无锡大剧院的建声设计与主客观音质评价

Architectural Acoustics Design and Subjective and Objective Acoustic evaluation of Wuxi Grand Theater

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Abstract: Wuxi grand theater with 1700-seat audience located in Wuxi, Jiangsu province is a complex theater for performance of opera, symphony, modern drama, drama, dance drama, large-scale variety show and ballet. The requirements of acoustic contain enough sound loudness in the auditorium, appropriate reverberation, uniform sound field, good diffusion, enough early reflection sound and lateral reflection sound, and deficiency of sound effect such as sound focus, echo and flutter echo should be avoided. This is the first theater in mainland which interior material of metope and floor of auditorium and armrest and back of seat are high-density ferula, and also the first one whose main stage, side stage and back stage contain five stages and whose diffusion and reflection ceiling is a center permeable huge disk.

Keywords: Acoustics; Architectural acoustical design; Acoustics evaluation

摘　要：江苏无锡大剧院大剧场（歌剧厅）总容座约 1700 人，是一座可上演歌剧、交响乐、话剧、戏剧、舞剧、大型综艺演出、及芭蕾的综合性演出的剧场。声学设计指标要求要达到观众厅内声音响度足够、混响合适、声场分布均匀，声场扩散良好，有足够的前次反射声和侧向反射声，无声聚焦，回声和颤动声等声缺陷。该大剧场是国内第一个在观众厅内墙面、地面、包括座椅的扶手及后背面全部采用高密度竹板作为主要装饰材料的剧场，舞台是目前国内第一个在主侧台及后台采用五个台的剧场，吊顶天花在国内首次设计为中心通透的类似于大圆盘的扩散反射吊顶。

关键词：声学; 建声设计; 音质评价

1 建筑概况

无锡大剧院位于江苏省无锡市蠡湖风景区，由 1700 座的歌剧厅和 800 座综合演艺厅构成。1700 座歌剧厅是一座可上演歌剧、交响乐、话剧、戏剧、舞剧、大型综艺及芭蕾的综合性剧院。歌剧厅观众厅平面形状呈“马蹄形”，厅内设二层挑台，左右两侧各设延伸侧包厢，台口天花设两排线数组主音箱，吊顶天花设两道明装面光灯，台口两侧墙各设两道明装耳光，两边音箱和面光灯均采用明装形式。观众厅池座后部设音控、灯控室。图 1 和图 2 分别为歌剧厅建筑平剖面和观众厅竣工后的内景照片。

