

Analytical Approach for Workplace Noise Assessment

Suebsak Nanthavanij

Management Technology Program, Sirindhorn International Institute of Technology,
Thammasat University, Pathumthani, Thailand

Abstract

This paper discusses an analytical approach for assessing noise hazard in industrial workplaces. Initially, the data about machine noise levels and machine locations is used to construct a noise contour map of the workplace. From the contour map, potential noise hazardous areas within the facility are identified by comparing their noise levels with the permissible noise exposure limits. In the case of multiple exposures, a partial noise dose is determined from the noise level and work duration within a given area. This computation is repeated for all areas in which the worker is expected to work. A daily noise dose is calculated by summing the partial doses over the 8-hour period. Finally, an 8-hour time weighted average (TWA) sound level (in decibel-*A*) is determined. The predicted TWA sound level is then compared with the permissible exposure level. This approach can be used to study the change in workplace noise levels when a new machine is installed in the facility and investigate how workers' health can be affected. It also enables safety practitioners to quickly determine areas where the use of hearing protection devices is required.

1. Introduction

Noise problems are eminent in industrial workplaces. In a manufacturing facility where a number of machines are concurrently operating, workers are constantly exposed to noise hazard. A significant amount of effort has been expended by researchers and practitioners to control noise levels in the workplace. Generally, industrial noise control can be achieved by various means. Through proper design, maintenance, lubrication, and alignment of machines, vibration can be reduced which will subsequently lower machine noise levels. Moving machines away from workers also helps to reduce the workers' exposure to noise levels. The use of barriers or shields can reflect high-frequency noise. Enclosing machines in an acoustically lined, sealed, double vault can also significantly reduce the noise. Workers who need to work in loud-noise areas may be required to wear hearing protection devices such as ear plugs and ear muffs. Furthermore, job reassignment and reduction of exposure times to high noise levels can be applied in conjunction with the use of hearing protection devices [1].

One of the most commonly used noise control approaches in industry is the use of hearing protection devices since it perhaps is the

cheapest and easiest. However its effectiveness can be doubtful. The noise reduction rating (NRR) values claimed by manufacturers tend to be dangerously optimistic [2] and the noise attenuation in the real-world situation is normally less than the ratings displayed on the devices. Wilson, Solanky, and Gage [3] reported that workers typically adjust their hearing protection devices for comfort rather than to achieve maximum attenuation, which can result from improper fit. In some manufacturing facilities, workers tend to choose not to wear hearing protection devices. Comfort is a major factor influencing whether or not these devices are worn by workers in the workplace [4]. These findings may explain why hearing loss is still a major health hazard and is prevalent among industrial workers.

Prior to initiating a noise control program, noise problems must be defined. This step consists of measuring noise levels in the workplace and identifying noise hazardous areas. Once the hazardous areas are identified, appropriate noise control techniques can be applied to protect workers who must be present in those areas. One way to identify noise hazardous areas is to construct a noise contour map of the facility. A noise contour is a contour

line connecting points on the factory layout which have an equal noise level. These points can be found by measuring noise levels throughout the entire factory using a sound level meter. However, the construction of a noise contour map is laborious and time consuming. Additionally, the existing noise contour map has to be reconstructed if a new machine is installed in the workplace.

Once the noise contour map has been constructed, engineers or safety practitioners will have insight into the noise situation of the workplace. Areas (or zones) which have combined noise levels greater than the permissible value are marked as noise hazardous areas. Workers in such areas must be instructed to wear appropriate hearing protection devices or the exposure duration must be limited. Additionally, it is essential to determine the daily noise dose that workers receive, especially when their presence is not limited to one area.

This paper discusses a practical way to conduct a workplace noise assessment by initially using an analytical method to construct a noise contour map of the workplace. Then, noise hazardous areas are identified and individual noise exposures are determined. Mathematical formulas which are used to determine both noise exposure time and noise levels are summarized. Finally, examples are given to demonstrate how these formulas are applied.

