Prediction of Sound Propagation From Power Transmission Plant

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Abstract

In ABB, Soundplan is the usually used software to predict the industrial noise for power transmission plants. However, the sound sources in Soundplan are modeled as point sources between which there are no sound reflections. For the real situation, the sound sources are very big and can be regarded as noise barriers. So it is important to take the reflections between sound sources into consideration.

COMSOL Multiphysics is Finite Element Method (FEM) software which can model acoustic object with sound-reflective boundaries. First, the COMSOL model for single component inside the power transmission plant will be discussed. Then the COMSOL model for the whole plant will be calculated at different frequencies. The total sound pressure level at different receivers will be compared between COMSOL and Soundplan results. COMSOL can be used to predict the sound propagation of the power transmission plant and it can give different results when the outline of the plant is changed.
Acknowledgement

I would like to thank Romain Haettel at ABB Corporate Research for the opportunity to conduct the thesis and my supervisor Mustafa Kavasoglu at ABB Corporate Research for all the help and instructions during the thesis during the autumn of 2012.

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Jingchao Sun
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Chapter 1 Introduction

1.1 Background and purpose

This master thesis is a project funded and directed by ABB Corporate Research in Västerås Sweden with the objective to predict the sound propagation of a power transmission plant. The power transmission plants are needed to be built not far to residence because these plants should be near to the customers who are using electricity. In order to avoid disturbing the residence around the plant, there are some requirements for the noise emitted from the power transmission plant. In the project, there is a power transmission plant near the residences. Considering the noise disturbance, it is important to predict and control the noise from this power transmission plant. Soundplan is a very useful tool in industrial noise prediction field now and it is also an often-used tool to predict the sound propagation from power transmission plants in ABB. A problem with Soundplan is that there are no reflections between different sound sources which are usually modeled as point sources. In order to take the reflections between different sound sources into consideration, COMSOL MULTIPHYSICS is introduced to calculate the sound propagation of power transmission plants. COMSOL is commercial FEM software which is used to solve various kinds of physics problems. In this project, COMSOL is used to predict the sound propagation of a power transmission plant.

The objective of the project is to build the sound propagation model for the power transmission plant using COMSOL and Soundplan and compare the results between two methods. With Soundplan, the sound pressure level doesn’t change when the outline of the power transmission plant is changed because there is no reflection between the sound sources in Soundplan [1]. However, the sound pressure level at the receiver changes when the outline of the plant is changed if we use COMSOL. That is because there are reflections between the sound sources in COMSOL. With this reflection, the sources themselves can also be regarded as ‘walls’ which can make sheltering effect on the sound propagation. With the results from COMSOL, we can check if it is possible to reduce the sound pressure level at the receivers by changing the outline of the power transmission plant.
1.2 Thesis structure

The report starts with a brief description of the background and purpose of this thesis. Next content is the review of the sound power of vibrating structures and their governing equations, and how these are re-written in order to be used in COMSOL. With this part, the COMSOL model for the single component inside the power transmission plant can be built. Next the transmission loss for a point source is also discussed. Then the model for the full power transmission plant is built and the results from the COMSOL model are compared with Soundplan model and measurement data. In the following section, both COMSOL and Soundplan model for the outline-changed power transmission plant is calculated and discussed. Finally, the conclusion is drawn.

1.3 Power transmission plant

The whole electrical system is divided into 3 parts which are electrical power generation system, electrical power transmission system and electrical power distribution system.

Power transmission plant is a plant which transfers electrical energy from the power generating plant to the electrical substations in the demanding area. The main components used in the power transmission plant are usually transformers, capacitors, resistance and coolers. All of these components are sound source and each of them has their own specific sound power spectrum.
Figure 1 Electrical power transmission system

Figure 1 shows a part of real electrical power transmission system.

Figure 2 Outline of the power transmission plant
In Figure 2, the outline of the power transmission plant model is shown and all the electrical components are built inside the model. Inside the plant, object 1 represents the transformers; object 2 represents reactors; object 3 represents the coolers; object 4 represents the control room; object 5 represent resistances. All these components except the control room are sound sources which are modeled as vibrating structure in COMSOL.

### 1.4 Theoretical background

According to the sound spectrum of each component inside the plant, COMSOL models for single component are going to be built. In COMSOL, there are two boundary conditions to build a sound source with specific sound power spectrum. One is to add volume velocity on the boundary and the other one is to add acceleration on the boundary. In this project, it is important to consider the reflections between different sound sources. So the boundary condition to add acceleration is chosen to build the model. In this part we discuss the relationship between the sound power and acceleration of a vibrating structure. Using equation of sound intensity, we can express the sound power \[ W \]

\[
W = \int_{S_y} \frac{\text{Re}(p V_y^*)}{2} dS_y, \quad (1)
\]

Where \( S_y \) is the bounding surface of the structure and \( V_y \) is the normal velocity of the bounding surface of the structure. Defining radiation impedance \( Z_{rad} = p/V_y \), equation (1) can be expressed as

\[
W = \int_{S_y} \text{Re}(Z_{rad}) V_y^2 dS_y \cdot (2)
\]

If we consider the radiation is in the air, then the impedance \( Z_{rad} = \rho_0 c \). In this situation, the sound power can be formed as

\[
W = \rho_0 c \langle V_y^2 \rangle S_y. \quad (3)
\]

In which \( \langle V_y^2 \rangle \) is the spatial average of the mean-squared normal velocity.

