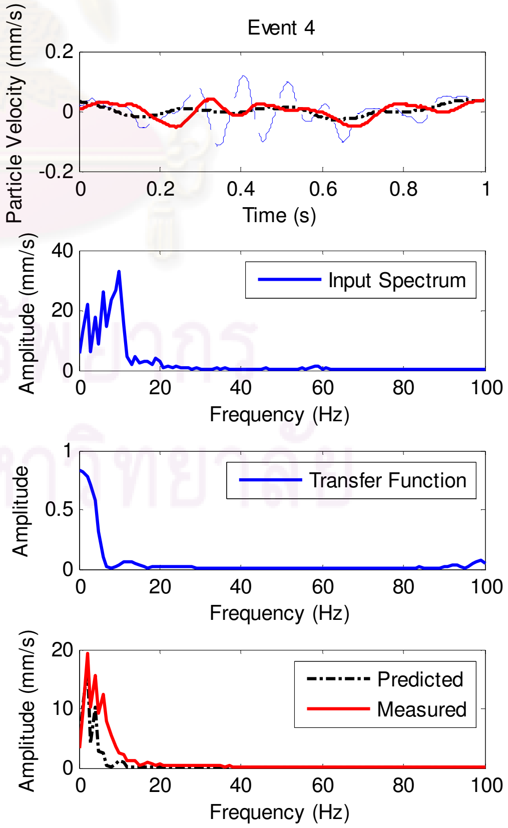
APPENDIX F

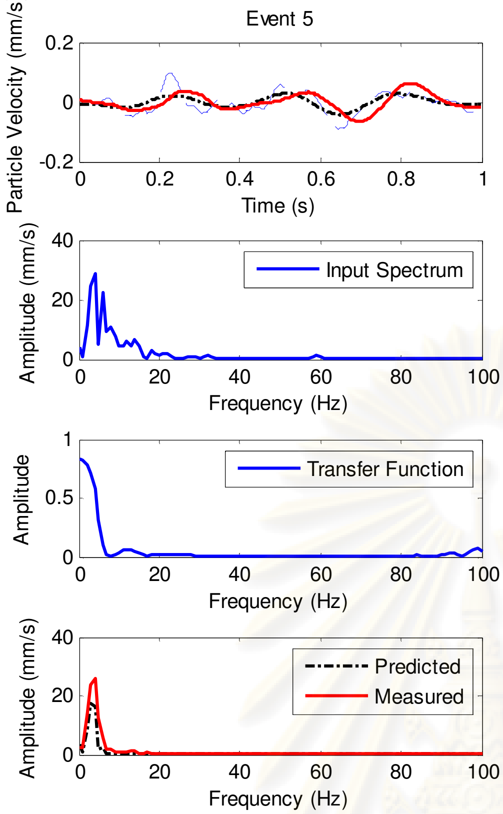
30 PREDICTED BUILDING RESPONSES IN RADIAL DIRECTION USING TF OF HAMMER VIBRATION

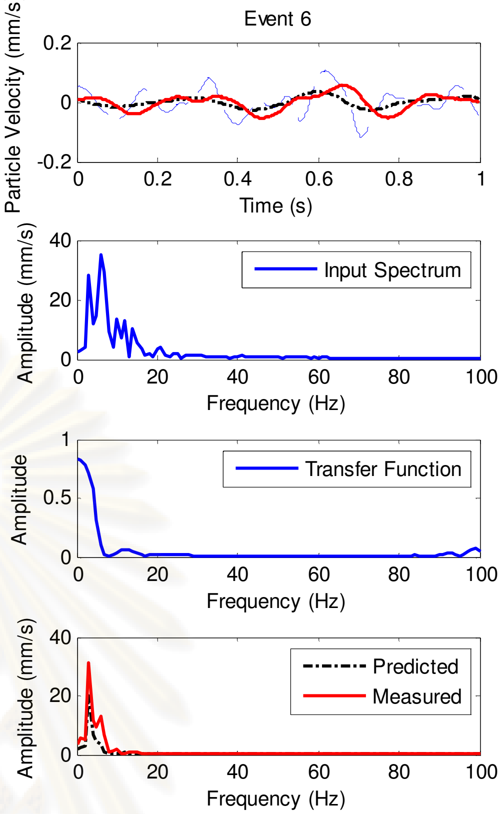

Event 1
Particle Velocity (mm/s)
0.2
0
-0.2
0
0.2
0.4
0.6
0.8
1
Time (s)
Amplitude (mm/s)
40
20
0
Input Spectrum
0
20
40
60
80
100
Frequency (Hz)
Amplitude
1
0.5
0
Transfer Function
0
20
40
60
80
100
Frequency (Hz)
Amplitude (mm/s)
40
20
0
Predicted
Measured
0
20
40
60
80
100
Frequency (Hz)

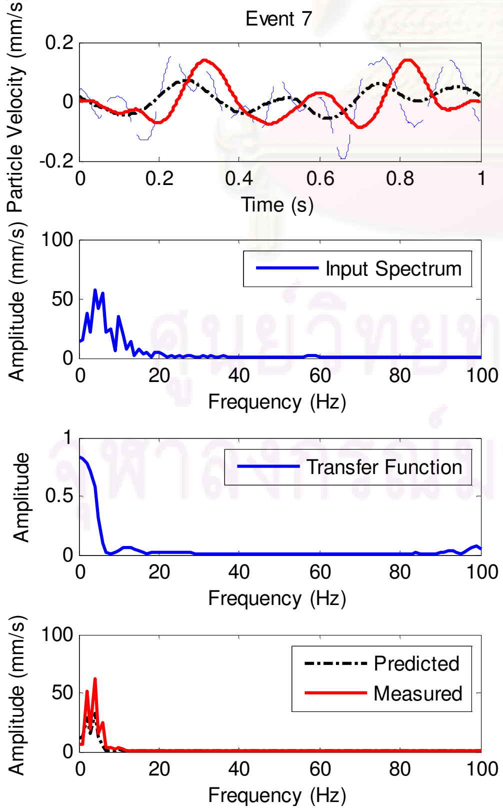

Event 2
Particle Velocity (mm/s)
0.2
0
-0.2
0
0.2
0.4
0.6
0.8
1
Time (s)
Amplitude (mm/s)
50
0
Input Spectrum
0
20
40
60
80
100
Frequency (Hz)
Amplitude
1
0.5
0
Transfer Function
0
20
40
60
80
100
Frequency (Hz)
Amplitude (mm/s)
40
20
0
Predicted
Measured
0
20
40
60
80
100
Frequency (Hz)

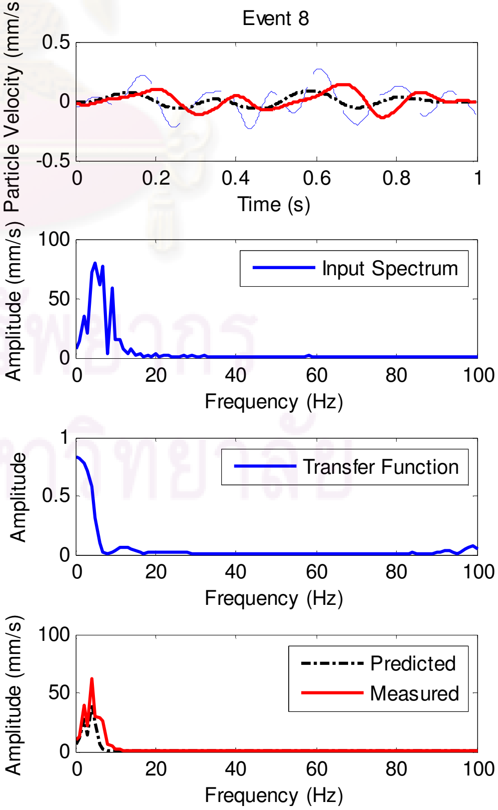

Event 3
Particle Velocity (mm/s)
0.2
0
-0.2
0
0.2
0.4
0.6
0.8
1
Time (s)
Amplitude (mm/s)
40
20
0
Input Spectrum
0
20
40
60
80
100
Frequency (Hz)
Amplitude
1
0.5
0
Transfer Function
0
20
40
60
80
100
Frequency (Hz)
Amplitude (mm/s)
20
10
0
Predicted
Measured
0
20
40
60
80
100
Frequency (Hz)

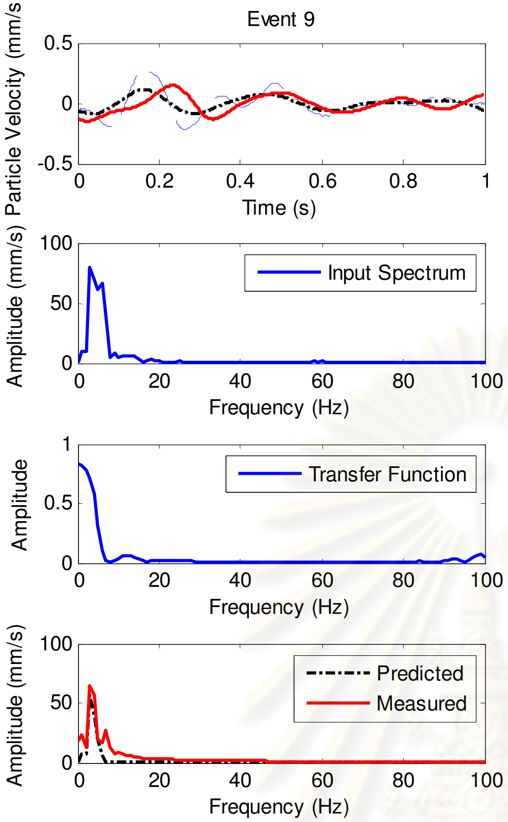

Event 4
Particle Velocity (mm/s)
0.2
0
-0.2
0
0.2
0.4
0.6
0.8
1
Time (s)
Amplitude (mm/s)
40
20
0
Input Spectrum
0
20
40
60
80
100
Frequency (Hz)
Amplitude
1
0.5
0
Transfer Function
0
20
40
60
80
100
Frequency (Hz)
Amplitude (mm/s)
20
10
0
Predicted
Measured
0
20
40
60
80
100
Frequency (Hz)

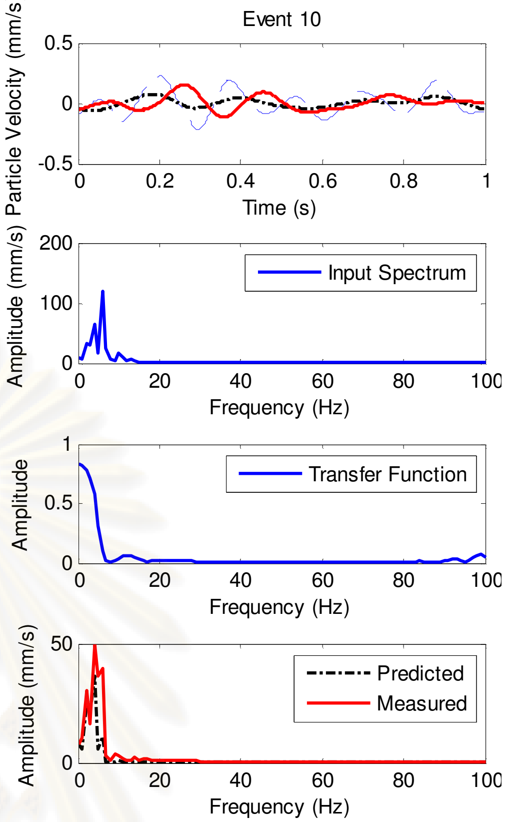

Event 5
Particle Velocity (mm/s)
0.2
0
-0.2
0
0.2
0.4
0.6
0.8
1
Time (s)
Amplitude (mm/s)
40
20
0
Input Spectrum
0
20
40
60
80
100
Frequency (Hz)
Amplitude
1
0.5
0
Transfer Function
Frequency (Hz)
Amplitude (mm/s)
Predicted
Measured
Frequency (Hz)

