Vibration isolation and seismic restraint for mechanical equipment in Chile

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Abstract

Vibration control of mechanical equipment in seismic countries is a subject that should be addressed with some caution. One of the most utilized elements in controlling vibration is a spring isolator, one that has high deflection (relative to neoprene isolators). The problem is that the resonant frequency can coincide with the disturbing frequency of an earthquake, which means that in an earthquake the spring will begin to ‘jump’, causing the displacement of the mechanical equipment. The displacement of the equipment, beyond generating high costs (damage, loss of use, flooding, etc.), also creates the risk of personal injury and even death. Due to the aforementioned risks, it is necessary to consider the seismic ‘variable’ when doing a proper vibration control design in a seismic country or region. Criteria, designs and recommendations are presented in this report in order to perform proper vibration isolation in conjunction with seismic restraint for mechanical equipment and systems in Chile. In addition, you will be shown some failures from the M8.8 earthquake on February 27, 2010 in Chile.

Keywords: Vibration isolation, seismic restraint
1 Introduction

The control of vibration transmission has received much attention in recent years due to its effect on the functionality of systems involved [1] and health. Vibration transmission can cause instability or even failure, as in the case in buildings subject to earthquakes [2]. Thus, vibration isolation is a vital requirement throughout much of engineering [3], particularly when there is a strong source of vibration such as a motor [4]. In this sense, technical or mechanical floors in any building project are a strong source of vibration due to the high density of equipment. In these scenarios, the direct radiation of a vibrating machine is usually not as serious as the radiation from the floor structure as a result of the structure-borne sound transmission from the machine to the floor structure [5]. In the past decade the use of active or semi-active vibration isolators had been a new trend for the designs of anti-vibration systems [6-11]. However, the advantage of the passive anti-vibration method are that they are stable and easy to set up [12]. Moreover, passive vibration isolators are the most simple, inexpensive and reliable means of protecting sensitive equipment from environmental shock and vibration [13]. Therefore, vibration isolation using passive isolators is very cost effective and hence is widely used in the engineering industry [14]. Thus, the passive isolation and seismic restraint of a structure from mechanical equipment is studied in this paper.

The use of vibration isolators (simply isolators from this point forward) in order to isolate mechanical equipment is a typical solution that engineers or acousticians always recommend. In the large range of isolators, neoprene and spring isolators are the most utilized, the reason being the static deflections that they offer. Spring isolators normally are offered between one inch and five inches of static deflection, which neoprene isolators are normally offered in a range between 0.15 inches and 0.55 inches [15]. Based on that, it is clear that when high deflection is required, springs be offered as the best solution. The problem with spring isolators is that they have a natural frequency that can potentially coincide with the frequency of an earthquake, which means that during an earthquake, the spring isolator can enter into resonance and being to jump violently. If the spring isolator does not have a seismic housing, the excitation of the spring will cause the equipment that it is supporting to being to move and fall over. If the machine is a fan or other airside type of HVAC equipment the danger is that it could fall over and pull down the ductwork, but if the equipment is wetside HVAC equipment it could fall over and bring down the piping with it, causing flooding within the building. Furthermore, if the equipment is located outdoors or on a roof, the possibility exists that the equipment could fall off the building.

In this work, the general concepts of the control of vibrations are presented along with a practical method of controlling vibrations of mechanical equipment and the design requirements per ASHRAE (American Society of Heating, Refrigerating and Air Conditioning Engineers) [16] in order to achieve an effective vibration control system for particular pieces of equipment. Furthermore, the Chilean Seismic Building Code, NCh-3357/2015 [17] will be described in detail with regard to non-structural components, which applies to all types of mechanical equipment in buildings. After that, some real life applications in certain projects will be shown and the conclusions drawn.
2 Vibration isolation

2.1 Overview
Vibration isolation is commonly adopted by engineers to reduce the vibratory effect caused by machines in buildings [18]. The mechanical vibration process can be subdivided into four main stages, generation-transmission-propagation-radiation. The transmission stage is often the best compromise for noise and vibration control activities in view of cost and practicability [19]. Under that premise, the most effective way to eliminate vibrations between the equipment and supporting structure is a vibration isolator [20].

2.2 Practical approach
The design of a complete vibration isolation system can be divided up into [21]:
1) The selection of the required transmissibility or static deflection for the vibration isolators.
2) Selection of the appropriate form of mounting.
3) Selection of the location for the vibration isolators and determination of the loads of each one.
4) The selection of suitable isolators to correspond with the previous three points.
5) The treatment of the various service connections to ensure that these do not cancel out the effect of the vibration isolators.

The static deflection needed to isolate a particular piece of equipment can be obtained by referring to ASHRAE (American Society of Heating, Refrigerating and Air Conditioning Engineers) [16]. In general a higher deflection is required to isolate lower equipment motor frequencies [22].

There are normally three possible ways of mounting equipment. The first is to attach vibration isolators directly to the existing mounting feet of the equipment. The second method is to mount the equipment on a steel frame and to attach the vibration isolators to this, while the third possibility is to mount the equipment on a concrete 'inertia' base [21]. In figure 1, the three cases are shown.