In the frequency domain, velocity \( \nu = a\omega \), in which \( \omega \) is the angular frequency and \( a \) is the acceleration. Combining the two equations, we can get

\[
a^2 = \frac{W\omega^2}{\rho_0 cs} \quad (4).
\]

Equation (4) can also be expressed as:
With equation (5), the acceleration can be calculated from sound power and frequencies. This calculated acceleration can be used in COMSOL model in order to build the sound sources with specific sound power.

Chapter 2 Methodology

In this chapter, the single component model in the plant and point source model will be introduced. In the first section, the Comsol model for single component in the plant is illustrated. Then we present the equations which are used for boundary conditions in COMSOL model. In the third part, the COMSOL model for single component inside the plant is shown.

2.1 Wave equations

In Comsol, the governing equations [3] for the sound waves can be written as:

$$\frac{1}{\rho c^2} \frac{\partial^2 p}{\partial t^2} + \nabla \left( \frac{1}{\rho} \left( \nabla p - q \right) \right) = Q \quad (6)$$

In wave equation (6), $\rho$ refers to the density, and $c$ refers to the speed of sound. The $q$ (SI unit: N/m$^3$) refers to the dipole source and the $Q$ (SI unit: 1/s$^2$) refers to monopole source. Both of the source terms are optional and the default value of the source terms is zero. The combination $\rho c^2$ is called the adiabatic bulk modulus. If the sound pressure is time-harmonic wave, the sound pressure can be written as:

$$p(x, t) = p(x) e^{i\omega t} \quad (7)$$

where $\omega = 2\pi f$ is the angular frequency, with $f$ referring to the frequency. The wave equation can be written as Helmholtz equation [3]:

$$\nabla^2 p(x) + k^2 p(x) = 0$$

(8)
With only Helmholtz equation we could not calculate the sound pressure unless some initial values are given. In this thesis, the boundary condition which is used in Comsol is Normal Acceleration. This boundary condition is to define acceleration on the boundary of the vibrating sound source. The equation for Normal Acceleration [3] can be written as:

\[-\mathbf{n}\left(-\frac{1}{\rho}(\nabla p - q)\right) = \mathbf{n}a_0\]  

Where \(\mathbf{n}\) is the unit vector with a direction of normal direction and \(a_0\) is the acceleration. Using Helmholtz equation (8) and boundary condition (9), the sound pressure can be calculated.

2.2 COMSOL model for single component in the plant

Using sound generation theory in Sound and Vibration, we can define an object with specific sound power. The sound power from a vibrating structure is associated with the vibrating speed of the structure. We can use this relation to model the components of the power transmission plant in COMSOL.

The transformer in the power transmission plant is usually modeled as a rectangle which has a vibrating boundary.
In Figure 3, the sound pressure field of the transformer calculated by COMSOL is shown. This model is a frequency domain model and is calculated at 100 Hz. The mesh size is 0.68 meter. The PML is added on the boundary of the field and the thickness of the PML is 4 meters. The expecting sound power level of this sound source is 70dB and the corresponding acceleration is 0.0178 m/s². The calculated sound power level from COMSOL is 69.5dB.
Figure 4 Reactor sound field from COMSOL computation

In Figure 4, the sound pressure field of reactor calculated by COMSOL is shown. This model is a frequency domain model and is calculated at 200 Hz. The mesh size is 0.343 meter. The PML is added on the boundary of the field and the thickness of the PML is 2.5 meters. The expecting sound power level of this sound source is 76dB and the corresponding acceleration is 0.1098 m/s². The calculated sound power level from COMSOL is 76.1dB.
Figure 5 The SPL directivity on the boundary of the sound field

In Figure 5, the directivity of sound pressure level on the boundary of the sound field is shown. The sound pressure level equals all the same on the boundary which is a circle with radius of 10 meters. The PML absorbs all the incident waves and this is a free field. So this result is reasonable.

Figure 6 Cooler sound field from COMSOL computation
The cooler plant is usually modeled as a line source which has specific sound power. In Figure 6, the sound pressure field of cooler calculated by COMSOL is shown. This model is a frequency domain model and is calculated at 100 Hz. The mesh size is 0.68 meter. The PML is added on the boundary of the field and the thickness of the PML is 2.5 meters. The expecting sound power level of this sound source is 76dB and the corresponding acceleration is 0.0771 m/s². The calculated sound power level from COMSOL is 76.3dB.

As each of the components can be modeled, then we can model the whole power transmission plant by combining them together.

2.3 Perfectly matched layer

If we want to model a free sound field, which has no reflecting sound at the exterior boundary of the domain, we need to use the perfectly matched layer. The key property of a PML is that it is designed to strongly absorb sound waves incident on PML from other medium without reflection [4]. Using PML, we can build a model which has no reflection from simulation domains boundary. In usual case the thickness of the PML is 1 wavelength.