2. Analytical Noise Assessment Methods

The first step in the noise hazard assessment of a workplace is to construct a noise contour map. This step requires safety personnel to measure workplace noise levels. Typically, some objectives of noise measurement are to evaluate working conditions which may be potentially hazardous to workers, to determine if the work environment is acceptable, and to establish noise contours of the facility. Readers are suggested to consult Wells [5] for further discussion about noise measurement procedures.

To define noise problems or to identify potential hazardous areas, it is necessary to measure sound levels in the workplace. There are a few principles which should be followed when measuring sound levels [1]. They are: (1) use the proper equipment and microphone, (2) use equipment which is well calibrated and in

good working order, (3) keep away from reflecting surfaces, (4) hold the equipment at arm length to avoid sound reflections from the body and the blocking of sound from particular directions, (5) shield the equipment and microphone if wind noise is present, and (6) do not take the reading too close to or too far away from the machine.

2.1 Constructing Noise Contour Map

To construct a noise contour map, several noise measurements are taken at different locations throughout the workplace. If the noise level tends to fluctuate with time, it is recommended that several noise levels at each location be recorded at different times. Its average value is then used as a representative noise level for that location. This procedure is found to be time consuming and may interfere with on-going manufacturing activities. Additionally, if a new machine is added in the facility, a new noise contour map must be constructed. Here we present an analytical procedure for constructing a noise contour map.

Nanthavanij *et al* [6] suggested the following analytical, step-by-step procedure for constructing a noise contour map. The procedure consists of three initialization steps and four computation steps. They are briefly described as follows.

Initialization

Step 1: The layout of the entire area must be obtained and the locations of all existing machines (or noise sources) must be plotted on the layout map. Since the computation requires the assumption of a pointed source, each machine must be represented by a point on the x - y plane. By selecting one corner of the layout map as the reference origin (usually the lower left corner), each machine location can be expressed as a pair of x and y coordinates which are measured from that reference point.

Step 2: The ambient noise level (in decibel- A , dBA) and sound levels (in dBA) of all existing machines must be determined. The measurement of the ambient noise is taken when machines are not operating. To obtain reliable data, it is recommended that several measurements be taken, from different

locations and at different times. The average sound level is calculated and used as the ambient noise level of the area. Machine sound levels are more difficult to measure since it may not be possible to isolate each machine in order to measure its generated sound level. If applicable, obtain the machine sound level when other machines are not in the operation mode.

Step 3: Next, the layout map must be divided into grids. The dimension of the grid depends on the size of the area and the required degree of accuracy of the noise contours. If the area is large and/or high degree of accuracy is required, the number of grids will be large (i.e., the grid size will be small). However, the more the number of grids, the longer time it takes to construct the noise contour map.

Computation Steps

Step 1: Convert the ambient noise level L_{ab} (in dBA) into sound intensity I_{ab} (in watts per squared meter, W/m^2) using

$$I_{ab} = 10^{\frac{L_{ab}-120}{10}} \quad (1)$$

Step 2: At each grid corner, convert the sound level of the machine that reaches the grid corner into its sound intensity. Firstly, the machine sound level (as measured at 1 meter from the source) is converted into sound intensity using Eq. 1. Then, its sound power P (in watts, W) is calculated by assuming that $d = 1$ m. As the distance from the source increases, sound intensity I decreases according to the inverse square law such that $I = [P/4\pi d^2]$. Thus, at location i , the sound intensity of machine j at distance d (in meters), I_{ij} , can be determined from

$$I_{ij} = \frac{10^{\frac{L_{ij}-120}{10}}}{d_{ij}^2} \quad (2)$$

where d_{ij} = Euclidean distance between location i and machine j
 $= [(x_i - x_j)^2 + (y_i - y_j)^2]^{1/2}$

$x_i, y_i = (x, y)$ coordinates of location i

$x_j, y_j = (x, y)$ coordinates of machine j .

Step 3: At location i , calculate the combined sound intensity \bar{I}_i from n machines using

$$\bar{I}_i = I_{ab} + \sum_{j=1}^n \frac{10^{\frac{L_{ij}-120}{10}}}{d_{ij}^2} \quad (3)$$

Step 4: Reconvert the combined sound intensity to sound level using the formula

$$L_i = 10 \log_{10} \left[\frac{\bar{I}_i}{I_0} \right], \quad (4)$$

where $I_0 = 10^{-12}$ watt/m²

Step 5: Repeat Steps 1-4 for all grid corners.