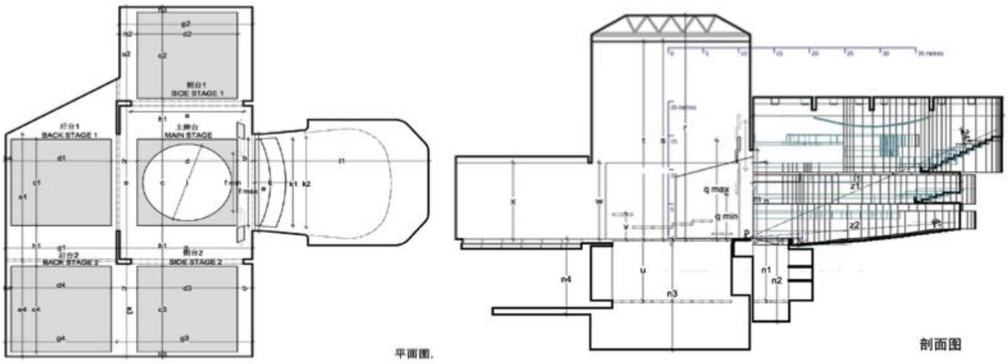


图 1 歌剧厅建筑平剖面

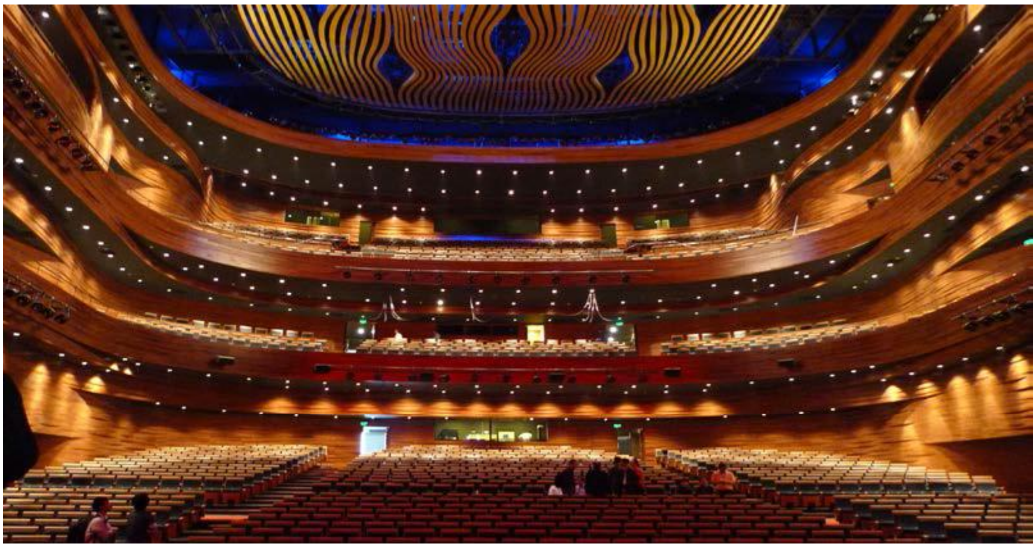


图 2 歌剧厅观众厅内景图

歌剧厅观众厅长约 31.9m；宽约 17.1~28.2m；高约 17.5m。总体积约为 15799m^3，对应单座容积约 9.30 m^3/人。舞台开口：18m×12m，池座最低标高+5.05m；天花设两道面光和一道追光。池座观众席共 25 排，观众席共设二层楼座，一层楼座下部开口高 4.3m，深(至池座最后一排距离)6.0m，高深比为 1:0.72。观众席一层楼座共 5 排。观众席二层楼座共 12 排。观众席前部设升降乐池，深 6.0m，最大宽约 17.8~18.8m，面积为 103m^2，可分别用于乐池，观众席和伸出舞台三种使用功能。

舞台包括一个主舞台、二个大小一致的侧舞台、二个大小不一的后舞台,总面积 2769m^2。舞台面标高为+ 6.00 m。主舞台高 31.0m，侧舞台和后舞台高 12.0m(主舞台设升降设备)。主舞台共设三层马道，离舞台高度分别为：13.6、16.7 及 19.8m 。声光控制室设于池座后墙的中部。反射乐罩开口宽 17m； 开口高 12m； 后挡板宽 9.2m ； 乐罩深 12m, 后挡板高 7m。

2 建声设计主要技术指标

根据本歌剧厅演出的功能定位以及观众厅的规模和容积，上演歌剧时中频混响时间(满场)为 1.60±0.10(s) (f=500～1000Hz),且要求混响时间频率特性为中高频基本平直,但高频允许下降 10～20%，低频混响要求有 10～20%提升。厅内应有足够的前次反射声和侧向反射声。

当上演交响乐时，(舞台上设置音乐反射罩条件下）中频混响时间应提升约 0.15～0.25s，即中频混响时间(满场)为 1.80 秒左右 (f=500～1000Hz)，其低频混响要求有 10～15%的提升，而高频混响则允许下跌 10～20%。交响乐演出及歌剧演出条件下的混响时间及其频率特性如表 1 所示。

表 1 歌剧及交响乐演出条件下混响时间设计目标

演出条件	中心频率(Hz)	125	250	500	1K	2K	4K
歌剧	T_{60}(秒)：	2.00	1.76	1.60	1.60	1.44	1.28
	混响比:	1.25	1.10	1.00	1.00	0.90	0.80
交响乐	T60(秒)：	2.25	1.98	1.80	1.80	1.62	1.44
	混响比:	1.25	1.10	1.00	1.00	0.90	0.80

当剧场上演话剧时，中频混响时间(满场)为: T_{60} =1.30±0.10(s) (f=500～1000Hz)。当剧场上演话剧时，主观众厅内应打开所有布置的可变吸声帘幕，以降低混响时间（在反射吊顶上部及侧墙上部布置了足够数量可变吸声帘幕）以保证上演话剧时的语言清晰度。