The physical explanation of the PML can be expressed as coordinate transformation. Inside the PML, $\frac{\partial}{\partial x}$, which is part of wave equation, is transformed to $\frac{1}{1 + i \frac{\sigma(x)}{\omega}} \frac{\partial}{\partial x}$ [5]. In the equation, $\omega$ is the angular frequency; inside the PML, $\sigma(x) > 0$ and the solutions of wave equation decay exponentially; outside the PML, $\sigma(x) = 0$ and the solutions are unchanged. In Comsol, the stretching coordinate of PML [3] can be expressed as:

$$\xi' = \text{sign}(\xi - \xi_0) |\xi - \xi_0| \frac{L}{\delta \xi n} (1 - i)$$  \hspace{1cm} (10)

In equation (10), $\xi$ is the coordinate direction; $\xi_0$ is the coordinate of the inner PML boundary; $\delta \xi$ is the width of the PML; and $n$ is the PML order which can be input from the PML setting.

Chapter 3 Comsol and Soundplan comparison for point source model
3.1 The geometry divergence and relating equations

In 2D COMSOL model, the coil or point source generates cylindrical waves. In the cylindrical wave field, the relationship between the sound power and sound intensity in cylindrical wave field is:

\[ W = I \times 2\pi r, \quad (11) \]

in which \( W \) is the sound power, \( I \) is the sound intensity and \( r \) is the distance the sound propagates.

Consider

\[ I = \frac{p^2}{\rho_0 c}, \quad (12) \]

\[ L_w = 10\log_{10} \frac{W}{W_{\text{ref}}} \quad (13) \]

\[ L_p = 10\log_{10} \frac{p^2}{p_{\text{ref}}^2} \quad (14) \]

In which \( L_w \) is the sound power level, \( L_p \) is the sound pressure level, \( \rho_0 \) is the density of the air, \( c \) is the speed of the sound, \( W_{\text{ref}} = 10^{-12} W \) is the reference value of sound power and \( p_{\text{ref}} = 2 \cdot 10^{-5} Pa \) is the reference value of sound pressure.

Combining equation (11) and equations above, we can derive:

\[ L_w = L_p + 10 \log_{10} (2\pi r). \quad (14) \]

In 3D COMSOL model, the point source generates spherical waves. In spherical wave field, the relationship between the sound power and sound intensity is:

\[ W = I \times 4\pi r^2, \quad (16) \]

In which \( W \) is the sound power, \( I \) is the sound intensity and \( r \) is the distance to the source.

Using the method similar to the method to derive equation (15), we can get a new equation:

\[ L_w = L_p + 10 \log_{10} (4\pi r^2). \quad (17) \]
This equation describes the relationship between the sound power sound pressure and the distance the sound propagates in spherical wave field.

Comparing equation (15) and equation (17), we can draw a conclusion that the sound pressure decreases slower in 2D model than 3D model. Equation $10 \log_{10}(2\pi r)$ in 2D situation and equation $10 \log_{10}(4\pi r^2)$ in 3D can both be called as geometry divergence attenuation [6] which can also be described as transmission loss.

### 3.2 2D and 3D COMSOL model for point source

In the 2D COMSOL model, the sound source is point source which generates cylindrical waves [3]. In Figure 7, it is a Comsol point source model. The calculating frequency is 125 Hz and the mesh size is 0.5 meter. The thickness of the PML is 2 meters. The source is defined as power point source which has RMS sound power 0.01W/m. The sound power 0.01 W/m is 100dB in sound power level.

![Figure 7: The sound pressure field of the 2D model](image)

The COMSOL 2D model is calculated at 125Hz and the results are shown in the following table.

<table>
<thead>
<tr>
<th>R(m)</th>
<th>100</th>
<th>200</th>
<th>300</th>
<th>400</th>
<th>500</th>
<th>600</th>
<th>700</th>
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<td></td>
</tr>
<tr>
<td></td>
<td>Geo div(dB)</td>
<td>27.82</td>
<td>30.83</td>
<td>32.59</td>
<td>33.84</td>
<td>34.81</td>
<td>35.60</td>
<td>36.27</td>
<td>36.85</td>
<td>37.36</td>
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</tr>
<tr>
<td><strong>Comsol results</strong></td>
<td>SPL (dB)</td>
<td>72.18</td>
<td>69.17</td>
<td>67.41</td>
<td>66.16</td>
<td>65.19</td>
<td>64.40</td>
<td>63.73</td>
<td>63.15</td>
<td>62.64</td>
</tr>
<tr>
<td></td>
<td>Geo div(dB)</td>
<td>28.0</td>
<td>31.0</td>
<td>32.8</td>
<td>34.0</td>
<td>35.0</td>
<td>35.8</td>
<td>36.4</td>
<td>37.0</td>
<td>37.5</td>
</tr>
<tr>
<td><strong>Analytical results</strong></td>
<td>SPL(dB)</td>
<td>72.0</td>
<td>69.0</td>
<td>67.2</td>
<td>66.0</td>
<td>65.0</td>
<td>64.2</td>
<td>63.6</td>
<td>63.0</td>
<td>62.5</td>
</tr>
</tbody>
</table>

Table 1 Calculation results of 2D point source model from Comsol and analytical method

In table 1, R is the distance which the sound waves propagate; Geo div is the geometry divergence attenuation; SPL is sound pressure level. The analytical results are calculated from equation (15). From comparison between Comsol and analytical method, the results from two methods are almost the same. The sound waves in 2D model are cylinder waves and the COMSOL results fit the analytical results well.