Using the above procedure, sound levels at all predetermined coordinates can be computed. The noise contour map is then constructed by drawing lines connecting points having equal sound level.

2.2 Identifying Noise Hazardous Areas

After the noise contour map is constructed, the next step is to determine the noise hazardous areas. In this paper, it is assumed that the acceptable noise exposure limits are based on the noise standards set by the Occupational Safety and Health Administration (OSHA) of the U.S. Department of Labor.

OSHA [7] has established permissible noise exposure limits for industrial workers. The OSHA reference specifies the permissible noise levels and exposure durations. The higher the exposed noise level, the shorter the reference duration is. Given the exposed noise level \bar{L} (measured using an A -weighted sound meter), the reference duration T (in hours) can be determined from

$$T = 8 \left[2^{\frac{L-90}{5}} \right]^{-1} \quad (5)$$

The reference duration determined from Eq. 5 indicates the maximum recommended

amount of time per 8-hour workday that a worker should be continuously exposed to the noise level \bar{L} . From the formula it is seen that the permissible exposure duration (continuous exposure) to the 90-dBA noise environment is 8 hours. For every 5 dBA increment, the permissible exposure time is decreased by half. And, vice versa.

Using the estimated noise contour map, areas where the noise level exceeds 90 dBA can be identified. Workers in such areas are then required to wear appropriate hearing protection devices as part of the noise control program.

2.3 Determining Daily Noise Dose and 8-hour Time Weighted Average Sound Level

The computation of the permissible exposure duration discussed in the previous section is based on an assumption of continuous exposure. When a worker has to work in several work areas and is exposed to different noise levels during an 8-hour workday, Eq. 5 must be modified to determine the correct (daily) noise exposure. By knowing the noise level of a given work area and the exposure duration, a partial noise exposure amount (dose) can be calculated. The total or daily noise dose is then equal to the sum of the partial doses.

Letting \bar{L}_i be the combined noise level (in dBA) of work area i , C_i the length of duration (in hours) a worker stays in work area i , T_i the theoretical permissible exposure duration (in hours) if the worker stays in work area i for the entire 8-hour workday, a partial noise dose D_i is calculated from

$$\begin{aligned} D_i &= \frac{C_i}{T_i} \\ &= \frac{C_i}{8} \left[2^{\frac{\bar{L}_i - 90}{5}} \right]. \end{aligned} \quad (6)$$

Letting m be the number of work areas, the daily noise dose D_T (in percent) is determined by summing all partial noise doses.

$$\begin{aligned} D_T &= 100 \sum_{i=1}^m D_i \\ &= 12.5 \sum_{i=1}^m C_i \left[2^{\frac{\bar{L}_i - 90}{5}} \right]. \end{aligned} \quad (7)$$

The daily noise dose of 100 percent is designated as the permissible exposure level.

In order to express the noise exposure level in dBA, the daily noise dose can be converted into an 8-hour time-weighted average (TWA) sound level. The TWA is the equivalent sound level (in dBA) that would produce a given noise dose if a worker were continuously exposed to that sound level over an 8-hour workday. The formula for calculating TWA is given below.

$$\begin{aligned} \text{TWA} &= 16.61 \left[\log_{10} \frac{D_T}{100} \right] + 90 \\ &= 16.61 \left[\log_{10} \left\{ \sum_{i=1}^m \frac{C_i}{8} \left(2^{\frac{\bar{L}_i - 90}{5}} \right) \right\} \right] + 90 \end{aligned} \quad (8)$$

If one is continuously exposed to a 90-dBA noise environment for 8 hours, it can be shown from Eqs. 7 and 8 that the predicted daily noise dose and TWA are 100% and 90 dBA, respectively.

Similar to $D_T = 100\%$, a TWA of 90 dBA is designated as the permissible exposure level for an 8-hour workday. For more discussion on the above topics, consult [7].