剧场内声场不均匀度要求为△L_P≤±4dB。

本底噪声允许值:符合 NR≤25 号噪声评价曲线。

观众厅的音质应保证观众席各处有足够的声音响度、均匀的声场分布、合适的混响特性、足够的早期反射声和侧向反射声，有良好的清晰度和丰满度。观众厅内任何位置上不得出现回声、颤动回声、声聚焦等声缺陷；

侧向反射系数 LF：在 15% ~ 25%之间（要求≥15%）；

声场力度 G：大于 0dB；

早期反射声延迟时间△t ：≤20 ~30ms；

舞台空间内的混响时间要求大幕下落及常用舞台设置条件下舞台空间的中频（500~1000Hz）混响时间与观众厅的空场混响时间相接近，本底噪声与观众厅基本相同；

考虑到歌剧厅上演交响乐的要求，建议歌剧厅观众厅单座容积值宜控制在 8.5 ~ 9.0m^3/人左右为宜。

3 歌剧厅室内声学装修要求及措施

1) 歌剧厅舞台内墙面的吸声处理

由于舞台空间体积比较大，为了避免舞台空间与观众厅空间之间因耦合空间大空间对观众厅音质产生的不利影响，声学设计要求舞台空间内的混响时间应基本接近观众厅的混响时间，最好比观众厅具有更短的混响时间。为此，舞台空间内墙面必须采取吸声处理。

声学设计要求在舞台（包括主舞台、侧舞台及后舞台）一层天桥以下墙面均做吸声处理。

2) 观众厅两侧墙墙面的扩散反射处理

观众厅两侧墙墙面设计成“凹凸条带弧形状”的扩散反射处理。

3) 观众厅后墙墙面的扩散反射处理

观众厅后墙墙面设计成“凹凸条带弧形状”的扩散反射处理。

观众厅墙面布置既可满足声音扩散的要求，同时也具有较强烈的装饰效果。

4) 观众厅内顶棚（吊顶天花）的设计

观众厅内顶棚的设计在很大程度上决定了一个大剧场音质的优劣。

歌剧厅观众厅内中心顶棚设计为中心通透的类似于大圆盘扩散反射吊顶，以增强观众反射声区域。

在通透反射吊顶的上空设计安装了新型箱式电动升降吸声帘幕。

在顶棚上空靠侧边马道下沿也安装了新型箱式电动升降吸声帘幕。

上空吸声帘幕安装约 480 m^2。

5) 挑台栏板和挑台天花声学处理

挑台栏板（外侧面）采用斜形或凹凸弧形结构，这能使前区观众得到较好的反射声，并有利声场均匀扩散。挑台栏板是厅内容易在前区造成回声的部位，建筑及室内设计中都应予以注意。

挑台栏板也可结合表面装饰做一些局部扩散处理，以有利于扩散声波，不至于产生回声、聚焦等声学缺陷。

挑台天花建议采用面密度≥20～25kg/m^{2}材料做吊顶，做成反射面结构，以利声音反射，挑台天花形状为平面或弧线形状。

6) 歌剧厅声闸

为了防止外界噪声通过出入门传入大剧场观众厅，因此出入观众厅的门均采用了双道厚重隔声门以形成声闸，且声闸内墙面均做吸声处理。

7) 观众席座椅的要求

在选择观众厅座椅时，既要考虑其用料、色彩、装饰及舒适性，同时也应重视座椅本身的声学性能，因为座椅的吸声量占整个观众厅总吸声量的比例最大（通常占到 1/2 到 2/3 左右），因此对观众厅内的混响时间指标起到决定性因素。

8) 公共空间的声学要求

大剧院公共空间应有一个安静的环境，特别是大堂空间体量很大，国内有些剧院在设计的过程中很重视剧场内声学效果，忽略公共空间的声学要求，混响时间很长，甚至于相互交谈也发生困难。所以在本项目中对大剧院公共空间的顶部都采取了声学吸声处理，除玻璃幕墙外，其它可做吸声的墙面和大堂顶面都采取了相应的吸声措施。