In the 3D model in COMSOL, the point source is in the center of the calculation domain. The source generates spherical waves. The thickness of the PML is 2 meters and the radius of propagation domain is 5 meters. The mesh size is 0.5 meter and the calculation frequency is 125Hz. The source is defined as power point source which has RMS sound power 0.01W. The sound power 0.01 W is 100dB in sound power level.
In Figure 8, the sound pressure field from a 3D Comsol model is shown. The outer blue domain is the PML domain and the inner domain is the sound propagation domain. As the PML absorbs all the sound waves, so the sound pressure is very low in the outer domain.

In Figure 9, the sound pressure field at 100 meters is shown.
In Figure 9, the sound pressure field at 100 meters away is shown. The biggest SPL and the smallest SPL on the surface are 49.87 dB and 49.55 dB. They are very close and the sound pressure level on the surface can be regarded as the same. Using the far field calculation, the sound pressure level at specific distance can be calculated.

![Figure 9](image_url)

**Figure 10** The sound pressure directivity at 100 meters at the X-Z surface

In Figure 10, the directivity of sound pressure level at the X-Z surface is shown. The sound pressure level is almost the same at the surface. This is a free field environment is built because with PML and there is only a point sound source inside the domain.

In table 2, the results from Comsol and analytical method at various distances are shown.

<table>
<thead>
<tr>
<th>R(m)</th>
<th>100</th>
<th>200</th>
<th>300</th>
<th>400</th>
<th>500</th>
<th>600</th>
<th>700</th>
<th>800</th>
<th>900</th>
<th>1000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geo div (dB)</td>
<td>49.01</td>
<td>42.99</td>
<td>39.47</td>
<td>36.97</td>
<td>35.03</td>
<td>33.44</td>
<td>32.11</td>
<td>30.95</td>
<td>29.92</td>
<td>29.01</td>
</tr>
<tr>
<td>Comsol results</td>
<td>SPL (dB)</td>
<td>49.20</td>
<td>43.18</td>
<td>39.66</td>
<td>37.16</td>
<td>35.22</td>
<td>33.64</td>
<td>32.30</td>
<td>31.14</td>
<td>30.12</td>
</tr>
</tbody>
</table>
### Analytical results

<table>
<thead>
<tr>
<th>Geo div (dB)</th>
<th>50.99</th>
<th>57.01</th>
<th>60.53</th>
<th>63.03</th>
<th>64.97</th>
<th>66.56</th>
<th>67.89</th>
<th>69.05</th>
<th>70.08</th>
<th>70.99</th>
</tr>
</thead>
<tbody>
<tr>
<td>SPL (dB)</td>
<td>49.01</td>
<td>42.99</td>
<td>38.97</td>
<td>36.97</td>
<td>35.03</td>
<td>33.44</td>
<td>32.11</td>
<td>30.95</td>
<td>29.92</td>
<td>29.01</td>
</tr>
</tbody>
</table>

Table 2 Calculation results of 3D point source model from Comsol and analytical method

In table 2, the analytical sound pressure level and geometry divergence attenuation is calculated by equation (17). Comparing the results from Comsol and analytical method, the far field sound pressure level and the geometry divergence attenuation from these 2 methods are very close. In the COMSOL 3D model, the geometry divergence of sound propagation is in a pattern of $10 \log_{10}(4\pi r^2)$.

### 3.3 Point source model in Soundplan

In Soundplan, the model is built by one point source and ten receivers. Both the point source and the receivers are in the same line. The distance between the source and receivers is 100 meters.

![Figure 11 The sound pressure field of the Soundplan model](image)
In Figure 11 the sound pressure field calculated by Soundplan is shown. The sound pressure level decreases with the increase of distance and the sound pressure level is the same.

The results of Soundplan for the point source model are shown in table 3.

<table>
<thead>
<tr>
<th>R(m)</th>
<th>100</th>
<th>200</th>
<th>300</th>
<th>400</th>
<th>500</th>
<th>600</th>
<th>700</th>
<th>800</th>
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</tr>
</thead>
<tbody>
<tr>
<td>Sound pressure level (dB)</td>
<td>49.00</td>
<td>42.97</td>
<td>39.55</td>
<td>36.99</td>
<td>35.03</td>
<td>33.43</td>
<td>32.15</td>
<td>30.95</td>
<td>29.95</td>
<td>29.05</td>
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<tr>
<td>Geo divergence attenuation (dB)</td>
<td>50.99</td>
<td>57.01</td>
<td>60.53</td>
<td>63.03</td>
<td>64.97</td>
<td>66.56</td>
<td>67.89</td>
<td>69.05</td>
<td>70.08</td>
<td>70.99</td>
</tr>
</tbody>
</table>

Table 3 Results in the model of Soundplan

From table 3, a conclusion can be drawn that the far field sound in Soundplan is calculated directly from equation (17).

3.4 Comparison between the three groups of results and correction coefficient

In this section, the results from Comsol Soundplan and analytical method will be compared and discussed.