3. Numerical Examples

To demonstrate the application of the proposed analytical noise assessment procedure, we consider the production facility of an electric appliance manufacturing company. The factory produces plastic bodies, shells, frames, and parts for final assembly. The process consists of three steps, namely, injection, finishing, and paint screening. Our main interest here is the plastic injection which is considered to be common among all parts. The data used in the analytical assessment of noise hazard is hypothetical.

The plastic injection facility occupies 1,944 m² (36 m × 54 m) and consists of the following departments. (The numbers in the parentheses are department areas.)

1. Raw materials stock room (262 m²)
2. Resin-pigment mixing room (74 m²)
3. Plastic injection area (532 m²)
4. Injection mold stock room (68 m²)
5. Office (54 m²)
6. Finished parts stock room (116 m²)
7. Cooling Tower area (108 m²)
8. Rest rooms (36 m²)

Initially, a general floor layout of the plastic injection facility showing existing machines, work areas, office, etc. is drawn as shown in Fig. 1. (The figure is not drawn to scale.) Some work areas do not have noise sources while some do (e.g., the resin-pigment mixing area, the plastic injection area, and the cooling tower area). Assuming that the reference origin is at the lower left corner of the layout map, the machine location can be expressed as a pair of x and y coordinates which are measured from the reference origin.

Next the noise levels of all existing noise sources must be determined. There are two mixers in the resin-pigment mixing area, ten injection machines in the plastic injection area, and two cooling towers in the cooling tower area. Table 1 lists the locations of all existing machines and the noise levels generated by individual machines (measured at 1 m from the noise source). It is also assumed that the ambient noise level (when there are no manufacturing activities) is 55 dB_A.

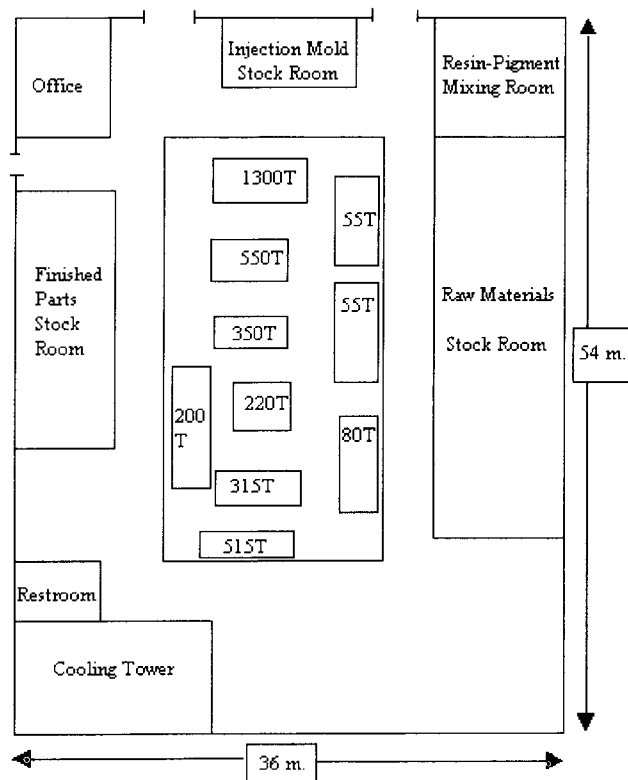


Figure 1: Floor layout of the plastic injection facility

Table 1. Location coordinates and noise level generated by each machine

Facility	Machine	(x, y) Coordinates	Noise Level (dBA)
1	Mixer 1	(32, 52)	80
2	Mixer 2	(35, 52)	80
3	55T Injector 1	(26, 38)	85
4	55T Injector 2	(26, 33)	85
5	80T Injector	(26, 26)	85
6	200T Injector	(14, 22)	90
7	220T Injector	(20, 23)	90
8	315T Injector	(19, 20)	90
9	350T Injector	(18, 30)	90
10	515T Injector	(18, 13)	95
11	550T Injector	(18, 35)	95
12	1300T Injector	(19, 40)	100
13	Cooling Tower 1	(4, 6)	95
14	Cooling Tower 2	(7, 6)	95

Firstly, the noise contour map of this plastic injection facility is constructed by following the initialization and computation steps in Section 2.1. The factory layout map is initially divided into grids. The grid dimensions used in this analysis are 1 m × 1 m (width × length). At each grid corner, the combined noise level is estimated using Eqs. 1 - 4.