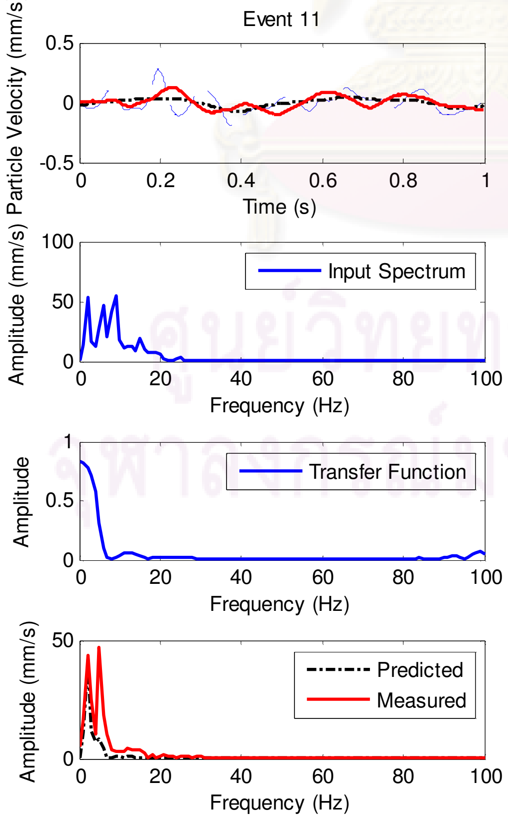

Event 6
Particle Velocity (mm/s)
0.2
0
-0.2
0
0.2
0.4
0.6
0.8
1
Time (s)
Amplitude (mm/s)
40
20
0
Input Spectrum
0
20
40
60
80
100
Frequency (Hz)
Amplitude
1
0.5
0
Transfer Function
Frequency (Hz)
Amplitude (mm/s)
Predicted
Measured
Frequency (Hz)

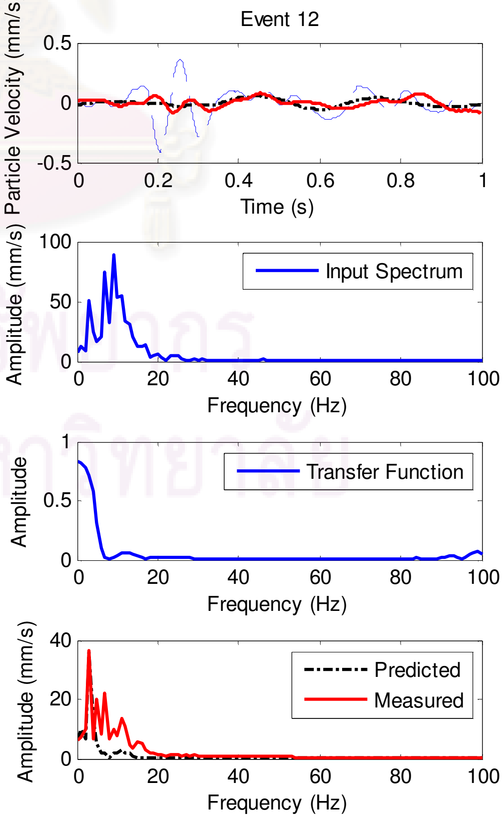

Event 7
Particle Velocity (mm/s)
0.2
0
-0.2
0
0.2
0.4
0.6
0.8
1
Time (s)
Amplitude (mm/s)
100
50
0
Input Spectrum
0
20
40
60
80
100
Frequency (Hz)
Amplitude
1
0.5
0
Transfer Function
Frequency (Hz)
Amplitude (mm/s)
Predicted
Measured
Frequency (Hz)

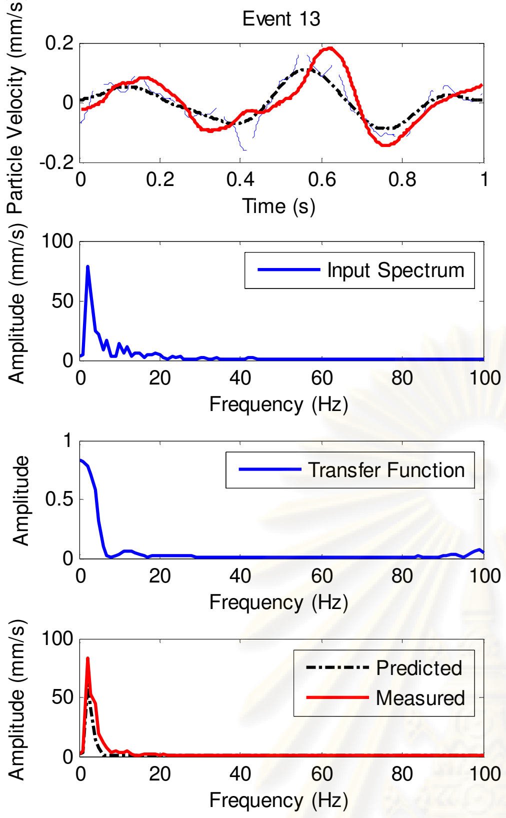

Event 8
Particle Velocity (mm/s)
0.5
0
-0.5
0
0.2
0.4
0.6
0.8
1
Time (s)
Amplitude (mm/s)
100
50
0
Input Spectrum
0
20
40
60
80
100
Frequency (Hz)
Amplitude
1
0.5
0
Transfer Function
Frequency (Hz)
Amplitude (mm/s)
Predicted
Measured
Frequency (Hz)

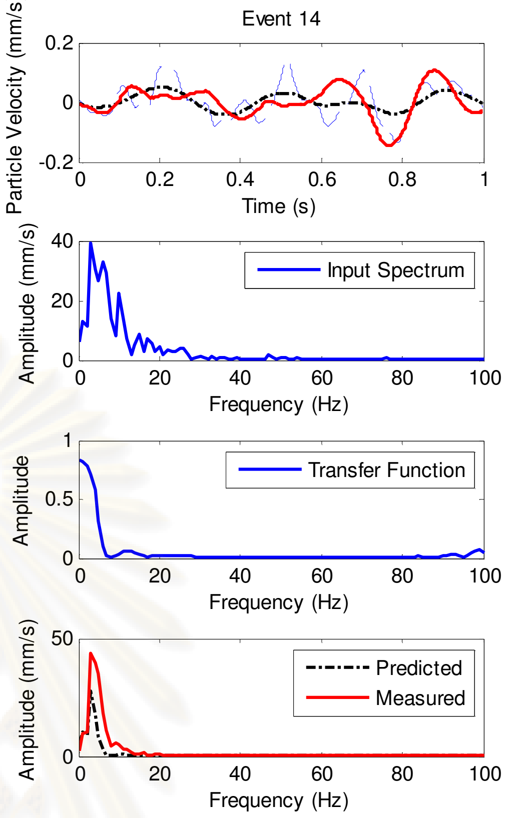

Event 9
Particle Velocity (mm/s)
0.5
0
-0.5
0
0.2
0.4
0.6
0.8
1
Time (s)
Amplitude (mm/s)
100
50
0
Input Spectrum
0
20
40
60
80
100
Frequency (Hz)
Amplitude
1
0.5
0
Transfer Function
Frequency (Hz)
Amplitude (mm/s)
100
50
0
Predicted
Measured
Frequency (Hz)

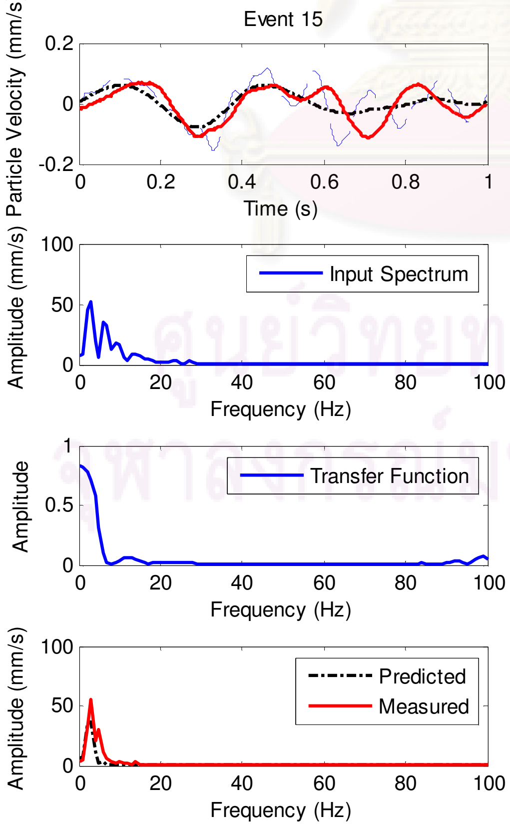

Event 10
Particle Velocity (mm/s)
0.5
0
-0.5
0
0.2
0.4
0.6
0.8
1
Time (s)
Amplitude (mm/s)
200
100
0
Input Spectrum
0
20
40
60
80
100
Frequency (Hz)
Amplitude
1
0.5
0
Transfer Function
Frequency (Hz)
Amplitude (mm/s)
50
0
Predicted
Measured
Frequency (Hz)

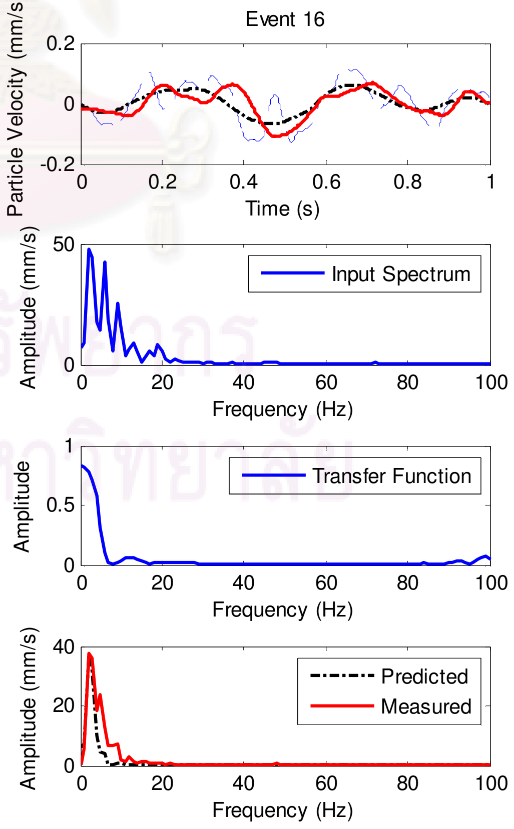

Event 11
Particle Velocity (mm/s)
0.5
0
-0.5
0
0.2
0.4
0.6
0.8
1
Time (s)
Amplitude (mm/s)
100
50
0
Input Spectrum
0
20
40
60
80
100
Frequency (Hz)
Amplitude
1
0.5
0
Transfer Function
Frequency (Hz)
Amplitude (mm/s)
50
0
Predicted
Measured
Frequency (Hz)

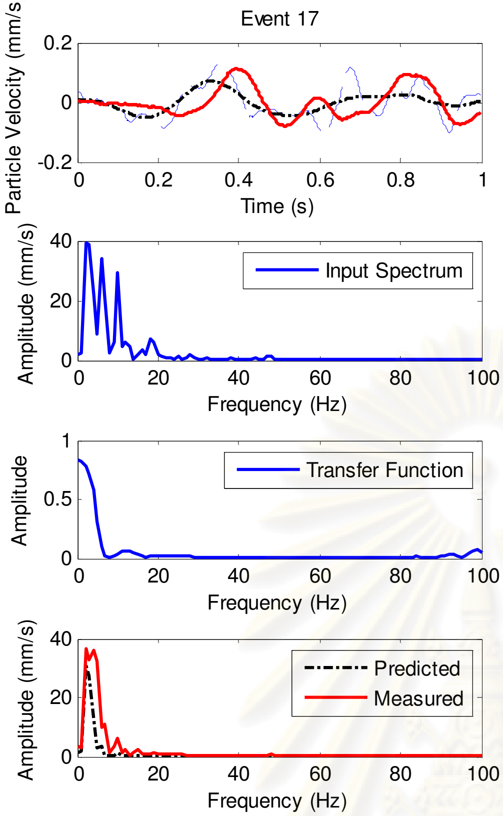

Event 12
Particle Velocity (mm/s)
0.5
0
-0.5
0
0.2
0.4
0.6
0.8
1
Time (s)
Amplitude (mm/s)
100
50
0
Input Spectrum
0
20
40
60
80
100
Frequency (Hz)
Amplitude
1
0.5
0
Transfer Function
Frequency (Hz)
Amplitude (mm/s)
40
20
0
Predicted
Measured
Frequency (Hz)

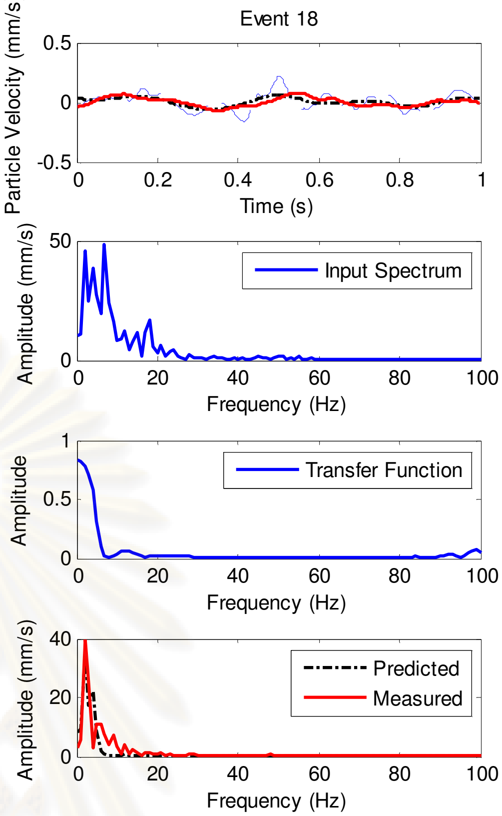

Event 13
Particle Velocity (mm/s)
0.2
0
-0.2
0
0.2
0.4
0.6
0.8
1
Time (s)
Amplitude (mm/s)
100
50
0
Input Spectrum
0
20
40
60
80
100
Frequency (Hz)
Amplitude
1
0.5
0
Transfer Function
Frequency (Hz)
Amplitude (mm/s)
100
50
0
Predicted
Measured
Frequency (Hz)