<table>
<thead>
<tr>
<th>R(m)</th>
<th>100</th>
<th>200</th>
<th>300</th>
<th>400</th>
<th>500</th>
<th>600</th>
<th>700</th>
<th>800</th>
<th>900</th>
<th>1000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soundplan Geo div (dB)</td>
<td>50.99</td>
<td>57.01</td>
<td>60.53</td>
<td>63.03</td>
<td>64.97</td>
<td>66.56</td>
<td>67.89</td>
<td>69.05</td>
<td>70.08</td>
<td>70.99</td>
</tr>
<tr>
<td>COMSOL 2D Geo div (dB)</td>
<td>27.82</td>
<td>30.83</td>
<td>32.59</td>
<td>33.84</td>
<td>34.81</td>
<td>35.60</td>
<td>36.27</td>
<td>36.85</td>
<td>37.36</td>
<td>37.82</td>
</tr>
<tr>
<td>COMSOL 3D Geo div (dB)</td>
<td>50.80</td>
<td>56.82</td>
<td>60.34</td>
<td>62.84</td>
<td>64.78</td>
<td>66.36</td>
<td>67.70</td>
<td>68.86</td>
<td>69.88</td>
<td>70.80</td>
</tr>
</tbody>
</table>

Table 4 The comparison of geometry divergence attenuation in Soundplan and COMSOL

With table 4, a conclusion can be drawn that the geometry divergence attenuation in 2D COMSOL model and 3D is different. This attenuation caused by propagation in Soundplan is close to COMSOL 3D model. If we want to make a comparison between the Soundplan model and COMSOL model, this difference should be taken into consideration. Especially when we compare COMSOL 2D model and Soundplan model, we should make a correction for the geometry divergence attenuation in 2D COMSOL model.
We can define the geometry divergence attenuation difference between the 2D and 3D model as correction coefficient. If this correction coefficient is subtracted from 2D COMSOL model results, the sound pressure level in Soundplan and 2D COMSOL model can be comparable.

<table>
<thead>
<tr>
<th>R(m)</th>
<th>100</th>
<th>200</th>
<th>300</th>
<th>400</th>
<th>500</th>
<th>600</th>
<th>700</th>
<th>800</th>
<th>900</th>
<th>1000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geo div in 2D COMSOL model (dB)</td>
<td>28.0</td>
<td>31.0</td>
<td>32.8</td>
<td>34.0</td>
<td>35.0</td>
<td>35.8</td>
<td>36.4</td>
<td>37.0</td>
<td>37.5</td>
<td>38.0</td>
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<tr>
<td>Geo div in 3D COMSOL model (dB)</td>
<td>50.8</td>
<td>56.82</td>
<td>60.34</td>
<td>62.84</td>
<td>64.78</td>
<td>66.36</td>
<td>67.70</td>
<td>68.86</td>
<td>69.88</td>
<td>70.80</td>
</tr>
<tr>
<td>Analytical 2D geo div (dB)</td>
<td>28.0</td>
<td>31.0</td>
<td>32.8</td>
<td>34.0</td>
<td>35.0</td>
<td>35.8</td>
<td>36.4</td>
<td>37.0</td>
<td>37.5</td>
<td>38.0</td>
</tr>
<tr>
<td>Analytical 3D geo div (dB)</td>
<td>50.99</td>
<td>57.01</td>
<td>60.53</td>
<td>63.03</td>
<td>64.97</td>
<td>66.56</td>
<td>67.89</td>
<td>69.05</td>
<td>70.08</td>
<td>70.99</td>
</tr>
<tr>
<td>Correction coefficient (dB)</td>
<td>22.99</td>
<td>26.01</td>
<td>27.73</td>
<td>29.03</td>
<td>29.97</td>
<td>30.76</td>
<td>31.49</td>
<td>32.05</td>
<td>32.58</td>
<td>32.99</td>
</tr>
</tbody>
</table>

Table 5: Difference of geometry divergence attenuation in 2D and 3D COMSOL model

In table 5 geometry divergence attenuation from Comsol Soundplan and analytical method is shown. The correction coefficient is calculated from analytical 2D and 3D geometry divergence attenuation.
In Figure 12 the results of different point source models are compared. After subtracting the correction coefficient from the 2D COMSOL model, the sound pressure level at the receivers is comparable to the results of Soundplan and 3D COMSOL model. If we want to compare the results of Soundplan and 2D COMSOL model, it is very necessary to consider the correction coefficient in 2D COMSOL model.

**Chapter 4 Plant model results**

In this chapter, COMSOL and Soundplan models for the whole power transmission plant will be discussed. For the COMSOL models, the results will be shown in different frequencies. Then these results will be compared with Soundplan results. Finally the total sound pressure level at all frequencies will be compared and discussed.

**4.1 Plant model results at 100 Hz**

The sound power spectra data for the sound sources come from ABB. These data are the same as the sound power in Soundplan model. The solution is calculated at 100 Hz. The thickness of the PML is 10 meters. The model is calculated in frequency domain and the calculation time is 114 seconds. The number of degrees of freedom solved is 544549.
In Figure 13, the sound pressure field of the plant at 100 Hz is shown. From the figure it can be concluded that the coolers are the dominating sound sources at 100 Hz. There are some sound sources generating no sound at 100 Hz.
In Figure 14, the sound pressure level field of the plant at 100 Hz is shown. PML is the outer domain and it absorbs all the outgoing sound waves.

In the Soundplan model there are 9 receivers which are A B B1 C C1 D EE1 F G. In COMSOL, the sound pressure is calculated in the entire field. As we know the coordinate of the 9 receivers, we can define these receivers with a relative distance and angle to the center point of the circle domain.
In Figure 15, the positions of receivers and power transmission plant are shown. Receiver B and B1 are the closest receivers to the plant and Receiver F and G are the farthest from the plant.