For example, consider a location designated by (15, 30) which is near the 200T Injector and the 350T Injector. The computation starts by firstly converting the ambient noise level (in dBA) into noise intensity (in W/m²). Using Eq. 1, I_{ab} is 3.1623×10^{-7} W/m². Secondly, the noise intensity of machine j , for $j = 1$ to 14, measured at (15, 30) is calculated from Eq. 2. Table 2 shows the noise intensity of each machine at location (15, 30).

Then, the combined sound intensity \bar{I}_i at (15, 30) is calculated from Eq. 3.

$$\begin{aligned}\bar{I}_i &= 3.1623 \times 10^{-7} + [(1.2939 \times 10^{-7}) + \dots \\ &\quad + (4.9404 \times 10^{-6})] \\ &= 3.3291 \times 10^{-4} \text{ W/m}^2\end{aligned}$$

From Eq. 4, we finally obtain the combined sound level \bar{L}_i at (15, 30).

$$\begin{aligned}\bar{L}_i &= 10\log_{10}[(3.3291 \times 10^{-4})/(10^{-12})] \\ &= 85.17 \text{ dBA}\end{aligned}$$

The above steps are repeated for every grid corner. Contour lines are then drawn to connect those points having the same combined sound level. Figure 2 shows the noise contour map of this plastic injection factory. (The map is constructed by a computer program called *Noise Manager* that is written based on the analytical procedure explained earlier.) The label on the right hand side of the map shows the range of noise levels for each color band.

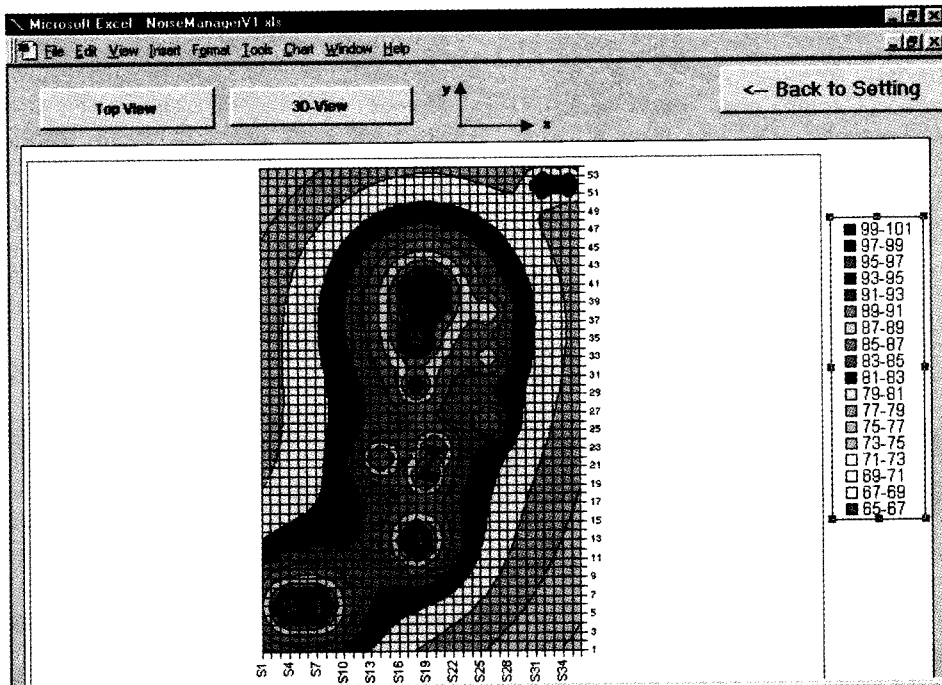
We then use Eq. 5 to determine the reference duration for the worker who is scheduled to work at this location for the entire day. The reference duration for the 85.17-dBA noise environment is

$$\begin{aligned}T &= 8 \left[2^{\frac{85.17-90}{5}} \right]^{-1} \\ &= 15.63 \text{ hours}\end{aligned}$$

It is clear that this worker is not being exposed to noise hazard since the recommended permissible duration (15.63 hours) is longer than the actual exposure time (8 hours). Therefore, the (15, 30) location is not designated as a noise hazardous location.