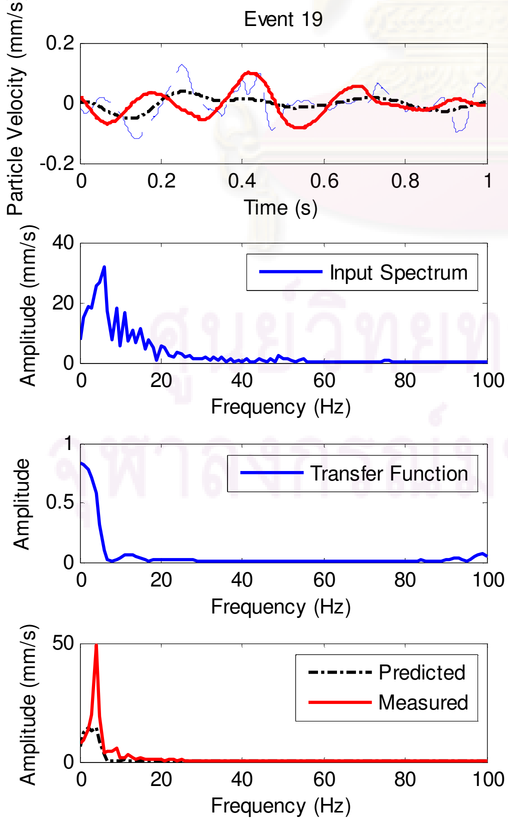

Event 14
Particle Velocity (mm/s)
0.2
0
-0.2
0
0.2
0.4
0.6
0.8
1
Time (s)
Amplitude (mm/s)
40
20
0
Input Spectrum
0
20
40
60
80
100
Frequency (Hz)
Amplitude
1
0.5
0
Transfer Function
Frequency (Hz)
Amplitude (mm/s)
50
0
Predicted
Measured
Frequency (Hz)

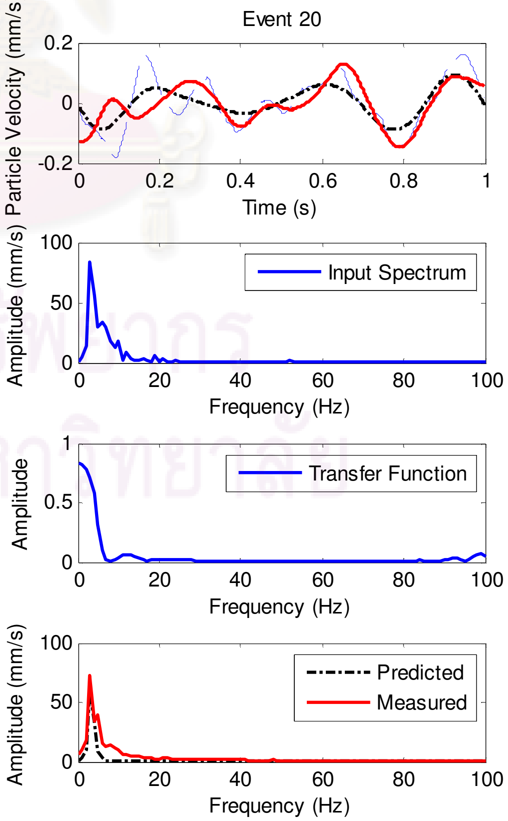

Event 15
Particle Velocity (mm/s)
0.2
0
-0.2
0
0.2
0.4
0.6
0.8
1
Time (s)
Amplitude (mm/s)
100
50
0
Input Spectrum
0
20
40
60
80
100
Frequency (Hz)
Amplitude
1
0.5
0
Transfer Function
Frequency (Hz)
Amplitude (mm/s)
100
50
0
Predicted
Measured
Frequency (Hz)

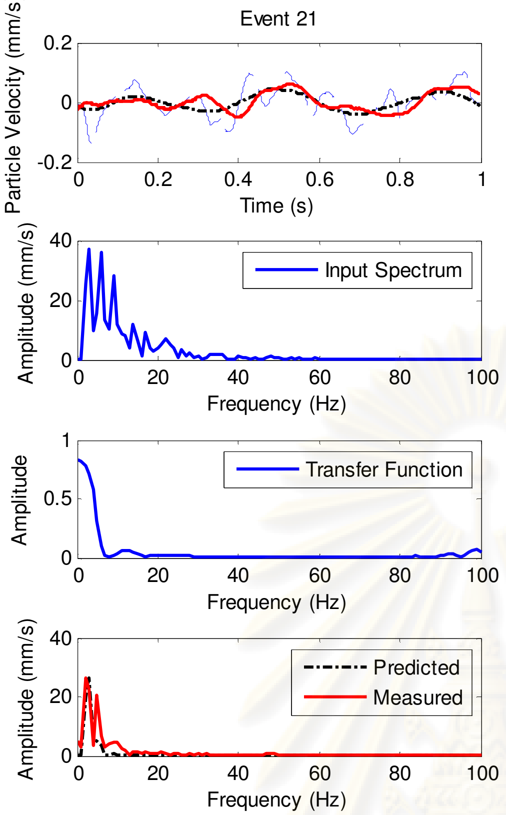

Event 16
Particle Velocity (mm/s)
0.2
0
-0.2
0
0.2
0.4
0.6
0.8
1
Time (s)
Amplitude (mm/s)
50
0
Input Spectrum
0
20
40
60
80
100
Frequency (Hz)
Amplitude
1
0.5
0
Transfer Function
Frequency (Hz)
Amplitude (mm/s)
40
20
0
Predicted
Measured
Frequency (Hz)

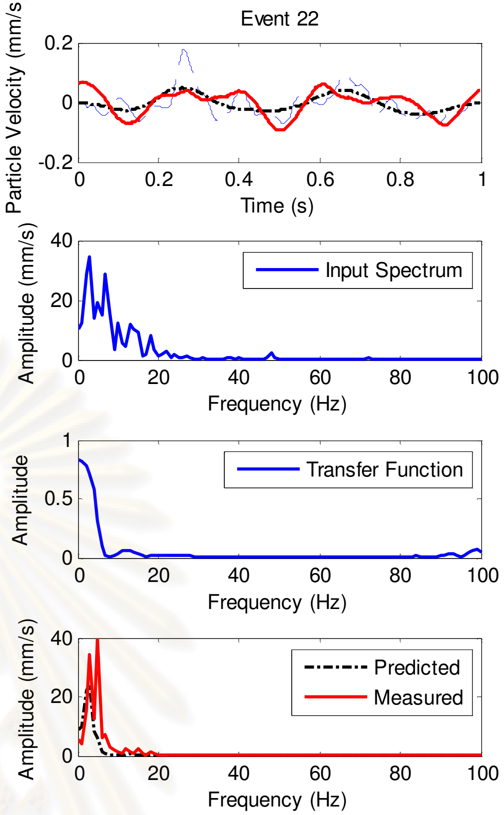

Event 17
Particle Velocity (mm/s)
0.2
0
-0.2
0
0.2
0.4
0.6
0.8
1
Time (s)
Amplitude (mm/s)
40
20
0
Input Spectrum
Frequency (Hz)
Amplitude
1
0.5
0
Transfer Function
Frequency (Hz)
Amplitude (mm/s)
40
20
0
Predicted
Measured
0
20
40
60
80
100
Frequency (Hz)

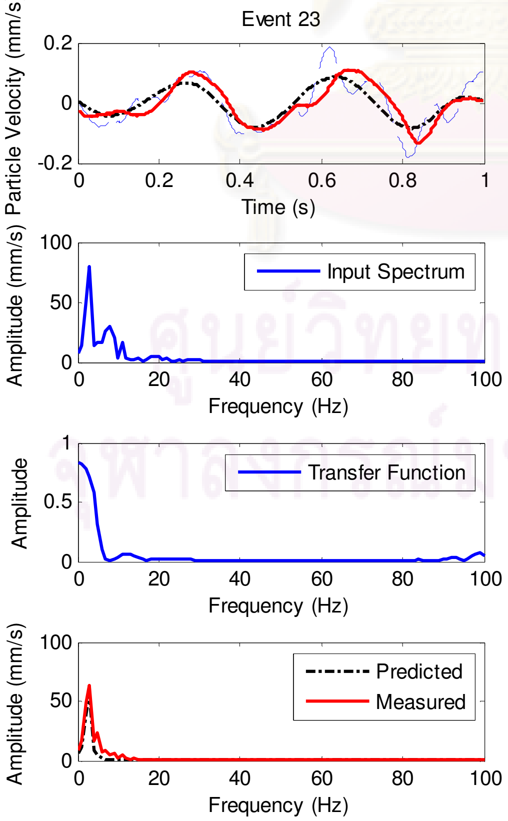

Event 18
Particle Velocity (mm/s)
0.5
0
-0.5
0
0.2
0.4
0.6
0.8
1
Time (s)
Amplitude (mm/s)
50
0
Input Spectrum
Frequency (Hz)
Amplitude
1
0.5
0
Transfer Function
Frequency (Hz)
Amplitude (mm/s)
40
20
0
Predicted
Measured
0
20
40
60
80
100
Frequency (Hz)

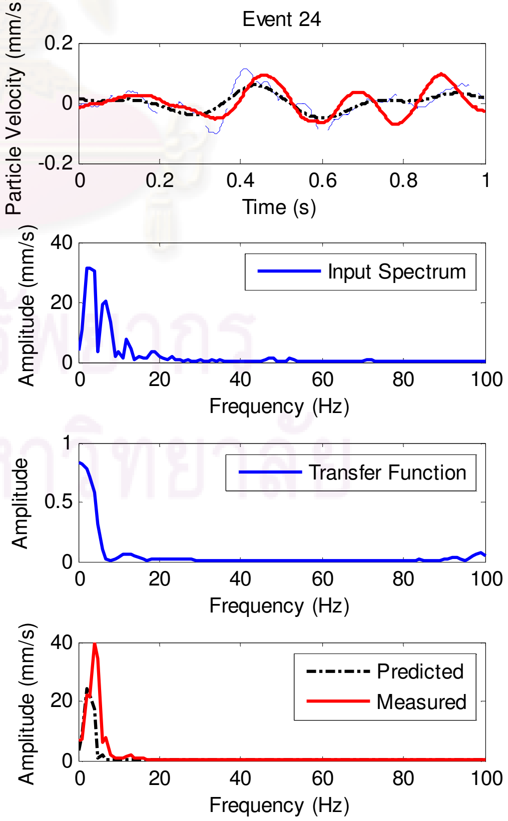

Event 19
Particle Velocity (mm/s)
0.2
0
-0.2
0
0.2
0.4
0.6
0.8
1
Time (s)
Amplitude (mm/s)
40
20
0
Input Spectrum
Frequency (Hz)
Amplitude
1
0.5
0
Transfer Function
Frequency (Hz)
Amplitude (mm/s)
50
0
Predicted
Measured
0
20
40
60
80
100
Frequency (Hz)

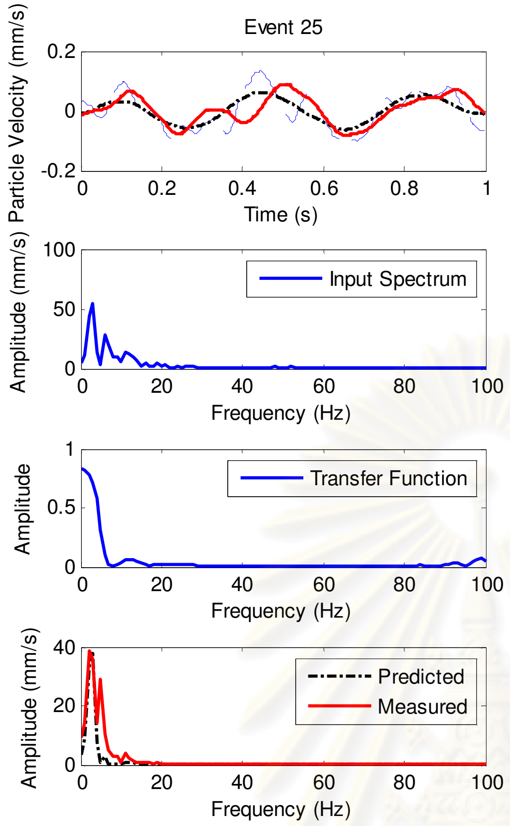

Event 20
Particle Velocity (mm/s)
0.2
0
-0.2
0
0.2
0.4
0.6
0.8
1
Time (s)
Amplitude (mm/s)
100
50
0
Input Spectrum
Frequency (Hz)
Amplitude
1
0.5
0
Transfer Function
Frequency (Hz)
Amplitude (mm/s)
100
50
0
Predicted
Measured
0
20
40
60
80
100
Frequency (Hz)