Table 6 Receiver information with distance and angle relative to the center point

Table 6 shows the receiver information used in Comsol model. The relative distance is the distance from the receivers to the center of the calculation domain. This information is used to calculate the sound pressure level at the receivers in Comsol model.
In Figure 16, the sound pressure level directivity of the plant at the distance of 584.7 meters is shown. And receiver A is in the relative angle of -162.3 which is 197.7 degree. The sound pressure level at 197.7 degree in figure 16 is the sound pressure level at receiver A at 100 Hz. In table 7, the sound pressure level at all receivers is shown.

<table>
<thead>
<tr>
<th>Receiver</th>
<th>A</th>
<th>B</th>
<th>B1</th>
<th>C</th>
<th>C1</th>
<th>D</th>
<th>EE1</th>
<th>F</th>
<th>G</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sound pressure level(dB)</td>
<td>38.9</td>
<td>36.5</td>
<td>34</td>
<td>21</td>
<td>32.5</td>
<td>33</td>
<td>42</td>
<td>37</td>
<td>24.5</td>
</tr>
</tbody>
</table>

Table 7  The sound pressure level at each receiver at 100 Hz

In receiver EE1, the sound pressure level is 42 dB which is the biggest sound pressure level and the sound pressure level at receiver C is 21 dB which is the smallest.

In order to check how the position of the sound source affects the sound field, a new power plant model is built. In the new plant the coolers are assumed to move 46 meters up. All the other sound sources are kept in the same place as pervious model. So all the setting keeps the same as previous model. The solution is calculated at 100 Hz. The thickness of the PML is 10 meters. The model is calculated in frequency domain and the calculation time is 118 seconds. The number of degrees of freedom solved is 544549.
Here are the results from COMSOL.

In Figure 17, the sound pressure field of the changed plant at 100 Hz is shown. From the figure the coolers are the dominating sound sources at 100 Hz and the sound field changes when the coolers are moved.
In figure 18, the sound pressure level field for the changed plant is shown. When the position of the coolers is changed, the sound pressure level is also changed. The sound pressure field behind the building changes a lot. When the position of the coolers is changed, the directivity of the sound filed is also changed.

Figure 19 Sound directivity in the distance of 584.7 m for the changed model
In Figure 19, the sound pressure level directivity at the distance of 584.7 meters for the changed plant is shown. With this directivity and the receivers information, the sound pressure level at all receivers can be calculated.

<table>
<thead>
<tr>
<th>Receiver</th>
<th>A</th>
<th>B</th>
<th>B1</th>
<th>C</th>
<th>C1</th>
<th>D</th>
<th>EE1</th>
<th>F</th>
<th>G</th>
</tr>
</thead>
<tbody>
<tr>
<td>Original SPL</td>
<td>38.9</td>
<td>36.5</td>
<td>34</td>
<td>21</td>
<td>32.5</td>
<td>33</td>
<td>42</td>
<td>37</td>
<td>24.5</td>
</tr>
<tr>
<td>SPL after changing</td>
<td>25.2</td>
<td>27</td>
<td>31.2</td>
<td>26.4</td>
<td>23.2</td>
<td>27</td>
<td>30.5</td>
<td>28.7</td>
<td>30.1</td>
</tr>
</tbody>
</table>

Table 8 Comparisons of sound pressure level between the original plant and changed plant at 100 Hz

In Table 8, the comparisons of sound pressure level at all receivers are made between the original and modified power transmission plant. After moving the coolers 46 meters up, the sound pressure level at the receivers decreases from 2.8 dB to 13.7 dB at 100 Hz. Most of the decrease comes from the reflection of the cooler sound sources. The model with original and changed plant in Soundplan can be discussed.

![Figure 20 The outline of Soundplan model for the original plant](image)

In Figure 20, the outline of the Soundplan model for the original plant is shown. With this model, the sound pressure level at all the receivers is calculated in Soundplan.
In Figure 21, the outline of the Soundplan model for the changed plant is shown. The coolers are moved 46 meters up comparing with the original plant.

<table>
<thead>
<tr>
<th>Receiver</th>
<th>A</th>
<th>B</th>
<th>B1</th>
<th>C</th>
<th>C1</th>
<th>D</th>
<th>EE1</th>
<th>F</th>
<th>G</th>
</tr>
</thead>
<tbody>
<tr>
<td>SPL in original plant (dB)</td>
<td>3.9</td>
<td>12.9</td>
<td>14</td>
<td>9.1</td>
<td>10.1</td>
<td>7.5</td>
<td>3.5</td>
<td>2.4</td>
<td>2.1</td>
</tr>
<tr>
<td>SPL in changed plant (dB)</td>
<td>3.2</td>
<td>12.3</td>
<td>13.2</td>
<td>8.5</td>
<td>9.2</td>
<td>6.8</td>
<td>3.1</td>
<td>2.8</td>
<td>2.4</td>
</tr>
</tbody>
</table>

Table 9 Sound pressure level at all the receivers in original and changed Soundplan plant model at 100 Hz

From table 9, the sound pressure level doesn’t change much in Soundplan model. This is because there is no reflection between sound sources. However, the difference of sound pressure level between the COMSOL model and Soundplan model is very big. Then big difference is caused by different geometry divergence attenuation. In 2D COMSOL model, the geometry divergence attenuation is smaller than the 3D case.

