2008-5435/14/63-31-38
INTERNATIONAL JOURNAL OF OCCUPATIONAL HYGIENE
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IJOH 8: 31-38, 2016

ORIGINAL ARTICLE

Empirical Feasibility of an Acoustic Cabin for Reduction the Workers' Exposure to High Frequency Noise in Typical Metal Industry

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Received September 04, 2015; Revised December 09, 2015; Accepted January 27, 2016

ABSTRACT

A practical solution which is sometimes efficient for noise control in the receiver locations is to enclose workers in an acoustic cabin. Accordingly, prediction of the noise insulation performance is regarded as an important aspect of the design a personnel cabin. This study empirically aims to design an acoustic cabin using sandwich panels in a typical metal industry and analyze its effectiveness for reduction the operators' exposure to high frequency noise. Sheet metal was used as main element of the personnel cabin, and it was coupled with damping materials to achieve efficient noise insulation. The simplified prediction equations were used for prediction of noise transmission loss of the main elements (steel sheet). For design of the cabin sandwich wall, based on the primary prediction results, selection of the other materials and their thickness was performed empirically. Determination of the noise reduction performance of the designed cabin was performed based on in situ measurements. The results indicated that all workers were continuously exposed to high noise levels before intervention. However, inside the designed cabin, the exposure levels actually reduced to of 66.6 dB (A) which was much lower than the national exposure limit. The designed cabin showed an overall noise reduction of 20.5 dB (L). The results empirically confirmed where high insulation performance is required; sandwich panels which have adequate mass, low stiffness and high damping can be usually preferred.

KEYWORDS: *Sandwich panels, Acoustic cabin, Noise exposure, High frequency noise, Metal industry*

INTRODUCTION

Noise is one of the most common occupational hazards produced by industrial processes, operations, and work activities. Prolonged exposure to excessive noise can cause permanent sensorineural hearing loss [1]. Noise can also adversely affect on performance and concentration of workers, and increase the risk of work accidents [2]. To protect exposed employees from the adverse effects of noise, a comprehensive hearing conservation program should be implemented by industrial managers [3-4].

Engineering control is considered as the most effective defense and the preferred method to prevent noise exposure in workplaces. Accordingly, the best approach is to eliminate or reduce the noise emissions at its sources. If the noise sources cannot be controlled, then the only alternative approach is to prevent as much of the noise as possible from reaching the worker. The experts responsible for the design and implementation of engineering controls must take into account significant physical, economic, production, and operational constraints [5].

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A practical solution which is sometimes efficient for noise control in receiver locations is to enclose workers in an acoustic cabin [6]. This is often the preferred approach in facilities where there are some noisy sources which can be operated, remotely. In other words, where noisy machines cannot be enclosed or where a few operators tend to a large number of machines, the best solution is to design a personnel cabin. It seems that, it is often more cost effective to build a fully cabin for the operators than to enclose or modify large or numerous items of noisy machines [5].

Acoustic cabin is most practical for those operations, such as product inspection or machine monitoring, where employee movement is restricted to a small area and all time is spent at one station [7-8].

The design concepts for personnel cabin are similar to those for machines enclosures, but since it is used to enclose people, safe access and egress, fresh air supply, and thermal and visual comforts are considered to be critical design considerations [8].

Control of the noise transmission does not always need clear determination of the main cause of noise, but focus principally on the noise frequency spectrum and room acoustic properties for better selection of the acoustical materials [9]. The first step in designing a personnel cabin is to perform an octave band analysis of the noise generated by the different noise sources in workstations.

The second step is to determine the spectral changes required to reduce the noise compared with the noise exposure limits. The performance of personnel cabin can be determined based on two main methods (1) noise reduction (NR), the difference in noise pressure levels between the outside and inside of the cabin, and (2) insertion loss (IL), the difference in noise pressure levels at the receiver location without and with the cabin in place [10-11].

The most important step is to design an enclosure whose insulation characteristics provide the necessary noise spectral changes [5]. The economic feasibility of lowering noise levels with engineering controls is an important factor in deciding whether to design and implement specific controls. Prediction of the transmission loss for walls is regarded as an important aspect of the design a personnel cabin. Calculations methods help us to predict the pre- and post-prevention control measures in terms of cost benefit and efficacy [12].

As mentioned, for design purposes, one must be able to predict noise reduction (NR) of the proposed cabin. In this regards, firstly, the transmission loss for the cabin walls over a wide range of noise frequencies must be estimated. The general variation of the transmission loss with frequency for a homogeneous is based on three general regions of behavior for the wall included the Region I: stiffness-controlled region, the Region II: mass-controlled region and the Region III: wave-coincidence region (damping-controlled region) [13-14].