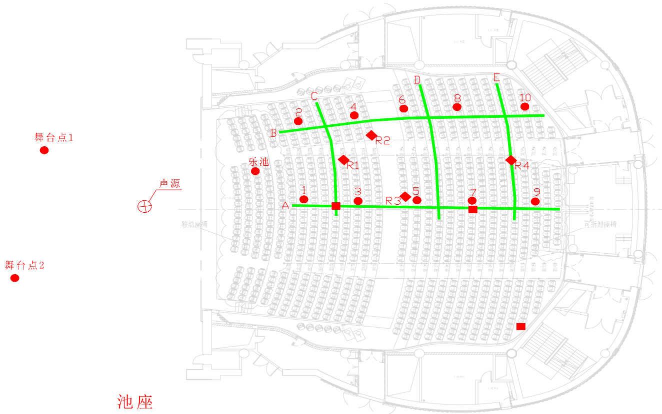
4 大剧院噪声振动控制设计

大剧院的噪声振动控制设计是大剧院声学设计的一个重要组成部分，是至关重要的。为保证大剧院其它相关技术用房内设计的背景噪声指标，除进行特别的建筑声学音质设计外，还必需对剧院中产生噪声振动的设备采取必要的控制措施，具体要求如下：

1) 设备机房噪声控制：包括机房的配置和隔声吸声设计；
2) 空调系统噪声控制： 根据观众厅空调系统设计、机组的选型及相关的技术参数配合空调设计专业确定送、回风管道系统消声处理的技术方案；
3) 配合空调系统施工，提供设备及管道安装连接中的隔声、隔振技术措施；
4) 大剧院内各种机电设备隔振降噪技术措施（包括空调机组、热泵、冷却塔、水泵、变压器房等）。

5 大剧院竣工后观众厅内主、客观音质评价

为检验歌剧厅的实际音质效果，2012年4月对观众厅进行了现场音质测试。主要建筑声学测量内容包括：观众厅内混响时间（空场）T30、早期衰减时间EDT、音乐透明度C80、语言清晰度D50、侧向反射系数LF、声场力度G、声场不均匀度△Lp、厅内本底噪声LA等主要声学参量。 同时，还分别对顶部可升降吸声帘幕和舞台音乐反射罩对观众厅内混响时间的可调幅度作了检测。剧场观众厅音质测试测点布置见图3~5。测试结果如表2所示。