<table>
<thead>
<tr>
<th>Receiver</th>
<th>A</th>
<th>B</th>
<th>B1</th>
<th>C</th>
<th>C1</th>
<th>D</th>
<th>EE1</th>
<th>F</th>
<th>G</th>
</tr>
</thead>
<tbody>
<tr>
<td>Analytical geo</td>
<td>35.7</td>
<td>33.2</td>
<td>32.8</td>
<td>34.4</td>
<td>34.1</td>
<td>35.5</td>
<td>34.6</td>
<td>36.5</td>
<td>36.2</td>
</tr>
<tr>
<td>div in 2D (dB)</td>
<td>Analytical geo div in 3D (dB)</td>
<td>Correction coefficient(dB)</td>
<td>Geo div in Soundplan(dB)</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td>---------------</td>
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</tr>
<tr>
<td></td>
<td>66.3</td>
<td>30.6</td>
<td>65.95</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>61.4</td>
<td>28.2</td>
<td>61.24</td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td></td>
<td>60.6</td>
<td>27.8</td>
<td>59.70</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>63.9</td>
<td>29.5</td>
<td>64.55</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>63.2</td>
<td>29.1</td>
<td>64.03</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>66.1</td>
<td>30.6</td>
<td>65.29</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>64.3</td>
<td>29.7</td>
<td>64.50</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>68.0</td>
<td>31.5</td>
<td>67.99</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>67.9</td>
<td>31.7</td>
<td>67.99</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 10 Comparison of divergence attenuation in different models at 100Hz

In table 10 analytical geometry divergence attenuation and geometry divergence attenuation in Soundplan are shown. The difference of geometry divergence attenuation between 2D and 3D COMSOL model is very large. The geometry divergence attenuation in 3D COMSOL model and in Soundplan is very close to each other.

In Figure 22, the sound pressure level at all receivers in Comsol and Soundplan models is shown. The corrected original SPL in COMSOL is the results that original sound pressure level in COMSOL reduces the correction coefficient. The corrected SPL after changing in COMSOL is the results that sound pressure level after changing in COMSOL reduces the correction coefficient. First, the sound pressure level at each receiver is different.
between COMSOL and Soundplan models. For the whole plant, only 2D COMSOL model is built because of memory consuming. The geometry divergence attenuation is different in Soundplan and 2D COMSOL model. Second, in Figure 22, the change of the results in Soundplan model is within 1 dB when the position of the coolers is changed. This is because there are no reflections between Soundplan sources. The change of the cooler position means there is a small change in the distance between the cooler sources to the receivers. With this small distance change, the sound pressure level changes a little in the receivers. Last, in COMSOL, the sound pressure field changes a lot when the position of the coolers is changed. This is caused by the reflections between the sound sources and building. However, the corrected sound pressure level for Comsol model at some receivers is smaller than 0 dB. The correction coefficient can be used to approach the 3D model results but not exactly the same. The error can be big.

4.2 Plant model results at 160Hz and 200 Hz

In this section, the plant models results from COMSOL and Soundplan at 160 Hz and 200 Hz will be shown.

<table>
<thead>
<tr>
<th>Receiver</th>
<th>A</th>
<th>B</th>
<th>B1</th>
<th>C</th>
<th>C1</th>
<th>D</th>
<th>EE1</th>
<th>F</th>
<th>G</th>
</tr>
</thead>
<tbody>
<tr>
<td>Original SPL in COMSOL</td>
<td>40.5</td>
<td>40.1</td>
<td>39.8</td>
<td>35.6</td>
<td>37.2</td>
<td>33.7</td>
<td>38.4</td>
<td>39.5</td>
<td>41.2</td>
</tr>
<tr>
<td>SPL after changing in COMSOL</td>
<td>26.2</td>
<td>37.4</td>
<td>29.7</td>
<td>34.6</td>
<td>31.1</td>
<td>29.4</td>
<td>37.7</td>
<td>29.9</td>
<td>35.3</td>
</tr>
<tr>
<td>SPL in Soundplan</td>
<td>18.4</td>
<td>27.4</td>
<td>28.5</td>
<td>23.6</td>
<td>24.6</td>
<td>22.0</td>
<td>18.0</td>
<td>16.9</td>
<td>16.5</td>
</tr>
<tr>
<td>SPL after changing in Soundplan</td>
<td>17.8</td>
<td>26.8</td>
<td>27.7</td>
<td>23.0</td>
<td>23.7</td>
<td>21.3</td>
<td>17.5</td>
<td>17.2</td>
<td>16.7</td>
</tr>
<tr>
<td>Corrected Original SPL in COMSOL</td>
<td>9.9</td>
<td>11.9</td>
<td>12.0</td>
<td>6.1</td>
<td>8.1</td>
<td>3.1</td>
<td>8.7</td>
<td>8.0</td>
<td>9.5</td>
</tr>
<tr>
<td>Corrected SPL after changing in COMSOL</td>
<td>-4.4</td>
<td>9.2</td>
<td>1.9</td>
<td>5.1</td>
<td>2.0</td>
<td>-1.2</td>
<td>8.0</td>
<td>-1.6</td>
<td>3.6</td>
</tr>
</tbody>
</table>

Table 11 Comparison of sound pressure level in different models at 160Hz
In table 11, the comparison of sound pressure level in different models at 160 Hz is shown.