Table 2. Noise intensities of existing facilities measured at location i (15, 30)

	Machine j	Distance (d_{ij} , m)	Noise Intensity (I_{ij} , W/m ²)
1	Mixer 1	27.80	1.2939×10^{-7}
2	Mixer 2	29.73	1.1314×10^{-7}
3	55T Injector 1	13.60	1.7097×10^{-7}
4	55T Injector 2	11.40	2.4333×10^{-6}
5	80T Injector	11.70	2.3101×10^{-6}
6	200T Injector	8.06	1.5394×10^{-5}
7	220T Injector	8.60	1.3521×10^{-5}
8	315T Injector	10.77	8.6214×10^{-6}
9	350T Injector	3.00	1.1111×10^{-4}
10	515T Injector	17.26	1.0615×10^{-5}
11	550T Injector	5.83	9.3036×10^{-5}
12	1300T Injector	10.77	8.6214×10^{-5}
13	Cooling Tower 1	26.40	4.5372×10^{-6}
14	Cooling Tower 2	25.30	4.9404×10^{-6}

Figure 2: Noise contour map of the plastic injection facility
(The values shown on the map are noise levels in dB(A).)

Using the same method, one can see that if this worker is assigned to work near the 1300T Injector at the (19, 38) coordinates, the combined noise level will be 94 dBA. In this case, T becomes 4.59 hours, which is the maximum amount of time that the worker should be allowed to work in this area. Using Eqs. 7 and 8, the worker's daily noise dose and TWA are found to be 174.11% (exceeding 100%) and 94 dBA (exceeding 90 dBA). Hence, the worker is exposed to noise hazard and the (19, 38) location is designated as a noise hazardous area.

The noise contour map of this plastic injection facility indicates that workers who are assigned to operate the injection machines and those who have to be near the cooling towers are required to wear hearing protection devices or their work schedules must be in compliance with the permissible duration.

Let us consider another example. Suppose that this worker is assigned to work in the raw materials stock room for 2 hours, in the resin-pigment mixing room for 3 hours, and in the injection area for 3 hours. In the mixing room, the worker is stationed at the location (33.50, 52) to operate both mixers. In the injection area, the worker firstly operates the 550T Injector for 1 hour and then the 80T Injector for 2 hours. The designated workstations at the 550T Injector and 80T Injector are at the locations (18, 34) and (24, 26), respectively.

From the noise contour map or from Eqs. 2, 3, and 4, the worker's noise exposure levels in the raw materials stock room and at the mixers, the 550T Injector, and the 80T Injector are 79, 81, 96, and 84 dBA, respectively. The TWA can then be calculated using Eq. 8.

$$\begin{aligned} \text{TWA} &= 16.61 \left[\log_{10} \left\{ \frac{2}{8} \left(2^{\frac{79-90}{5}} \right) + \frac{3}{8} \left(2^{\frac{81-90}{5}} \right) \right. \right. \\ &\quad \left. \left. + \frac{1}{8} \left(2^{\frac{96-90}{5}} \right) + \frac{2}{8} \left(2^{\frac{84-90}{5}} \right) \right\} \right] + 90 \\ &= 85.79 \text{ dBA} \end{aligned}$$

Since the resulting TWA is less than 90 dBA, this work assignment does not impose any noise hazard on the worker.

With the analytical approach described in this paper, the management can predict if the present work conditions are hazardous to workers. When a change (addition of a new

machine or a machine replacement) is anticipated, the effect of the new work condition can be predicted in advance. The result will enable the management to foresee the effect of the change in work conditions and decide if such action is advantageous.

4. Conclusion and Discussion

The procedure presented in this paper shows that noise hazardous areas within industrial workplaces can be predicted by firstly constructing a noise contour map using an analytical method. This map is then used to identify areas which have high noise levels. These areas should be marked as noise hazardous areas since workers who need to be present in these areas over an extended period may be subject to noise hazard. Mathematical formulas are given to help safety practitioners to calculate the daily noise dose and the 8-hour time-weighted average (TWA) sound level. The results can be compared with the permissible levels to determine if workers are being exposed to a noise hazardous environment. With this knowledge and the suggested procedure, safety practitioners can easily develop suitable work assignments to ensure that the workers' noise exposure level does not exceed the permissible level.