池座

注：● 表示空场混响测点（十二个点）；◆ 表示满场混响测点（四个点）；
■ 表示本底噪声测点；
— 表示声场不均匀度测点（三横二纵43个点）；

图3 歌剧厅池座观众席声学测点布置图

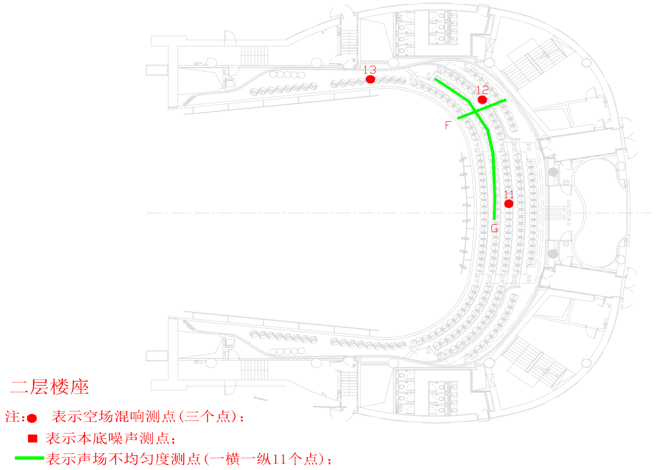


图 4 歌剧厅二楼观众席声学测点布置图

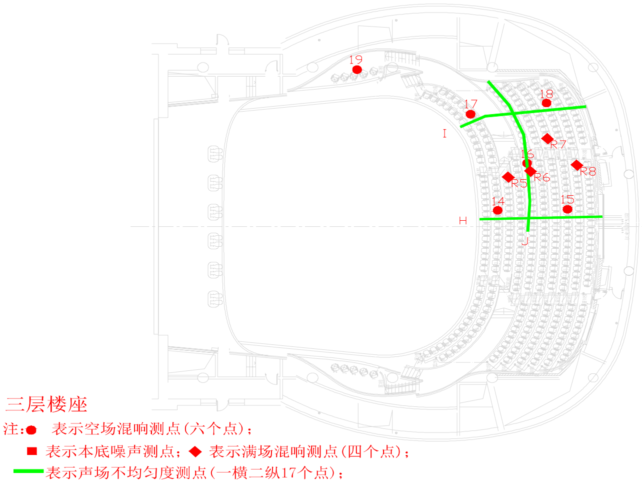


图 5 歌剧厅三楼观众席声学测点布置图

表 2 歌剧厅观众厅内音质测试结果

参量	**倍頻帶中心頻率 *f*（Hz）**					
	125	250	500	1000	2000	4000
T_{30} /s（空场，吸声帘幕全部打开）	1.69	1.61	1.59	1.52	1.46	1.34
T_{30} /s（空场，吸声帘幕全部关闭）	1.67	1.71	1.70	1.62	1.56	1.42
T_{30} /s（空场，加乐罩，吸声帘幕全部关闭）	1.61	1.86	1.88	1.92	1.84	1.66
T_{30} /s（满场，吸声帘幕全部关闭）	1.80	1.47	1.56	1.43	1.40	1.24
EDT /s	1.35	1.45	1.50	1.43	1.38	1.24
C_{80} /dB	1.33	1.65	1.97	2.20	2.50	3.48
D_{50}	0.37	0.46	0.47	0.48	0.50	0.55
LF	0.38	0.37	0.37	0.36	0.38	0.46
G /dB	2.85	3.78	5.55	4.53	5.17	6.58
ΔLp /dB	±4.6	±3.0	±2.8	±2.9	±2.7	±2.6

混响时间是建声设计中最重要的音质评价指标，由表 2 可以得出，吸声帘幕完全升起关闭时场内空场 19 点平均中频（500 Hz~1000 Hz）混响时间为 1.66 秒，吸声帘幕完全下降打开时场内空场 19 点平均中频（500 Hz~1000 Hz）混响时间为 1.50 秒， 当舞台加装乐罩时，空场 19 点平均中频（500 Hz~1000 Hz）混响时间提高到 1.9 秒，混响特性总体较满意，都符合设计预期要求。混响时间实测结果表明舞台音乐罩及升降吸声帘幕的共同使用，可使观众厅内的混响时间得到 0.4 秒左右的变化幅度。乐罩和升降吸声帘幕

各起到了一半的作用。

表 2 同时表明，实测低音比 BR 值平均为 1.15,高频混响仅略有下跌，清晰度 D50 参数主要用于评价观众厅内的语言清晰度，观众厅内中高频（500~4KHz）平均 D50 值为 0.50 左右、达到该歌剧厅音质设计的预期要求。

从厅内音乐明晰度指标 C80 值实测结果分析可见，观众厅的 C80（3）平均值为 3.36dB、，达到该厅 C80（3）的设计预期要求范围值，表明厅内有较好的音乐明晰度和语言清晰度。

本次现场测量还利用先进的可调指向性测试话筒对歌剧厅观众厅进行了侧向反射声系数 LF 值的测量，结果表明观众厅全频 LF 值达 0.36~0.46，中频平均达 0.37。表明本歌剧厅有很好的侧向反射声系数，侧向反射声十分丰富，这也说明观众厅的平面体形设计和声场扩散处理都是十分成功的。

观众厅内池座和楼座共 71 个测点各频率的建声平均声场不均匀度为≤±3.1dB。表明观众厅的声场十分均匀，都符合设计预期要求，可见观众厅的平面体形设计是科学合理的。

歌剧厅观众厅内空调开时实测本底噪声仅为 28dBA,达到并优于空调噪声与振动控制设计的预期要求。

从半年多来的演出使用表明，无锡大剧院歌剧厅的音质效果得到了业主单位，国内外演出院团和众多观众的好评。

6 结语

无锡大剧院作为国内第一个在观众厅内墙面、地面、包括座椅的扶手及后背面全部采用高密度竹板作为主要装饰材料的剧场，也是目前国内第一个拥有五个台的剧场。其建筑设计无疑是成功的，而通过国内外建声设计团队的紧密合作，歌剧厅的客观音质测试结果及主观听音评价结果均表明建声设计也是相当成功的。