The most common empirical methods for calculation of transmission loss of typical panel are based on the three general regions of behavior which has been described in the valid acoustics literatures [14].

Current empirical calculation methods presented up to now are applied for transmission of noise through homogenous, single component panels, while common forms of cabin constructions structured by multi layer walls. The walls of an enclosure may consist of several elements; each of them may be characterized by a different transmission loss [15]. Hence, in real situation, accurate prediction of acoustic performance for complex panels used in the personnel cabin is considered to be a technical challenge.

This study empirically aimed to design a personnel cabin based on light sandwich panels in a noisy process of typical metal industry and analyze its effectiveness in reducing operators’ exposure to high frequency noise.

MATERIALS AND METHODS

This study was performed in cutting unit of the Saveh Rolling and Profile Mills Company located in Markazi Province, central Iran).

Steel coils are cut to the required widths (pipe circumference), and then transported to production line. Due to the diversity of products, coils of different specifications, width, and thickness are used. In this unit, numbers of slitting machinery are programmed to perform these tasks. The operators of large slitting machines as common used metal coil cutting equipments are exposed to high noise level in their workstations as shown in Fig 1. Different steps for design and evaluation of personnel cabin for operators of slitting machines are presented as follows.

Fig 1. The workstation of the noise exposed operators in the cutting unit

Assessment of operators' noise exposure: Personal noise exposure was measured using a noise dosimeter, TES-1354, in the workstations of workers according to ISO 9612 [16]. The noise dosimeter was calibrated using TES-1356 sound level calibrator. Note that, all operators are working all the time at the same workstations. The output of a typical dosimeter frequently includes the equivalent noise level, in units of dB (A). In this way, the noise dosimeter was clipped to the workers' clothes with the microphone close to the ear.

Design of acoustic cabin: The acoustic cabin is designed in accordance with the ISO 15667 and ISO 11546 standards based on the light structure of sandwich panel [8, 11]. The noise exposure limits is used to specify acceptable exposure levels in occupied spaces for hearing preservation, and annoyance. The occupational exposure limit of 85 dB (A) for 8 h per day is recommended by the Iranian center for occupational and environmental health. Determination of the noise reduction performance of acoustic cabin was performed using in situ measurements based on the ISO 11957 [10]. For characterizing the acoustical performance of a typical cabin, if the sound fields can be considered to be reverberant on the two sides of a complete cabin, then the noise reduction (NR) can be calculated as Equation 1 [15].

Equation 1: $NR = LP_1 - LP_2 = TL + 10\log\frac{A_2}{S_e}$

Where LP_1 and LP_2 are the noise pressure level on the transmission and receiving sides of the cabin, A_2 is the effective absorption area inside the cabin, TL is the transmission loss of the walls of the cabin, and S_e is the surface area (walls) of the cabin. In this way, the measurements of noise level along with frequency analysis in one octave band were conducted using the sound level meter Cell-450.

Calculation methods of transmission loss: In the preliminary design, it is often required to estimate the transmission loss spectrum for an acoustic panel. As mentioned, the general variation of the transmission loss of the panel is based on three general regions of behavior. The first resonant frequency of panel (f_{11}) as boundary between Region I and Region II is calculated as Equation 2 [14].

Equation 2: $f_{11} = 0.4534\ c_L h\left[(\frac{1}{a})^2 + (\frac{1}{b})^2\right]$

Where c_L is the longitudinal sound wave speed (m/s), h is the thickness of panel (m), a and b are the width and height of panel (m).

Based on the Equation 2 , if the panel dimensions (a) and (b) are at least 20 times the panel thickness (h), the first resonant frequency for the panel is principally less than 125 Hz, so the main portion of the transmission loss curve will consisting of the Regions II and III [14]. A practical method for calculation of the transmission loss curve for the Regions II and III is as follows. Transmission loss (dB) in the Regions II is calculated from Equation 3 [17].

Equation 3: $TL = 20\log(M_S) + 20\log(f) - 47.3$

Where MS is surface mass (kg/m2), f is frequency (Hz), ρ is density (kg/m3), and Z1 is characteristic impedance of air.

Note that, the total specific mass of the sandwich panel is equal to the sum of specific masses of the panel elements. The critical or wave coincidence frequency (f_c) as boundary between the Region II and the Region III are calculated as Equation 4 [14]:

Equation 4: $f_c = \frac{C_a^2}{1.8\times C_L\times t\times \sin^2\alpha_i}$

Transmission loss (dB) in the Region III: wave-coincidence region is calculated from Equation 5 [14].