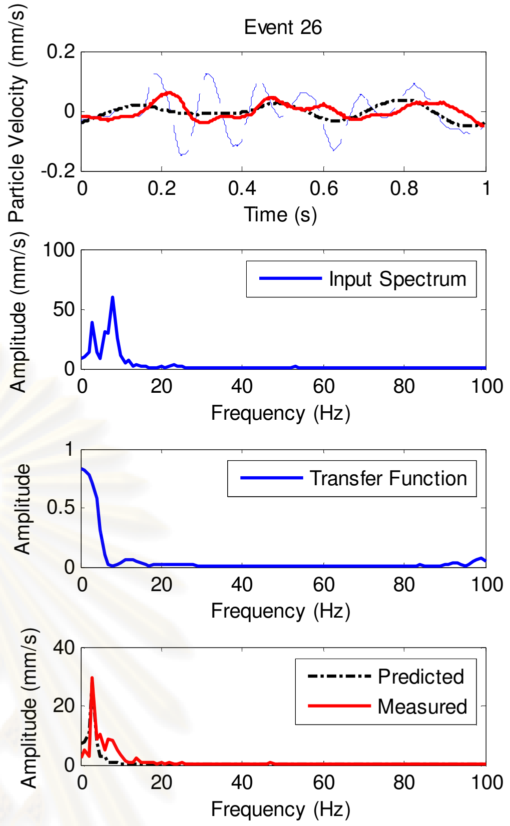

Event 21
Particle Velocity (mm/s)
0.2
0
-0.2
0
0.2
0.4
0.6
0.8
1
Time (s)
Amplitude (mm/s)
40
20
0
Input Spectrum
Frequency (Hz)
0
20
40
60
80
100
Amplitude
1
0.5
0
Transfer Function
Frequency (Hz)
Amplitude (mm/s)
40
20
0
Predicted
Measured
Frequency (Hz)

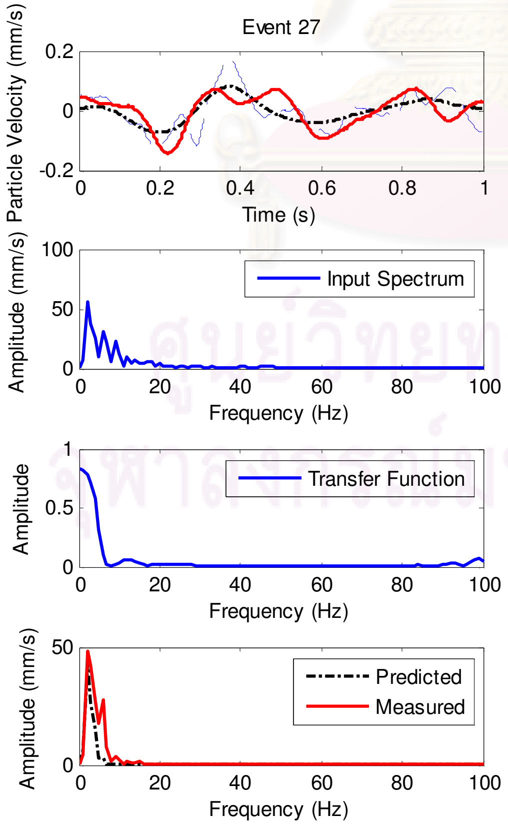

Event 22
Particle Velocity (mm/s)
0.2
0
-0.2
0
0.2
0.4
0.6
0.8
1
Time (s)
Amplitude (mm/s)
40
20
0
Input Spectrum
Frequency (Hz)
0
20
40
60
80
100
Amplitude
1
0.5
0
Transfer Function
Frequency (Hz)
Amplitude (mm/s)
40
20
0
Predicted
Measured
Frequency (Hz)

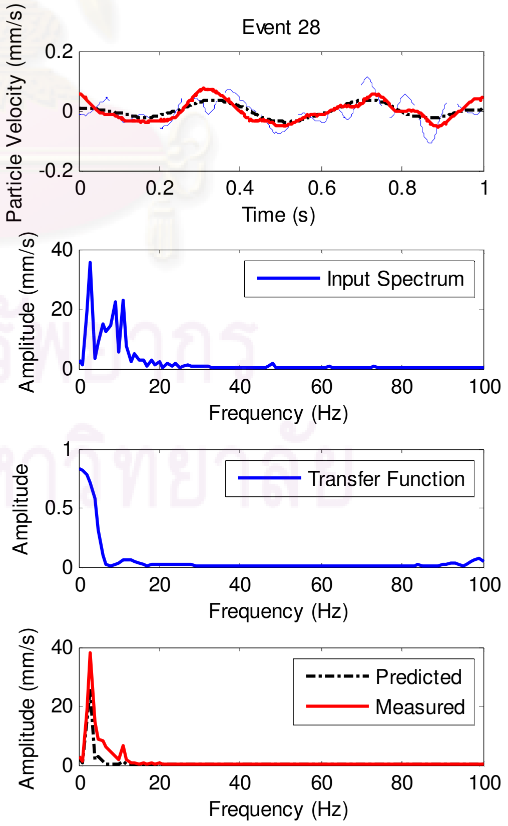

Event 23
Particle Velocity (mm/s)
0.2
0
-0.2
0
0.2
0.4
0.6
0.8
1
Time (s)
Amplitude (mm/s)
100
50
0
Input Spectrum
Frequency (Hz)
0
20
40
60
80
100
Amplitude
1
0.5
0
Transfer Function
Frequency (Hz)
Amplitude (mm/s)
100
50
0
Predicted
Measured
Frequency (Hz)

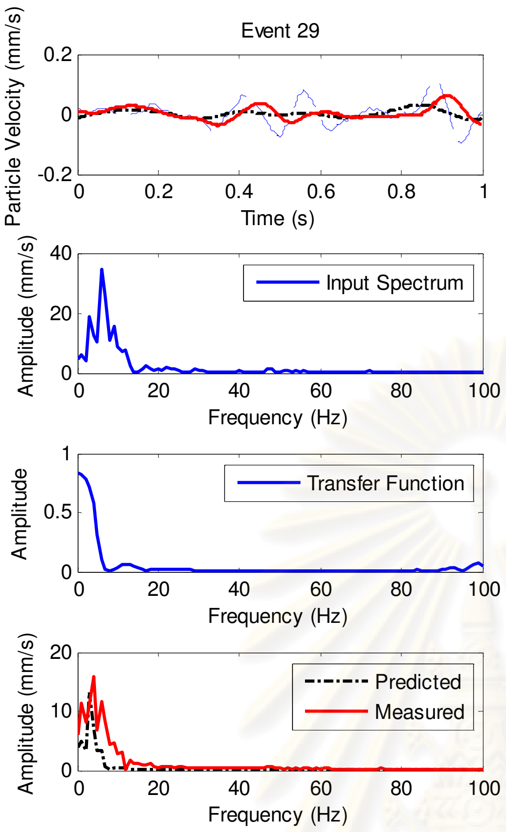

Event 24
Particle Velocity (mm/s)
0.2
0
-0.2
0
0.2
0.4
0.6
0.8
1
Time (s)
Amplitude (mm/s)
40
20
0
Input Spectrum
Frequency (Hz)
0
20
40
60
80
100
Amplitude
1
0.5
0
Transfer Function
Frequency (Hz)
Amplitude (mm/s)
40
20
0
Predicted
Measured
Frequency (Hz)

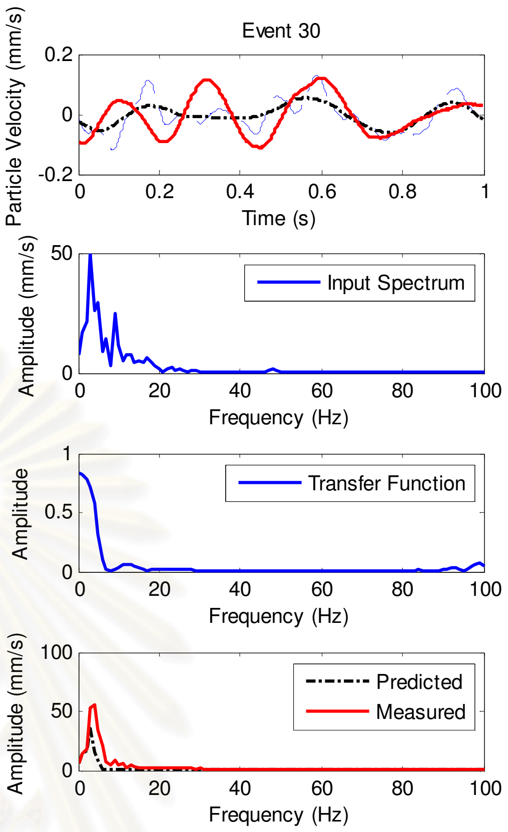

Event 25
Particle Velocity (mm/s)
0.2
0
-0.2
0
0.2
0.4
0.6
0.8
1
Time (s)
Amplitude (mm/s)
100
50
0
Input Spectrum
0
20
40
60
80
100
Frequency (Hz)
Amplitude
1
0.5
0
Transfer Function
Frequency (Hz)
Amplitude (mm/s)
40
20
0
Predicted
Measured
Frequency (Hz)


Event 26
Particle Velocity (mm/s)
0.2
0
-0.2
0
0.2
0.4
0.6
0.8
1
Time (s)
Amplitude (mm/s)
100
50
0
Input Spectrum
0
20
40
60
80
100
Frequency (Hz)
Amplitude
1
0.5
0
Transfer Function
Frequency (Hz)
Amplitude (mm/s)
40
20
0
Predicted
Measured
Frequency (Hz)


Event 27
Particle Velocity (mm/s)
0.2
0
-0.2
0
0.2
0.4
0.6
0.8
1
Time (s)
Amplitude (mm/s)
100
50
0
Input Spectrum
0
20
40
60
80
100
Frequency (Hz)
Amplitude
1
0.5
0
Transfer Function
Frequency (Hz)
Amplitude (mm/s)
50
0
Predicted
Measured
Frequency (Hz)

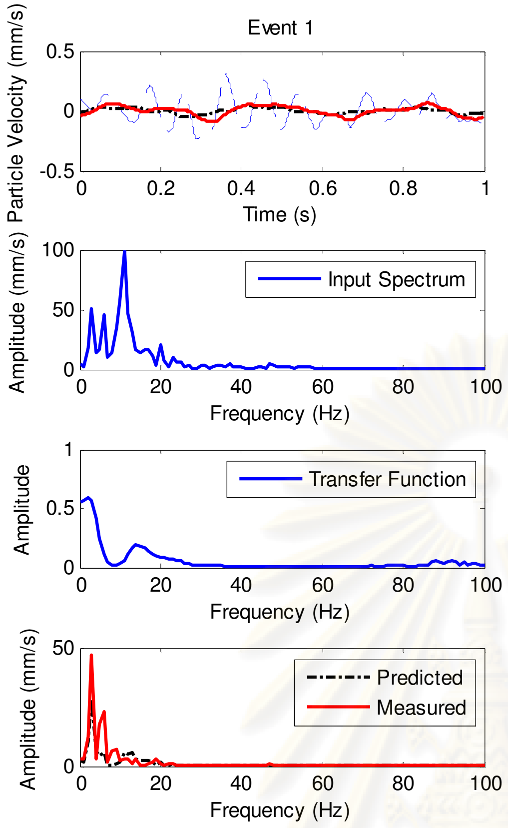

Event 28
Particle Velocity (mm/s)
0.2
0
-0.2
0
0.2
0.4
0.6
0.8
1
Time (s)
Amplitude (mm/s)
40
20
0
Input Spectrum
0
20
40
60
80
100
Frequency (Hz)
Amplitude
1
0.5
0
Transfer Function
Frequency (Hz)
Amplitude (mm/s)
40
20
0
Predicted
Measured
Frequency (Hz)