In Figure 23, there is a big difference between the Soundplan and COMSOL results. When the position of the cooler is changed, there is small change in Soundplan results and there is big change in COMSOL results.

<table>
<thead>
<tr>
<th>Receiver</th>
<th>A</th>
<th>B</th>
<th>B1</th>
<th>C</th>
<th>C1</th>
<th>D</th>
<th>EE1</th>
<th>F</th>
<th>G</th>
</tr>
</thead>
<tbody>
<tr>
<td>SPL in Comsol</td>
<td>44.2</td>
<td>42</td>
<td>50.8</td>
<td>39.2</td>
<td>46.8</td>
<td>55.7</td>
<td>48.5</td>
<td>49.3</td>
<td>53</td>
</tr>
<tr>
<td>SPL in changed Comsol</td>
<td>38.2</td>
<td>48.8</td>
<td>38.8</td>
<td>42.4</td>
<td>51</td>
<td>53.7</td>
<td>36</td>
<td>39.7</td>
<td>48.4</td>
</tr>
<tr>
<td>SPL in Soundplan</td>
<td>14.6</td>
<td>21.8</td>
<td>22.7</td>
<td>20.2</td>
<td>20.9</td>
<td>18.2</td>
<td>11.9</td>
<td>14.4</td>
<td>13.9</td>
</tr>
<tr>
<td>SPL in changed Soundplan</td>
<td>14.1</td>
<td>21.7</td>
<td>22.5</td>
<td>20.0</td>
<td>20.6</td>
<td>18.0</td>
<td>11.8</td>
<td>14.8</td>
<td>14.2</td>
</tr>
<tr>
<td>Corrected SPL in Comsol</td>
<td>13.6</td>
<td>13.8</td>
<td>23.0</td>
<td>9.7</td>
<td>17.7</td>
<td>25.1</td>
<td>18.8</td>
<td>17.8</td>
<td>21.3</td>
</tr>
</tbody>
</table>
Corrected SPL in changed Comsol | 7.6 | 20.6 | 11.0 | 12.9 | 20.9 | 23.1 | 6.3 | 8.2 | 16.7  

Table 12: Comparison of sound pressure level in different models at 200 Hz

In table 12, the comparison of sound pressure level in different models at 200 Hz is shown. The results in Soundplan models for original and changed plant keep almost the same; the results in Comsol models for original and changed plant change a lot.

![Comparison of SPL in different models at 200 Hz](image)

Figure 24: Comparison of sound pressure level in different models at 200 Hz

In Figure 24, at receiver A B1 C1 F, the COMSOL results and Soundplan results fit well. When the position of the cooler is changed, there is small change in Soundplan results and there is big change in COMSOL results.

4.3 Plant model results at 400 Hz and 500 Hz

In this section, the plant models results from COMSOL and Soundplan at 400 Hz and 500 Hz will be shown.
In Figure 25, the results at 400 Hz in COMSOL and Soundplan are compared. In Soundplan models, the change of sound pressure level is still very small when the position of coolers is changed. In COMSOL models, the sound pressure level at receiver B1 C and F changes a lot when the coolers are moved up. This is because the directivity of the sound field is changed.
In Figure 26, the difference between the results of the two COMSOL models is very small. In COMSOL model, changing the position of the coolers doesn’t change the sound field so much. Because the sound power of the coolers is not dominating in the whole sound power spectra of all the sources. When the position of the cooler is changed, there is small change in Soundplan results.

In order to verify the calculation results from COMSOL and Soundplan, some measurement data are introduced. These measurement data are from ABB[7][8]. And these data are put into Figure 29 to make comparison between measured data and simulation results.
In Figure 27, it shows the sound pressure level at all receivers from measurement, Soundplan and COMSOL. The COMSOL results are calculated from 9 groups of frequencies. At receiver A B and B1, the results from COMSOL are smaller than the results from measurement and Soundplan. At receiver C, C1 and F, the results from both COMSOL and Soundplan are very close to the measurement data. At receiver EE1, the results from COMSOL are closer to the measurement data than the results from Soundplan. However, at receiver G, the COMSOL results are much bigger than the measurement data.
Chapter 5 Conclusions

The results from 2D COMSOL model without correction have a very big difference with the results from Soundplan model. In order to compare the results, we use a correction coefficient to modify the 2D COMSOL results. The modified results are used to approximate the 3D situation. Comparing with 2D COMSOL results, the modified 2D COMSOL results are more close to the Soundplan results.

With the comparison of measurement COMSOL and Soundplan, a conclusion can be draw that COMSOL is suitable for predicting the sound propagation of power transmission plants. But the COMSOL model for the power transmission plant needs super computer to calculate the results because it requires hundreds GB of memory. Also, it needs much more time to run the model compared with the Soundplan calculation time.

Comparing the results of COMSOL and Soundplan model at all the frequencies, a conclusion can be drawn that there is reflection between sound sources in COMSOL model. And changing the outline of the power transmission plant in COMSOL model can affect the sound directivity of the sound field. When we design the outline of the power transmission plant, we can first use COMSOL to predict the sound propagation of the plant in order to check the noise at all the receivers.
Reference

[1] Soundplan training for ABB Power Tech. AB. 2010


[8] Sound propagation study-ABB. 2011