Figure 1: Left: Chiller mounted directly on isolators. Center: Fan mounted on a metal base and isolators. Right: Pump mounted on concrete inertia base with isolators.
The manufacturer of the equipment generally gives the location of the isolators since the equipment usually has mounting hole locations (typically in the corners) where the equipment can be anchored [20].

For equipment that is installed on steel bases or concrete inertia bases where the base is too long with respect to the width, one ought to install intermediate isolators so that that base itself does not have excessive bending or collapse upon its length. This means that upon selecting isolators, the intermediate supports will typically have to support a greater load than that of the corner isolators. In Figure 2, an example of this case is shown.

![Figure 2: Cooling tower mounted on 6 isolators, 4 in the corners and 2 intermediate.](image)

Normally when dealing with the connections between equipment and piping, the focus is on spherical connectors or flexible hoses when dealing with wetside equipment such as pumps, chillers, cooling towers, etc. To avoid vibration the typical choice is a long flexible stainless steel hose, usually longer than stock connectors. To avoid blade passage frequency, spherical connectors are used which accept both minimal axial and longitudinal movement.

### 2.3 Criteria of design

As mentioned in section 2.2, the criteria used to select isolators, the type of base and the minimum static deflection is ASHRAE. The selection is made as a function of the following variables:

- Type of Equipment
- Horsepower
- Revolutions per minute
- Distance between supporting columns

It is important to mention that one of the most important variables with regard to minimum static deflection required to isolate equipment is the distance between support columns and where the equipment is located with respect to that gap. This is due to the fact that ASHRAE considers what the deflection will be in the structural floor below because the isolators should have more static deflection than the floor below.

In Table 1, the type of isolator, type of base and the minimum static deflection for different HVAC equipment are shown, depending on the previously mentioned variables.
Table 1: Type of Isolator Recommended for Different HVAC Equipment. Source: [16]

<table>
<thead>
<tr>
<th>Equipment Type</th>
<th>Shaft Power, kW and Other</th>
<th>Rpm</th>
<th>Base Isolator Type</th>
<th>Min Defl., in.</th>
<th>0- to 300 L/s</th>
<th>&gt; 300 L/s</th>
<th>0.125 in.</th>
<th>0.75 in.</th>
<th>0.5 in.</th>
<th>1 in.</th>
<th>1.5 in.</th>
<th>2 in.</th>
<th>3 in.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Refrigeration Machines and Chillers</td>
<td>All</td>
<td></td>
<td>A</td>
<td>2</td>
<td>0.25</td>
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<td></td>
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<tr>
<td>1. Pad, rubber or glass fiber</td>
<td>All</td>
<td></td>
<td>A</td>
<td>1</td>
<td>0.25</td>
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<tr>
<td>2. Structural steel rails or base</td>
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<td>3. Concrete inertia base</td>
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<td>4. Chilled water tower</td>
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<td>9. Coolers</td>
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<tr>
<td>27. Axial fans</td>
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<tr>
<td>28. Ducted rotating equipment</td>
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<tr>
<td>29. Packaged Rooftop Equipment</td>
<td>All</td>
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<td>A</td>
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<tr>
<td>30. Engine-Driven Generators</td>
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</table>
3 Seismic restraint

3.1 Overview

Even though seismic restraint is not related to acoustics or noise, new technological advances in isolation have been able to create a product that not only isolates vibrations but also can provide seismic restraint. As mentioned previously, it is a big problem for acoustical consultants that work in seismic countries when having to deal with vibration isolation while keeping in mind seismic restraint. When taking into account the seismic restraint, the tension and shear of the mount and their connecting anchor points should be calculated along with the equipment to isolator connections. If there is a failure amongst the three above points, the entire system can fail during an earthquake. In order to calculate the tension and shear forces, the Steel Construction Manual [23] or the most current concrete anchor codes should be consulted.

3.2 Earthquakes and codes in Chile

Chile is one of the most seismically active countries in the world. Various studies exist that show the long history of the great quantity of earthquakes in the history of the country in the last century [24-27]. The three earthquakes that affected the country and helped to develop the seismic codes are the following:

1) 1960 Earthquake that occurred in the city of Valdivia, Magnitude 9.5 on the Richter Scale [28]. After that earthquake, building code NCh433-1996 was developed [29].

2) 1985 Earthquake that occurred in the city of Valparaíso, Magnitude 7.8 on the Richter Scale [26]. After the occurrence of that earthquake, building codes NCh2369-2003 [30] and Nch2745-2003 [31] were developed.

3) 2010 Earthquake that occurred in the Bío Bío region, Magnitude 8.8 on the Richter Scale [30]. After that earthquake, building codes NTM-001 from MINVU [33], that is based on the American code ASCE-07 [34], and in 2015, NCh-3357/2015 [17].