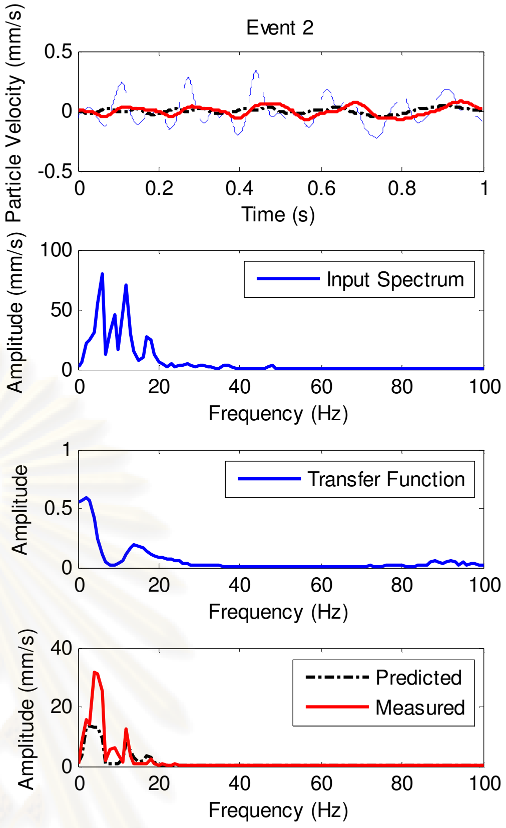

Event 29
Particle Velocity (mm/s)
0.2
0
-0.2
0
0.2
0.4
0.6
0.8
1
Time (s)
Amplitude (mm/s)
40
20
0
Input Spectrum
0
20
40
60
80
100
Frequency (Hz)
Amplitude
1
0.5
0
Transfer Function
0
20
40
60
80
100
Frequency (Hz)
Amplitude (mm/s)
20
10
0
Predicted
Measured
0
20
40
60
80
100
Frequency (Hz)

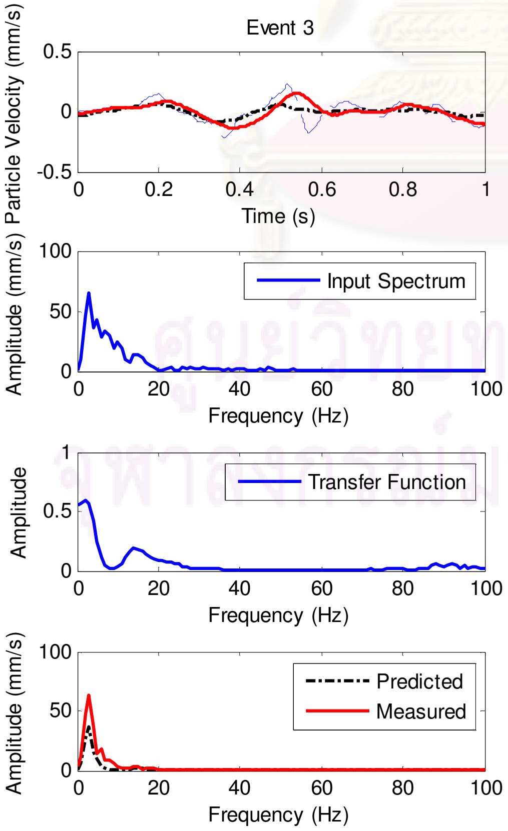

Event 30
Particle Velocity (mm/s)
0.2
0
-0.2
0
0.2
0.4
0.6
0.8
1
Time (s)
Amplitude (mm/s)
50
0
Input Spectrum
0
20
40
60
80
100
Frequency (Hz)
Amplitude
1
0.5
0
Transfer Function
0
20
40
60
80
100
Frequency (Hz)
Amplitude (mm/s)
100
50
0
Predicted
Measured
0
20
40
60
80
100
Frequency (Hz)

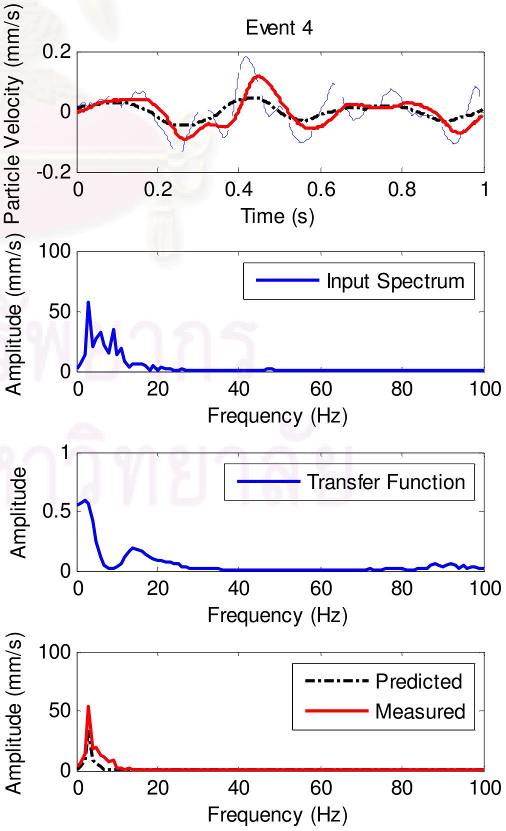
APPENDIX G

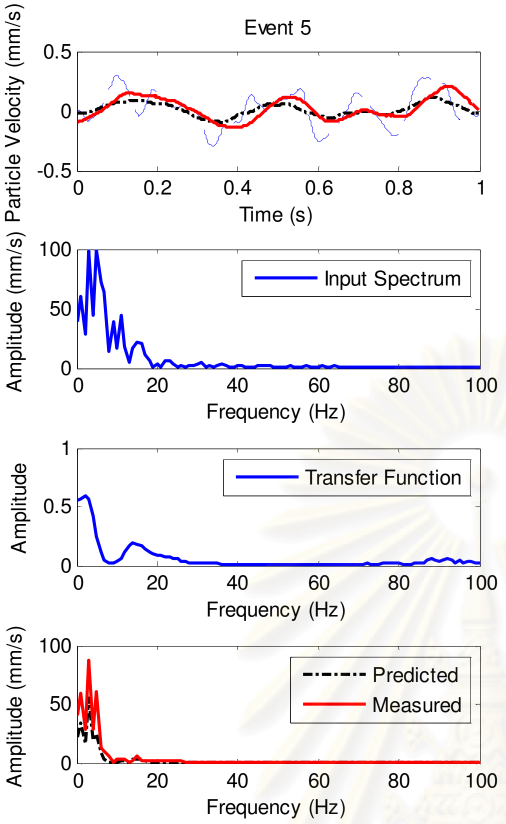
26 PREDICTED BUILDING RESPONSES IN TRANSVERSAL DIRECTION USING TF OF HAMMER VIBRATION

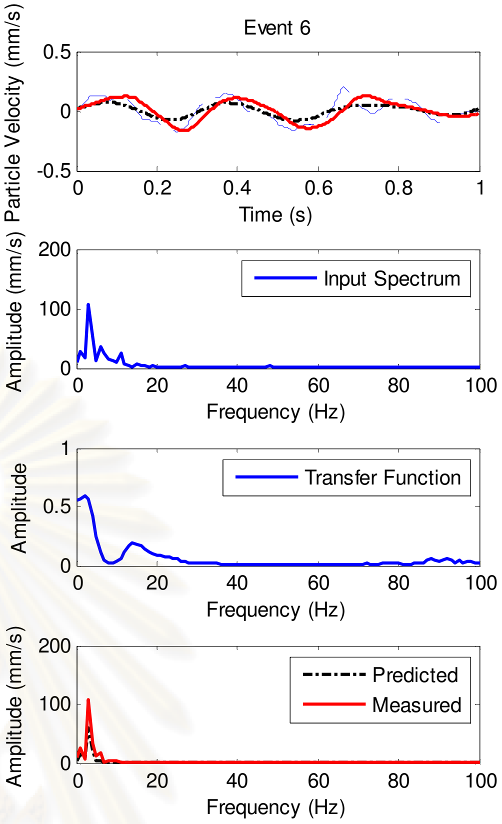

Event 1
Particle Velocity (mm/s)
0.5
0
-0.5
0
0.2
0.4
0.6
0.8
1
Time (s)
Amplitude (mm/s)
100
50
0
Input Spectrum
Frequency (Hz)
0
20
40
60
80
100
Amplitude
1
0.5
0
Transfer Function
Frequency (Hz)
Amplitude (mm/s)
50
0
Predicted
Measured
Frequency (Hz)

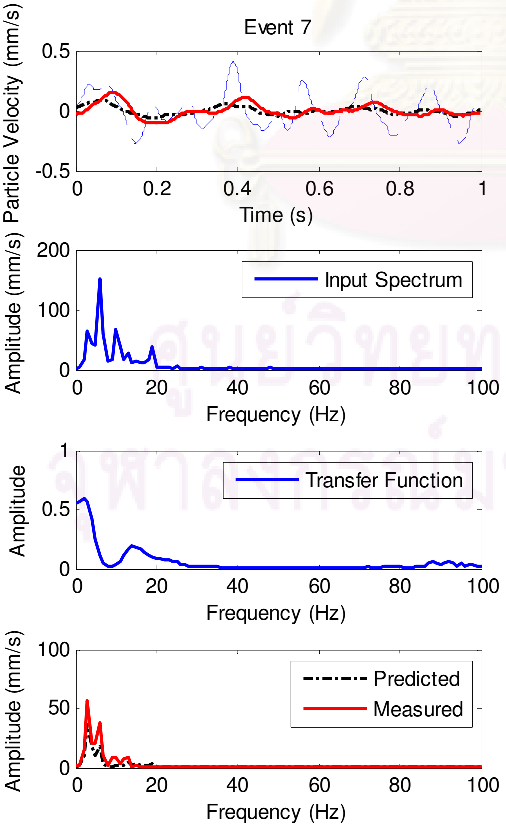

Event 2
Particle Velocity (mm/s)
0.5
0
-0.5
0
0.2
0.4
0.6
0.8
1
Time (s)
Amplitude (mm/s)
100
50
0
Input Spectrum
Frequency (Hz)
0
20
40
60
80
100
Amplitude
1
0.5
0
Transfer Function
Frequency (Hz)
Amplitude (mm/s)
40
20
0
Predicted
Measured
Frequency (Hz)

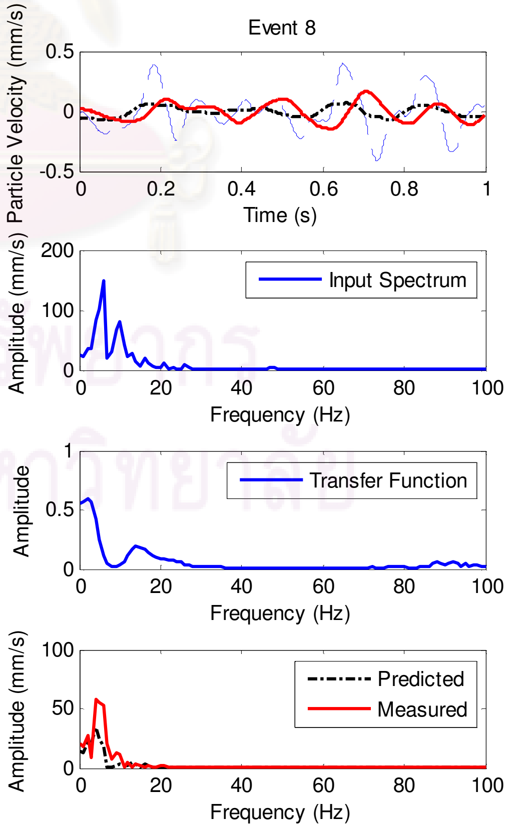

Event 3
Particle Velocity (mm/s)
0.5
0
-0.5
0
0.2
0.4
0.6
0.8
1
Time (s)
Amplitude (mm/s)
100
50
0
Input Spectrum
Frequency (Hz)
0
20
40
60
80
100
Amplitude
1
0.5
0
Transfer Function
Frequency (Hz)
Amplitude (mm/s)
100
50
0
Predicted
Measured
Frequency (Hz)