Equation 5:

$$TL = TL_n(f_c) + 10\log(\eta) + 33.22\log(f/f_c) - 5.7$$

Where

$$TL_n(f_c) = 10\log\left[1 + (\frac{\pi M_S f_c}{\rho_1 c_1})^2\right]$$

A cabin walls will be frequently composed of two or more elements, i.e., doors, windows, etc., and the average transmission loss of the composite wall can also be calculated [18].

RESULT

Characterizations of the acoustic cabin: The personnel cabin is designed based on the light structure of sandwich panel. Generally, if the materials are suitably used, the acoustic performance of sandwich panel is sufficient in terms of transmission loss. The dimensions of the designed cabin were 7 m × 3.8 m × 3 m. Three windows with size of 1.8 m × 0.75 m in each longitudinal wall of cabin, four windows with size of 0.75 m × 0.75 m in transverse walls were included. The cabin windows have the double glazing glass and surface density of 7 kg/m^2. A door with size of 2 m × 0.80 m, 47 mm thickness and surface density of 49 kg/m^2 were also used. General ventilating system and accessories were provided. The structure and chassis was fabricated by heavy profiles with size of 80×80 mm. The designed sandwich panel with total surface density of 49 kg/m^2 for the acoustic cabin as (Fig 2) was structured as follows:

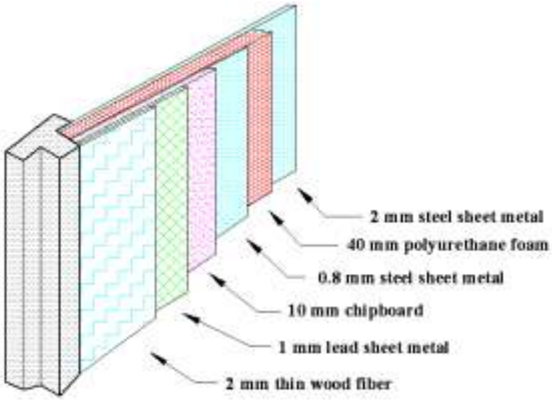

Fig 2. Detail structure of the complex sandwich panel of the acoustic cabin

A) Outer shell, 2 mm steel sheet, as main elements of the panel, with a minimum mass per unit area of 16 kg/m^2. Based on Equation 2, the first resonant frequency of the proposed panel was much lower than 125 Hz. The longitudinal sound wave speed (m/s) for basic material of the panel (steel sheet) was 5046 m/s. The critical or wave coincidence frequency (f_c) as boundary between Region II and Region III based on Equation 6 was 6465 Hz. Note that, steel sheet metal has damping coefficient of 0.0013.

The results of the predicted transmission loss of 2 mm steel sheet based on one octave spectrum of noise level were shown in Table 1.

Additional insulating performance can be obtained by using damping materials as the inner layers of the sandwich panel as follows:

B) Absorbent lining on the inside as damping layer, 40 mm polyurethane foam with a minimum mass per unit area of 2 kg/m^2 , was used as filler within the panels. Note that, polyurethane foam has damping coefficient of 0.48.

C) Inner layer, 0.8 mm steel sheet, with a minimum mass per unit area of 8 kg/m^2.

D) 10 mm chipboard with the surface density of 7 kg/m^2 was used for covering the steel sheet. Note that, chipboard has damping coefficient of 0.03.

E) The middle heavy layer, 1 mm lead sheet, with a minimum mass per unit area of 13 kg/m^2. Lead sheet has damping coefficient of 0.015.

F) 2 mm soft wood fiber with medium density fiberboard with the surface density of 3 kg/m^2 was used for covering the lead sheet as interior wall coverings. The chipboard has damping coefficient of 0.008 and has a good sound absorption coefficient about 0.3.

G) The floor of cabin was constructed from plywood for all types of weathers and PVC floor covering.
For design an acoustic cabin, it is firstly important to determine the critical frequency of the main elements of the panel materials. The critical frequency of 2 mm steel sheet was 6465 Hz which was far above the dominant frequency of our main noise sources (4000 Hz).

Table 1. The predicted noise transmission loss of steel sheet in one octave spectrum

Frequency (Hz)	31.5	63	125	250	500	1000	2000	4000	8000
Transmission Loss (dB)	6.7	12.7	18.7	24.7	30.76	37	42.8	48.8	25.9

The factor limiting the acoustical performance of cabin is often the number and size of acoustical leaks. Therefore, door, windows, and walls of the designed cabin were well sealed at edges, interior surfaces of cabin were covered with sound absorptive material, and ventilation openings were provided with acoustic attenuators. Based on chart for calculating the effect of acoustical leaks, the maximum opening of 0.1% was considered [15]. The outside and inside of the designed personnel cabin were shown in Figs 3 and 4.