3.3 Code NCh-3357/2015 [17]

This code establishes the minimum criteria of seismic design for non-structural components and systems that are permanently fixed in buildings. This applies to mechanical equipment, such as generators, fans, cooling towers, etc. Below the definitions and equations used per the codes in order to calculate the seismic requirements in non-structural components will be presented:

1) **Seismic design force**: The horizontal seismic design force \( F_p \) is applied to the center of gravity of the component or distributed about the mass of the component and determined by Equation 1.

\[
F_p = \frac{0.4 a_p \alpha A W_p}{g \left( \frac{R_p}{l_p} \right)} \left( 1 + 2 \frac{Z}{h} \right)
\]
The code specifies that the value of $F_p$ should be in the following range:

$$\frac{0.3 \alpha_A I_p W_p}{g} < F_p < \frac{1.6 \alpha_A I_p W_p}{g} \tag{2}$$

where $F_p$ is the seismic force of the non-structural component, $\alpha_A$ is the design spectral acceleration, classified by D.S.61/2011 of MINVU [35]. In Table 2 the possible values are shown. $\alpha_p$ is the dynamic amplification factor, which varies between 1.0 and 2.5. $I_p$ is the importance factor, which varies between 1.0 and 1.5. $W_p$ is the operating weight of the component. $R_p$ is the response modification factor, which varies between 1 and 8. $z$ is the height of the component with respect to the ground and building height. For components located below ground the value should be $z = 0$, $h$ is the height of the building with respect to the ground, and $g$ is the gravitational acceleration, in cm/s$^2$.

The horizontal seismic design force, $F_p$, ought to be applied in two orthogonal directions in combination against the load of the component. In addition, there will be a simultaneous vertical seismic design force, $F_{pv}$, equal to $\pm (0.24 \alpha_A W_p)/g$.

**Table 2: Parameter $\alpha_A$ of design acceleration. Source: [35].**

<table>
<thead>
<tr>
<th>Type of ground</th>
<th>$\alpha_A$</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>977 Z</td>
</tr>
<tr>
<td>B</td>
<td>1.101 Z</td>
</tr>
<tr>
<td>C</td>
<td>1.144 Z</td>
</tr>
<tr>
<td>D</td>
<td>1.455 Z</td>
</tr>
<tr>
<td>E</td>
<td>1.576 Z</td>
</tr>
</tbody>
</table>

Where the parameter $Z$, which depends on the seismic zone, is defined in Table 3. For ground type F, according to code NCH433-1996 [29], a special study shall determine seismic forces.

**Table 3: Modification factor $Z$ of spectral acceleration according to seismic zone. Source: [29].**

<table>
<thead>
<tr>
<th>Seismic zone</th>
<th>$Z$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.5</td>
</tr>
<tr>
<td>2</td>
<td>0.75</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
</tr>
</tbody>
</table>

4 Failures during earthquakes

In this section, mention will be made of the failures that occurred during the earthquake of February 27, 2010 in Chile (referred to as 27F going forward). The pictures were taken the 28th of February, 2010 in different work sites during a technical inspection that was undertaken in Santiago, Chile by the company Silentium, Ingeniería del Silencio. The principal failures that were seen on 27F were with regard to the selection of isolators, installation of isolators, and the selection of the anchor bolts. Each one of the aforementioned failures will be detailed below.
4.1 Selection of isolators

One of the principle problems is the selection of isolators that do not also provide seismic restraint. It is necessary to utilize isolators that have a rigid housing that restricts excessive movement of the isolator and the equipment once an earthquake occurs.

![Figure 3: Left: Isolators to the side of collapsed chiller to which they belonged. Right: Failure of isolation system of pump inertia base due to lack of snubbers.](image)

4.2 Installation of isolators

Another problem that was seen on 27F was that the correct isolators with seismic restraint were selected but installed with concrete anchors too close to the border of the housekeeping pad, causing a failure of the anchor bolt system. Figure 4 below shows this example.

![Figure 4: Isolator in tack but concrete failure below, installed too close to the edge of housekeeping pad.](image)

4.3 Anchor bolt selection

Important variables that should not be overlooked are the connection between the equipment and isolator and the connection between the isolator and structure. On 27F, there were failures seen due to the shear forces acting on insufficiently selected anchors.

![Figure 5: Failure of bolt due to poor selection, acted on by shear forces of earthquake.](image)
5 Conclusions

Keeping in mind what has been explained in this report, it can be concluded that the design of vibration control systems for mechanical equipment in a seismic country must consider the seismic variable in its design. The design recommendations are based in the international criteria in ASHRAE for vibration control and the Chilean seismic code NCh-3357/2015 for seismic restraint. Upon unifying these two criteria, an effective and integral design of vibration control can be achieved and furthermore guaranteeing the continued operation of isolated equipment during and after an earthquake. The damages that a vibration control system that is not equipped with seismic restraint can cause aside from being very costly can be lethal. Finally, it can be concluded that engineers or acoustical consultants that work in seismic countries and develop vibration control projects have the responsibility to include seismic restraint considerations, since the lack of doing so could put the lives of people in great risk.

References


[34] American Society of Civil Engineers (2002). Minimum design loads for buildings and other structures. SEI/ASCE 7-02 Second Edition.