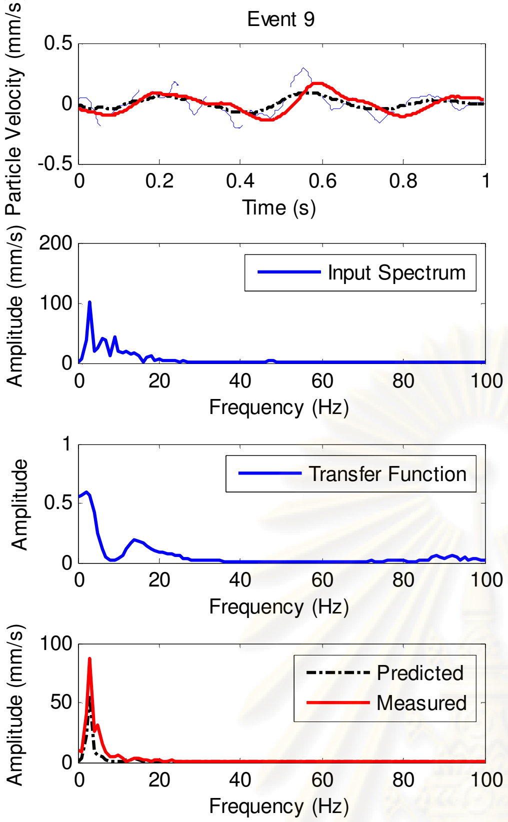

Event 4
Particle Velocity (mm/s)
0.2
0
-0.2
0
0.2
0.4
0.6
0.8
1
Time (s)
Amplitude (mm/s)
100
50
0
Input Spectrum
Frequency (Hz)
0
20
40
60
80
100
Amplitude
1
0.5
0
Transfer Function
Frequency (Hz)
Amplitude (mm/s)
100
50
0
Predicted
Measured
Frequency (Hz)

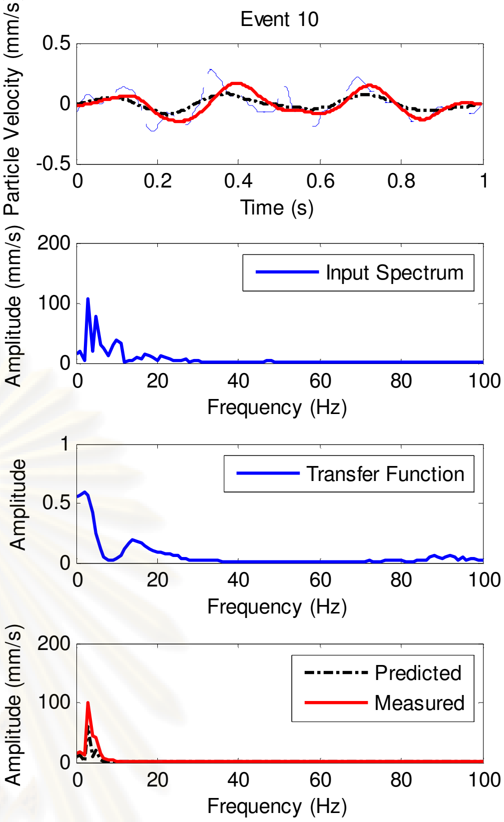

Event 5
Particle Velocity (mm/s)
0.5
0
-0.5
0
0.2
0.4
0.6
0.8
1
Time (s)
Amplitude (mm/s)
100
50
0
Input Spectrum
0
20
40
60
80
100
Frequency (Hz)
Amplitude
1
0.5
0
Transfer Function
0
20
40
60
80
100
Frequency (Hz)
Amplitude (mm/s)
100
50
0
Predicted
Measured
0
20
40
60
80
100
Frequency (Hz)

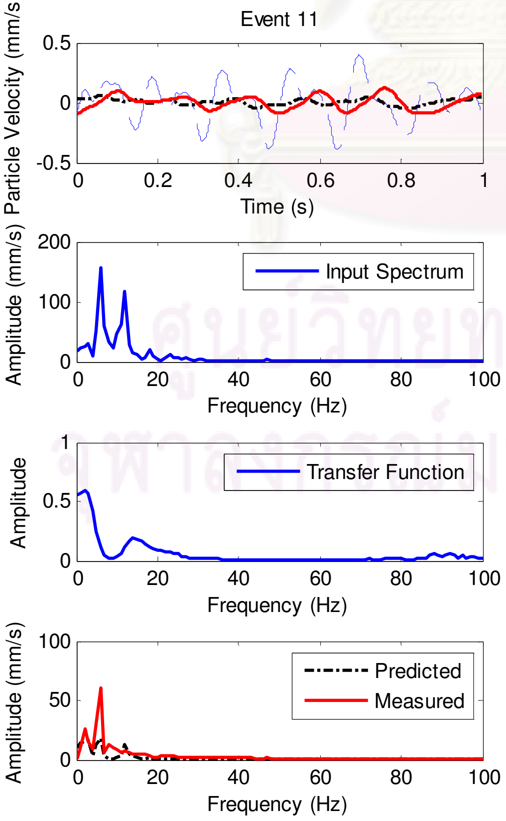

Event 6
Particle Velocity (mm/s)
0.5
0
-0.5
0
0.2
0.4
0.6
0.8
1
Time (s)
Amplitude (mm/s)
200
100
0
Input Spectrum
0
20
40
60
80
100
Frequency (Hz)
Amplitude
1
0.5
0
Transfer Function
0
20
40
60
80
100
Frequency (Hz)
Amplitude (mm/s)
200
100
0
Predicted
Measured
0
20
40
60
80
100
Frequency (Hz)

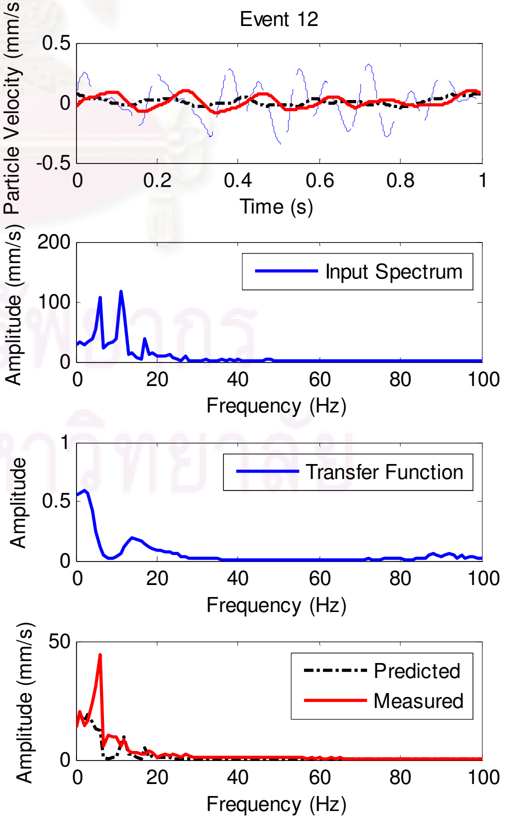

Event 7
Particle Velocity (mm/s)
0.5
0
-0.5
0
0.2
0.4
0.6
0.8
1
Time (s)
Amplitude (mm/s)
200
100
0
Input Spectrum
0
20
40
60
80
100
Frequency (Hz)
Amplitude
1
0.5
0
Transfer Function
0
20
40
60
80
100
Frequency (Hz)
Amplitude (mm/s)
100
50
0
Predicted
Measured
0
20
40
60
80
100
Frequency (Hz)

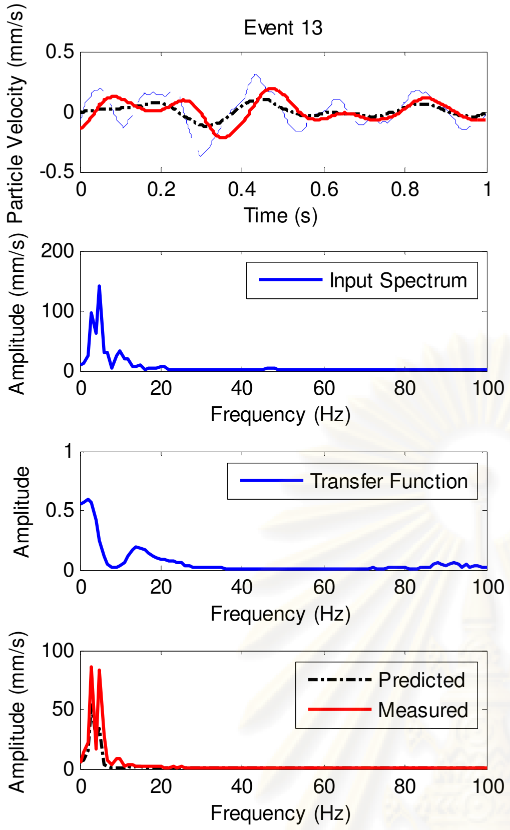

Event 8
Particle Velocity (mm/s)
0.5
0
-0.5
0
0.2
0.4
0.6
0.8
1
Time (s)
Amplitude (mm/s)
200
100
0
Input Spectrum
0
20
40
60
80
100
Frequency (Hz)
Amplitude
1
0.5
0
Transfer Function
0
20
40
60
80
100
Frequency (Hz)
Amplitude (mm/s)
100
50
0
Predicted
Measured
0
20
40
60
80
100
Frequency (Hz)

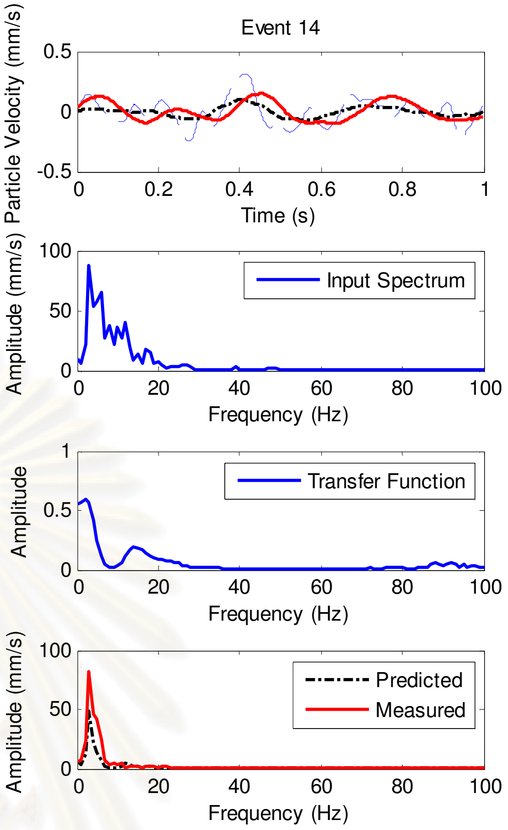

Event 9
Particle Velocity (mm/s)
0.5
0
-0.5
0
0.2
0.4
0.6
0.8
1
Time (s)
Amplitude (mm/s)
200
100
0
Input Spectrum
0
20
40
60
80
100
Frequency (Hz)
Amplitude
1
0.5
0
Transfer Function
Frequency (Hz)
Amplitude (mm/s)
100
50
0
Predicted
Measured
Frequency (Hz)

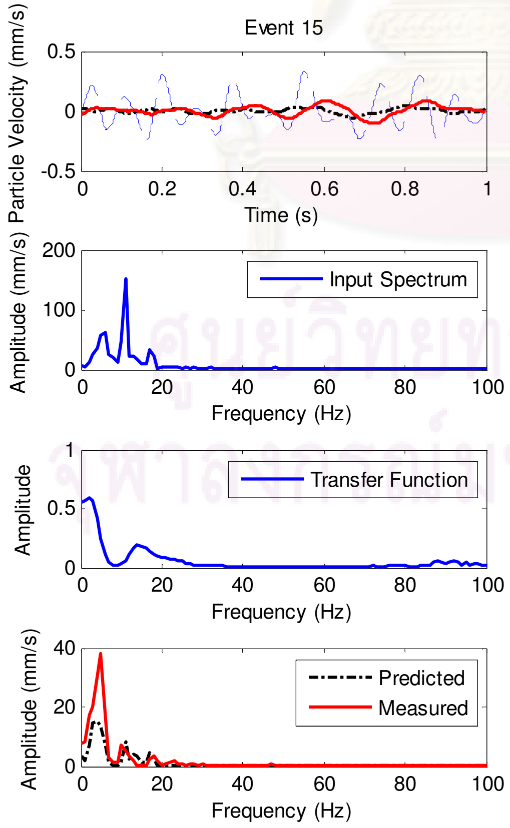

Event 10
Particle Velocity (mm/s)
0.5
0
-0.5
0
0.2
0.4
0.6
0.8
1
Time (s)
Amplitude (mm/s)
200
100
0
Input Spectrum
0
20
40
60
80
100
Frequency (Hz)
Amplitude
1
0.5
0
Transfer Function
Frequency (Hz)
Amplitude (mm/s)
200
100
0
Predicted
Measured
Frequency (Hz)