Performance of the acoustic cabin: The results of personal noise exposure level in dB (A) during different operations in the cutting unit before intervention were shown in Table 2. This indicates that compared with the national occupational exposure limit (85 dB (A) for 8 h per day), almost all workers were continuously exposed to high noise levels.

Inside the designed cabin, the workers exposed to equivalent noise level of 66.6 dB (A) which was even lower than national noise criteria for operator’s cabin. Noise criteria are used to specify acceptable background noise levels in occupied spaces for speech communication, and annoyance. Equivalent noise limit of 75 dB (A) as noise criteria is recommended by the Iranian center for occupational and environmental health for design operator’s cabin in industrial environments.

Determination of the noise reduction performance of the designed cabin showed that the overall noise level inside the cabin was measured to be 79 dB (L) while the noise level outside the cabin was measured to be 99.5 dB (L). Based on in situ measurements, the sandwich panels of the designed personnel cabin showed an overall noise reduction of 20.5 dB (L).

Fig 3. The outside of the designed acoustic cabin

Fig 4. The inside of the designed acoustic cabin

Fig 5 provides variations of noise emission levels in dB (L) in one octave band inside and outside of the designed cabin. As shown in Fig 5, the dominant frequency of noise emission is 4000 Hz. Accordingly, the sandwich panels of designed personnel cabin showed high noise reduction in high frequency noise.

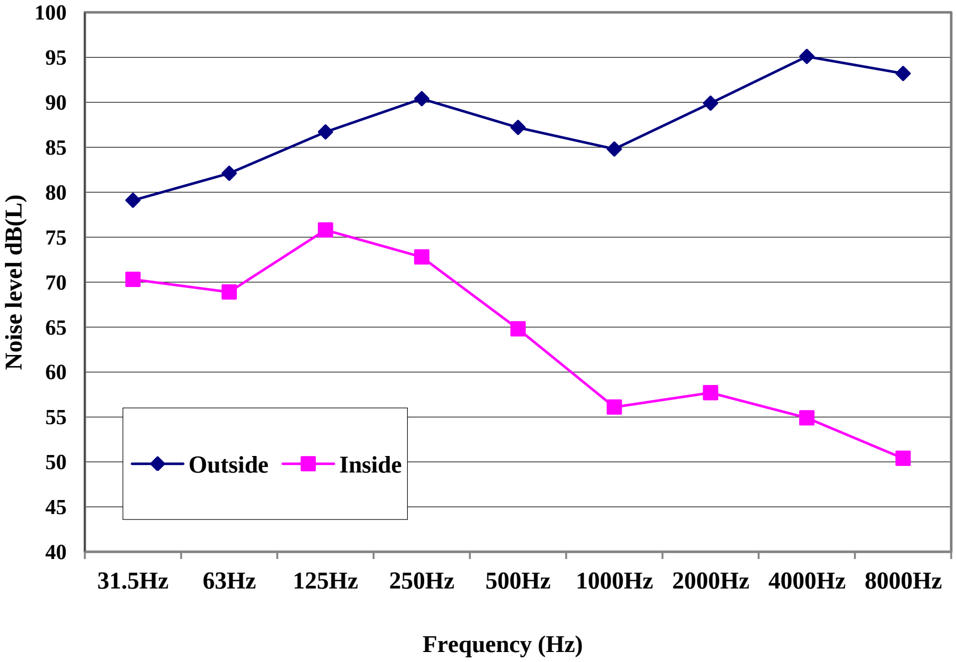

Fig 5. The variations of noise levels inside and outside of the designed cabin

The noise reduction in the dominant frequency of 4000 Hz is equal to 40.2 dB. However, the noise reductions in the low frequencies were noticeably low compared with the high frequencies. Use of high internal damping materials could increase the effectiveness of transmission loss in the high frequency noise.

Since the coincidence phenomenon depends on flexural bending of the material, in the current study, use of high internal damping materials could minimize the effect of coincidence phenomenon. Steel as the main element of the designed sandwich panels have little internal damping and therefore can vibrate for a long time when struck, while the employed inner materials such as foam or lead have high internal damping and could effectively reduce the transmission loss.

DISCUSSION

All workers were continuously exposed to high noise levels compared with the national occupational exposure limit (85 dB (A) for 8 h per day). Design of acoustic cabin could efficiently reduce noise exposure levels in the workstations. Scientific literature confirmed that the noise reductions of 20 to 30 dB are common with full acoustic cabins and the noise reduction about 50 dB can be achieved along with special treatment for the acoustic cabins [19]. Therefore, for the designed acoustic cabin, the additional performance can be achieved through reducing the negligible acoustical leaks if practically possible.