Certain assumptions used in this analytical approach may raise some concerns about the validity of the results. For example, machines are considered as pointed noise sources and it is assumed that the noise sources and workers appear on the two-dimensional plane; thus, ignoring their heights. When standing, the workers' ears should be at the height range between 1.50 to 1.80 m, approximately. The noise sources which mainly are industrial machines will be three-dimensional objects, not points on the floor. For each machine, it is reasonable to assume that the height level of the noise source (very likely to be its motor) will be some distance above the floor. In the three-dimensional world, the correct distance (d) between the noise source and the worker can be calculated from

$$d = \sqrt{x^2 + y^2 + z^2},$$

where z is the difference in the vertical heights between the noise source and the workers' ears.

When z is much smaller than x and y , its effect becomes negligible. Thus, z can be dropped from the consideration.

Another concern may arise from the fact that the workplace noise level is time-variant. To make the approach more realistic, safety practitioners can follow the following suggestions. If the noise level fluctuates with time but the variation is quite consistent and small, it is suggested that several noise level measurements be conducted and recorded at different times and the average level be used to represent the workplace noise level. In case that the workplace noise level greatly fluctuates but some patterns may be observed, it is possible to divide the work duration into work periods and the average noise level of each work period can be determined and used as a representative for the workplace noise level (of that time period). For the situation in which the noise level greatly fluctuates and no patterns can be observed, safety practitioners may assume the worst-case situation by using the maximum noise level to represent the workplace noise level.

The noise formulas used in the construction of the noise contour map have been tested in the laboratory to check their validity. The results showed that the predicted sound level at a given location is insignificantly different from the measured value if that location is not near the wall or the corner. In reality, machines are usually located not too close to the wall or the corner to allow easy access. Therefore, the proposed approach is believed to provide valid results.

The major contribution of this analytical approach is its practicality and simplicity. Although the discussion on noise and permissible noise exposures can be found in several ergonomics textbooks, very few practical formulas and examples are given. Here we have shown how noise problems can be investigated using an analytical approach. Safety practitioners can easily predict the combined noise levels at individual workstations

and use the results to determine the TWA. A computer program can be written to calculate and draw a noise contour map of the workplace, and determine the reference exposure duration, daily noise dose, and TWA. This approach thus helps to enhance the occupational workplace safety which will subsequently reduce the number of workers suffering from occupation-induced hearing loss.

Acknowledgments

The research study was supported by the Faculty Research Budget from Sirindhorn International Institute of Technology (SIIT), Thammasat University.

References

- [1] Sanders, M.S. and McCormick, E.J., *Human Factors in Engineering and Design*, McGraw-Hill, New York, 1993.
- [2] Gasaway, D., 1984 NIOSH Compendium Hearing Protector Attenuation, *National Safety News*, November, pp. 26-34, 1984.
- [3] Wilson, C., Solanky, H., and Gage, H., *Hearing Protector Effectiveness*, Professional Safety, pp. 19-24, 1981.
- [4] Casali, J., Lam, S., and Epps, B., *Rating and Ranking Methods for Hearing Protector Wearability*, *Sound and Vibration*, Vol. 21, No. 12, pp. 10-18, 1987.
- [5] Wells, R., *Noise Measurements: Methods*. In *Handbook of Noise Control*, C.M. Harris (ed.), McGraw-Hill, pp. 6-1 - 6-12, 1979.
- [6] Nanthavanij, S., Boonyawat, T., and Wongwanthanee, S., *Analytical Procedure for Constructing Noise Contours*, *International Journal of Industrial Ergonomics*, Vol. 23, pp. 123-127, 1999.
- [7] *Occupational Safety and Health Administration, Occupational Noise Exposure: Hearing Conservation Amendment*, *Federal Register*, Vol. 48, pp. 9738-9783, 1983.