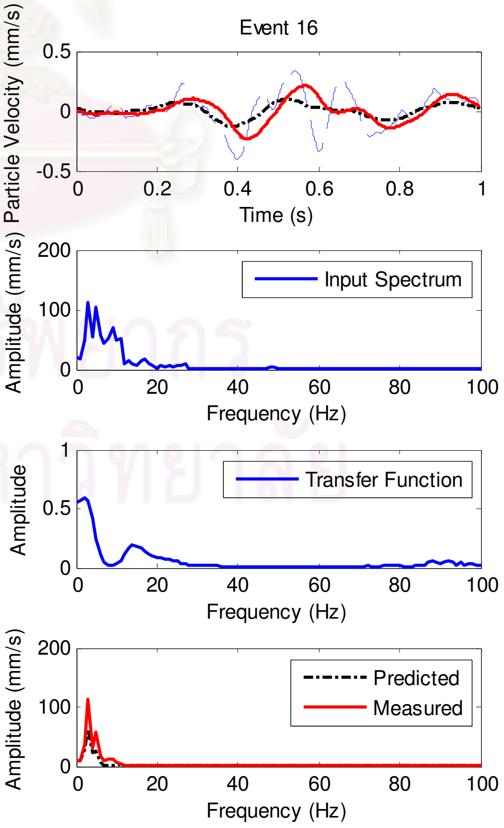

Event 11
Particle Velocity (mm/s)
0.5
0
-0.5
0
0.2
0.4
0.6
0.8
1
Time (s)
Amplitude (mm/s)
200
100
0
Input Spectrum
0
20
40
60
80
100
Frequency (Hz)
Amplitude
1
0.5
0
Transfer Function
Frequency (Hz)
Amplitude (mm/s)
100
50
0
Predicted
Measured
Frequency (Hz)

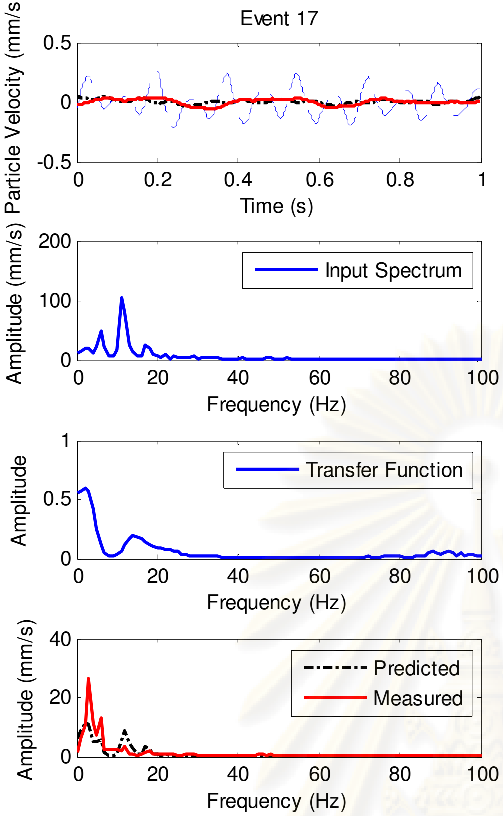

Event 12
Particle Velocity (mm/s)
0.5
0
-0.5
0
0.2
0.4
0.6
0.8
1
Time (s)
Amplitude (mm/s)
200
100
0
Input Spectrum
0
20
40
60
80
100
Frequency (Hz)
Amplitude
1
0.5
0
Transfer Function
Frequency (Hz)
Amplitude (mm/s)
50
0
Predicted
Measured
Frequency (Hz)

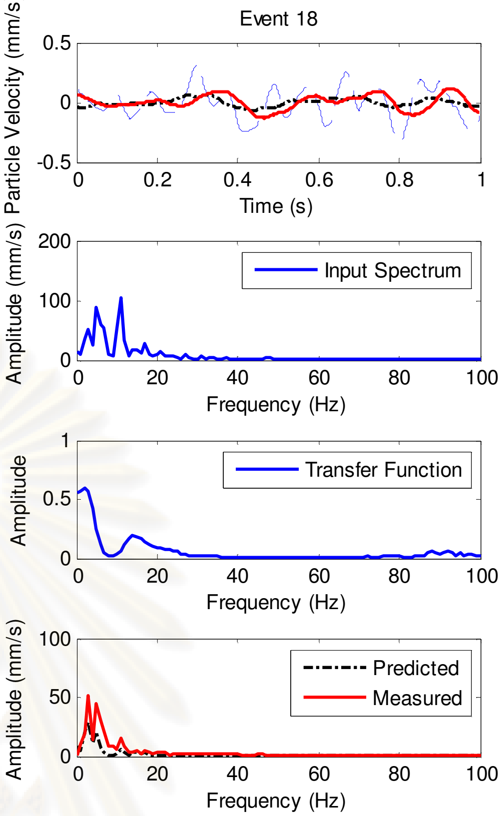

Event 13
Particle Velocity (mm/s)
0.5
0
-0.5
0
0.2
0.4
0.6
0.8
1
Time (s)
Amplitude (mm/s)
200
100
0
Input Spectrum
0
20
40
60
80
100
Frequency (Hz)
Amplitude
1
0.5
0
Transfer Function
Frequency (Hz)
Amplitude (mm/s)
100
50
0
Predicted
Measured
Frequency (Hz)

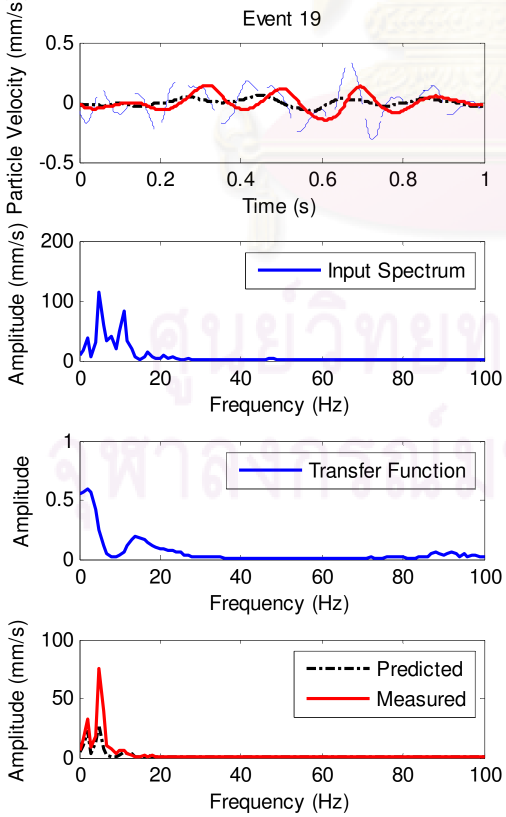

Event 14
Particle Velocity (mm/s)
0.5
0
-0.5
0
0.2
0.4
0.6
0.8
1
Time (s)
Amplitude (mm/s)
100
50
0
Input Spectrum
0
20
40
60
80
100
Frequency (Hz)
Amplitude
1
0.5
0
Transfer Function
Frequency (Hz)
Amplitude (mm/s)
100
50
0
Predicted
Measured
Frequency (Hz)

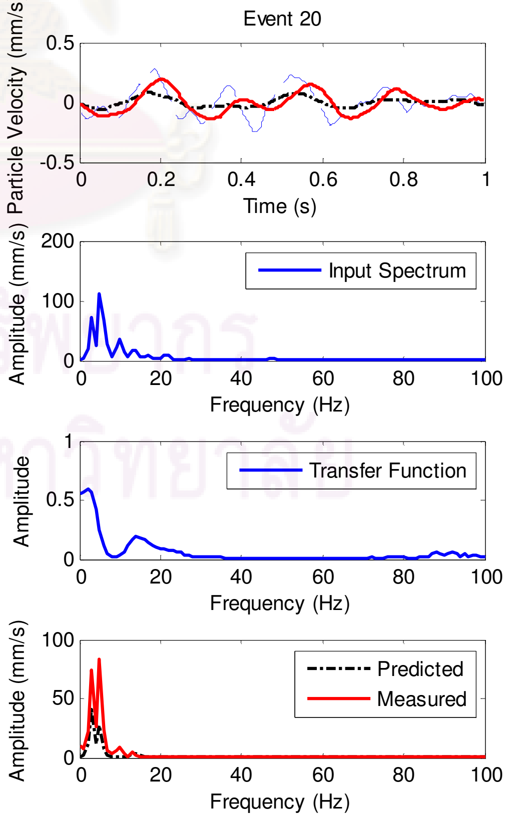

Event 15
Particle Velocity (mm/s)
0.5
0
-0.5
0
0.2
0.4
0.6
0.8
1
Time (s)
Amplitude (mm/s)
200
100
0
Input Spectrum
0
20
40
60
80
100
Frequency (Hz)
Amplitude
1
0.5
0
Transfer Function
Frequency (Hz)
Amplitude (mm/s)
40
20
0
Predicted
Measured
Frequency (Hz)

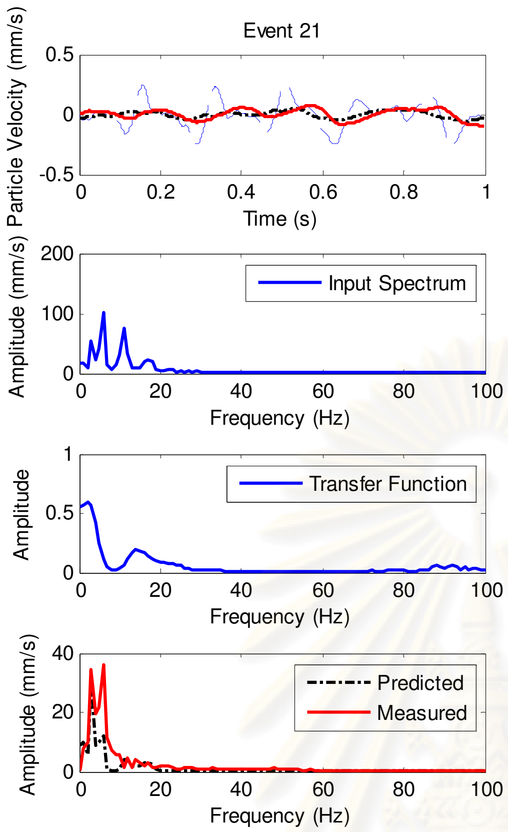

Event 16
Particle Velocity (mm/s)
0.5
0
-0.5
0
0.2
0.4
0.6
0.8
1
Time (s)
Amplitude (mm/s)
200
100
0
Input Spectrum
0
20
40
60
80
100
Frequency (Hz)
Amplitude
1
0.5
0
Transfer Function
Frequency (Hz)
Amplitude (mm/s)
200
100
0
Predicted
Measured
Frequency (Hz)

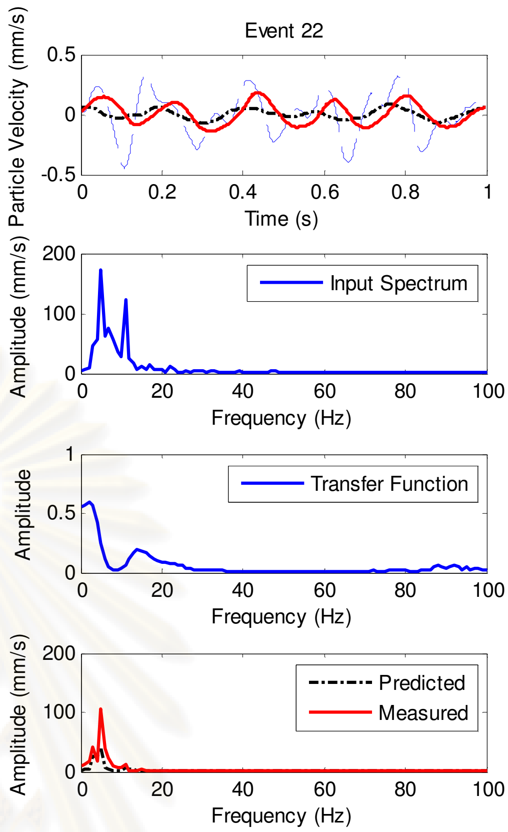

Event 17
Particle Velocity (mm/s)
0.5
0
-0.5
0
0.2
0.4
0.6
0.8
1
Time (s)
Amplitude (mm/s)
200
100
0
Input Spectrum
0
20
40
60
80
100
Frequency (Hz)
Amplitude
1
0.5
0
Transfer Function
Frequency (Hz)
Amplitude (mm/s)
40
20
0
Predicted
Measured
Frequency (Hz)