The performance of the complex lightweight panel of the designed cabin was noticeably high in the high frequencies compared with the low frequencies. The results showed that within the range of practical interest, the most effective way of increasing transmission loss is through increasing the inner layer mass density. Compared with the heavy structure of building materials, the designed sandwich panel could reduce weight and space restrictions while providing adequate noise reductions. The coincidence effects related to steel sheet could minimize using inner layers with different damping materials and thicknesses. Coincidence dips are a problem for materials with low internal damping and high bending stiffness (such as metals) [20]. Steel sheet has very low damping characteristics. The results empirically confirmed where high insulation performance is required; the sandwich panels which have adequate mass, low stiffness and high damping can be usually preferred. Note that, the noise reduction potentials of applying damping materials derives from the fact that when the mechanical energy is dissipated, it is not reradiated in the form of airborne noise or conducted along structurally [21].

However, the costs of application sandwich panel are usually higher than the common building materials. In this study, the cost of providing each square meter of the designed sandwich panel was $180. Since the satisfaction of the production managers and workers, design and application of the new acoustic cabins were performed in the other noisy units of the studied industry.

The empirical equations for estimation of the transmission loss curve are presented for relatively simple and homogenous panel constructions [15, 22-23]. In practice, the sandwich panels employed for design of the acoustic cabin are usually much more complicated in terms of construction. The design goal of acoustic cabin is to find a set of materials and geometric parameters that produced the highest noise transmission loss. In these cases, the estimation of the transmission loss curve by the existing empirical equations cannot be practical and reliable [19, 24]. On the other hands, based on the scientific literature review, the accurate database about the insulation performance of various type structures of sandwich panels was not existed [14-15].

Therefore, in the primary stage of the current study, the simplified prediction equations of transmission loss were only used for determination of acoustic performance of the main elements (steel sheet) of the panel. In the next stage, based on the performance results of the used steel sheet, selection of the other materials of the designed sandwich panel and their thickness was performed empirically based on ISO standard recommendations [8].

The calculation equations can be applied for multilayer structures which contain a sound-absorbing material inside. However, the equations for calculation of the transmission loss are limited by the range of application. The boundary of these is the so-called coincidence frequency. These equations are valid only for mass law below the coincidence frequency [7]. The other approaches such as the ray-tracing models have been used for the prediction of the noise insertion loss of the acoustic cabins [25].

Sound transmission loss of the multi layer panels can be also calculated based on the complex wave based equations [26]. The wave based method is used to predict the airborne and structure-borne sound insulation of single and sandwich panel. These prediction models in building acoustics often assume infinite structures (like the transfer matrix method) or diffuse sound fields (statistical energy methods) [27] . However, due to huge and complex computational efforts, the use of this deterministic technique is practically restricted. Acoustic professionals practically need to simple empirical method which can be useful in acoustic performance of the various wall structures and may facilitate the preliminary selection of a type structure faster.

Therefore, up to now, the simple empirical equations for transmission loss of the non homogenous sandwich panel commonly used in acoustic cabin have been not developed. For this reason, the current study proposed the experimentally scientific researches about determination of transmission loss of different complex sandwich panels. Following, sound transmission for different structure types of usual multiple layer panels can be provided based on standard method [28].

During the last decades, artificial intelligence methods have offered an interesting opportunity for analyzing the nonlinear and vague information located in the complex phenomena of the actual world [3]. Despite the increasing use of neural networks as a new approach for empirically predicting acoustic performance of absorbents [29, 30], no studies about performance of acoustic multilayer panels in terms of sound transmission loss has been not existed.

Finally, based on new prediction approach, empirical models for transmission loss prediction of the non homogenous panel can be developed.

CONCLUSION

The complex lightweight panels could effectively reduce high frequency noise. Proper design of personnel cabin and proper application of a variety of well-selected materials is critical to optimizing sound insulation properties. The results empirically confirmed where high insulation performance is required; the sandwich panels which have adequate mass, low stiffness and high damping can be usually preferred. Due to lack of insulation performance database for non homogenous panels, this study proposed new experimentally researches about transmission loss determination of the different types of complex sandwich panels. Based on new prediction approach as artificial intelligence, empirical models for transmission loss prediction of the sandwich panels can be developed.

ACKNOWLEDGEMENT

The authors would like to thank managers of Saveh Rolling and Profile Mills Company for providing financial support for this project. Furthermore, thanks to workers for their cooperation. The authors declare that there is no conflict of interests.

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