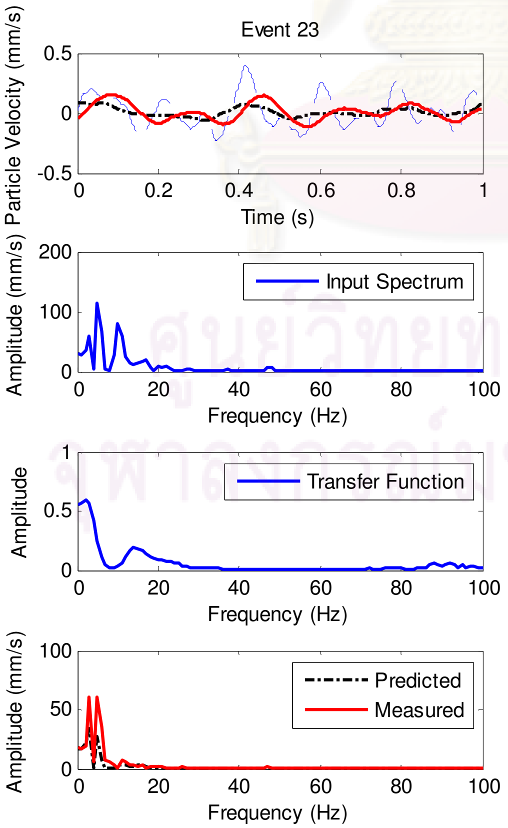

Event 18
Particle Velocity (mm/s)
0.5
0
-0.5
0
0.2
0.4
0.6
0.8
1
Time (s)
Amplitude (mm/s)
200
100
0
Input Spectrum
0
20
40
60
80
100
Frequency (Hz)
Amplitude
1
0.5
0
Transfer Function
Frequency (Hz)
Amplitude (mm/s)
100
50
0
Predicted
Measured
Frequency (Hz)

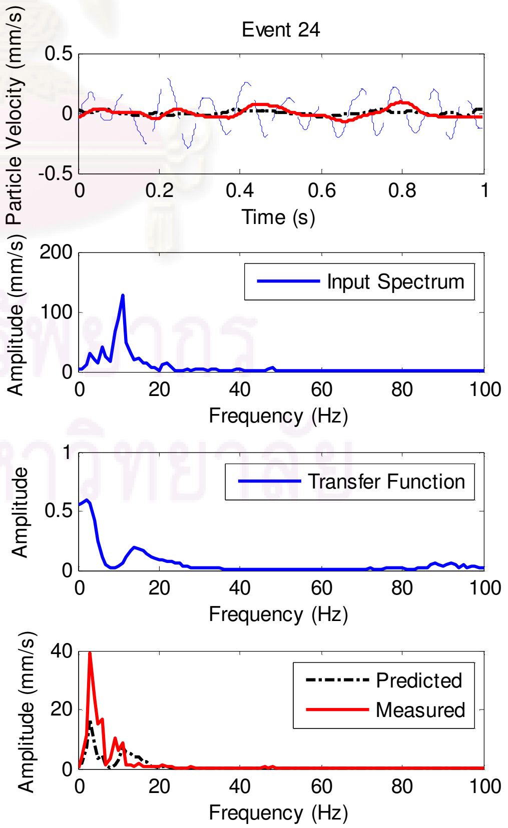

Event 19
Particle Velocity (mm/s)
0.5
0
-0.5
0
0.2
0.4
0.6
0.8
1
Time (s)
Amplitude (mm/s)
200
100
0
Input Spectrum
0
20
40
60
80
100
Frequency (Hz)
Amplitude
1
0.5
0
Transfer Function
Frequency (Hz)
Amplitude (mm/s)
100
50
0
Predicted
Measured
Frequency (Hz)

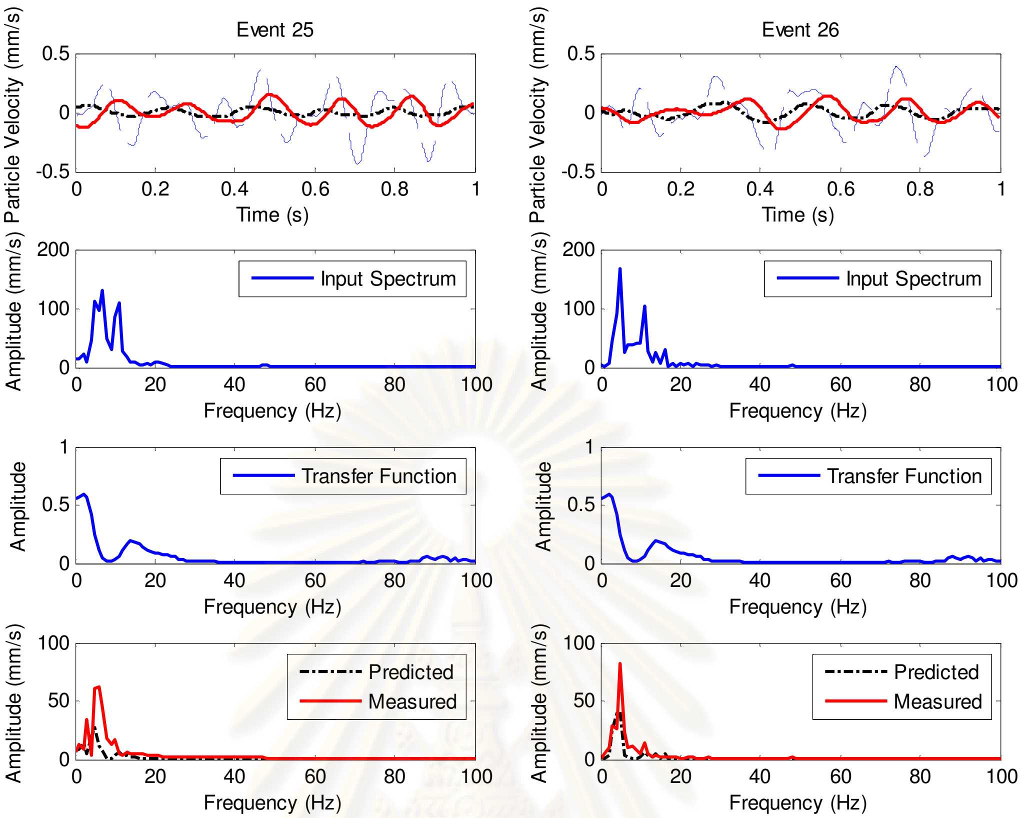

Event 20
Particle Velocity (mm/s)
0.5
0
-0.5
0
0.2
0.4
0.6
0.8
1
Time (s)
Amplitude (mm/s)
200
100
0
Input Spectrum
0
20
40
60
80
100
Frequency (Hz)
Amplitude
1
0.5
0
Transfer Function
Frequency (Hz)
Amplitude (mm/s)
100
50
0
Predicted
Measured
Frequency (Hz)


Event 21
Particle Velocity (mm/s)
0.5
0
-0.5
0
0.2
0.4
0.6
0.8
1
Time (s)
Amplitude (mm/s)
200
100
0
Input Spectrum
0
20
40
60
80
100
Frequency (Hz)
Amplitude
1
0.5
0
Transfer Function
Frequency (Hz)
Amplitude (mm/s)
40
20
0
Predicted
Measured
Frequency (Hz)


Event 22
Particle Velocity (mm/s)
0.5
0
-0.5
0
0.2
0.4
0.6
0.8
1
Time (s)
Amplitude (mm/s)
200
100
0
Input Spectrum
0
20
40
60
80
100
Frequency (Hz)
Amplitude
1
0.5
0
Transfer Function
Frequency (Hz)
Amplitude (mm/s)
200
100
0
Predicted
Measured
Frequency (Hz)


Event 23
Particle Velocity (mm/s)
0.5
0
-0.5
0
0.2
0.4
0.6
0.8
1
Time (s)
Amplitude (mm/s)
200
100
0
Input Spectrum
0
20
40
60
80
100
Frequency (Hz)
Amplitude
1
0.5
0
Transfer Function
Frequency (Hz)
Amplitude (mm/s)
100
50
0
Predicted
Measured
Frequency (Hz)


Event 24
Particle Velocity (mm/s)
0.5
0
-0.5
0
0.2
0.4
0.6
0.8
1
Time (s)
Amplitude (mm/s)
200
100
0
Input Spectrum
0
20
40
60
80
100
Frequency (Hz)
Amplitude
1
0.5
0
Transfer Function
Frequency (Hz)
Amplitude (mm/s)
40
20
0
Predicted
Measured
Frequency (Hz)


Event 25
Event 26
Particle Velocity (mm/s)
0.5
0
-0.5
0
0.2
0.4
0.6
0.8
1
Time (s)
Amplitude (mm/s)
200
100
0
20
40
60
80
100
Frequency (Hz)
Input Spectrum
Amplitude
1
0.5
Transfer Function
Amplitude (mm/s)
100
50
Predicted
Measured

APPENDIX H

Guideline of DIN 4150 standard used to evaluate the severity of vibration onto building

Table H-1 Guideline values for vibration velocity to be used when evaluating the effects of short-term vibration on structures

Line	Type of structure	Guideline values for velocity, *v*, in mm/s			
		Vibration at the foundation at frequency of			Vibration at horizontal plane of highest floor at all frequencies
		1 to 10Hz	10 to 50Hz	50 to 100*Hz	
1	Building used for commercial	20	20 to 40	40 to 50	40
2	Dwellings	5	5 to 15	15 to 20	15
3	Building under preservation	3	3 to 8	8 to 10	8
*) At frequencies above 100 Hz, the values given in this column may be used as minimum values.					

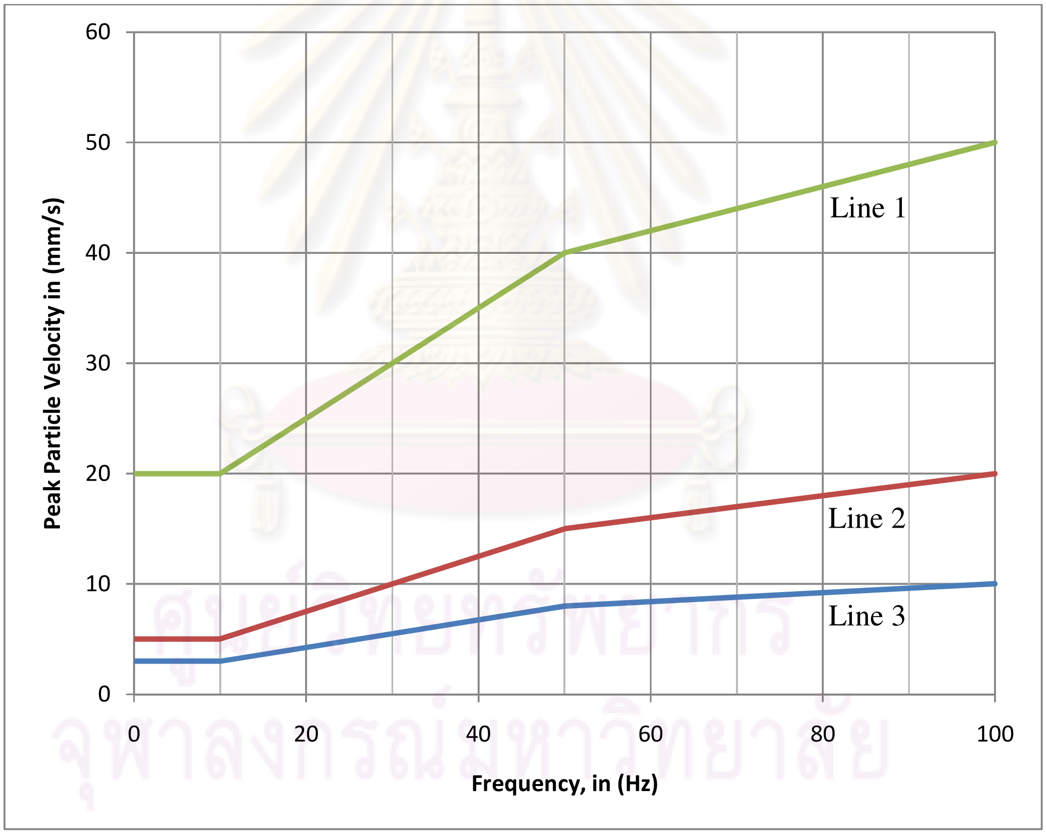


Figure H-1 Curves for guideline values specified in table H-1 for velocities measured at the foundation (German Standard DIN 4150-3: 1999-02)

BIOGRAPHY

Sang Ping

Sang Ping was born on 27 May, 1983 in Banteay Meanchey Province, Cambodia. After he finished high school at Samdach Ouv High School in 2003, he quickly moved to capital city, Phnom Penh, for attending the University Diploma of Engineering degree in Geotechnical Engineering at Institute of Technology of Cambodia (ITC) for five years. During the last year of his degree, he applied for the scholarship to study Master’s Degree Program under support of AUN/SEED-Net (JICA). Shortly, after his successful graduation in June 2008, he attained the scholarship award for further study in Master’s program in Civil Engineering department at Chulalongkorn University, Thailand. He already submitted one paper to The 7th National Transportation Conference (NTC7), Thailand, while this thesis is a partial fulfillment of the requirements for the degree.