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Architectural design: Finland PES- architects Design Team
Shanghai institute of architectural design & research，Shanghai Xian Dai Architectural Design(group) Co. Ltd
Overseas architectural acoustic design: Belgium Kahle Acoustics
Inland architectural acoustic design: Zhang Kuisheng Acoustical Design and Research Studio, Shanghai Xian Dai Architectural Design(group) Co. Ltd

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Abstract: A shear type tuned mass damper has been developed to reduce rail noise radiation and rail corrugation. The oscillation masses in the rail damper are designed to vibrate along the shear direction of resilient layers such that they absorb rail vibration in both vertical and lateral directions. Rail damper design parameters were optimized for rail vibration reduction for frequency range of 300-4000Hz. For critical low frequency (300-1000Hz), damping is provided by tuned mass damping using multiple oscillation masses. For high frequency (1000-4000Hz), damping is provided by viscous layers. The mechanical loss factor of resilient materials are chosen such that each oscillation mass provide effective vibration absorption for a frequency bandwidth of 25 – 35%. The rail dampers were installed in operational railway lines in Hong Kong to test the noise and vibration reduction performance. Rail vibration was reduced by ~10dB while noise level was reduced by 3 to 4 dB(A). Rail corrugation growth was slowed down by ~45%.

Key words: Rail damper; Rail Noise and Vibration Control; Rail Corrugation Control

摘要：本文討論一種新類型的調諧質量阻尼器對於鐵軌噪音及波磨的抑制。這種阻尼器能夠利用彈性材料的剪切變形，同時吸收鐵軌的竪直方向和橫向的振動。阻尼器的設計參數進行了優化使其函括了鐵軌振動頻率(300-4000Hz)。它利用多個共振質量透過調諧質量阻尼吸收低頻振動(300-1000Hz)，利用黏性層吸收高頻振動(1000-4000Hz)，并且透過選擇合適的阻尼損耗因子，使每個調諧質量對 25－35%頻寬內的振動有效地吸收。該阻尼器已被安裝到運行中的路軌段進行測試。鐵軌振動減低了 10 分貝，A 加權噪音則減低了 3 到 4 分貝。而且鐵軌波磨的增長亦被減低約 45%。

关键词：鐵軌阻尼器；鐵軌噪音及振動控制；鐵軌波磨控制

1 INTRODUCTION

Railway noise and vibration control becomes a critical concern in environmental impact assessment when many new residential developments are built close to railway lines as a result of Transit Oriented Development in Hong Kong. Conventionally noise barriers and enclosures are used to mitigate noise impact along its transmission path. However erection of noise barriers in existing railway is usually restricted in many cases owning to structural loading, ventilation, aesthetic concerns, etc. In the past two decades, rail dampers are being extensively investigated to control rail noise at source [1,2,3,4,5].

On the other hand, rail corrugation leads to exceptional annoying noise levels at many curve locations. It significantly increases wheel/rail interaction noise at a particular frequency band corresponding to the corrugation wavelength. Frequent rail grinding would control rail corrugation and reduce rail noise emission, but reduces rail service life and increases maintenance costs. In this decade, use of rail dampers to control rail corrugation has been studied theoretically by various researchers [6,7,8]. However there is very limited on-site verification of the theory. An investigation project at operational metro railway was launched to examine the effect of rail dampers on noise reduction and corrugation growth slowing down.

2 DAMPER DESIGN

The rail dampers installed at the test site were of a shear oscillation type Tuned Mass Damper developed by Wilson Acoustics Limited. A sample is shown in Figure 1. Every damper comprises multiple oscillation masses sandwiched between resilient layers. For rail vibration in the frequency range of 300-1000Hz, a tuned mass damping mechanism is employed. The shear stiffness and mechanical loss factors of the resilient layers are selected such that each oscillating mass covers a resonance bandwidth of 20-40% depending on frequency. As bending waves propagate along the rail, most of the vibration energy is transferred to the damper and dissipated by hysteresis in the resilient layers. For high frequency rail vibration above 1000Hz, a viscous damping layer is employed for broadband vibration absorption.

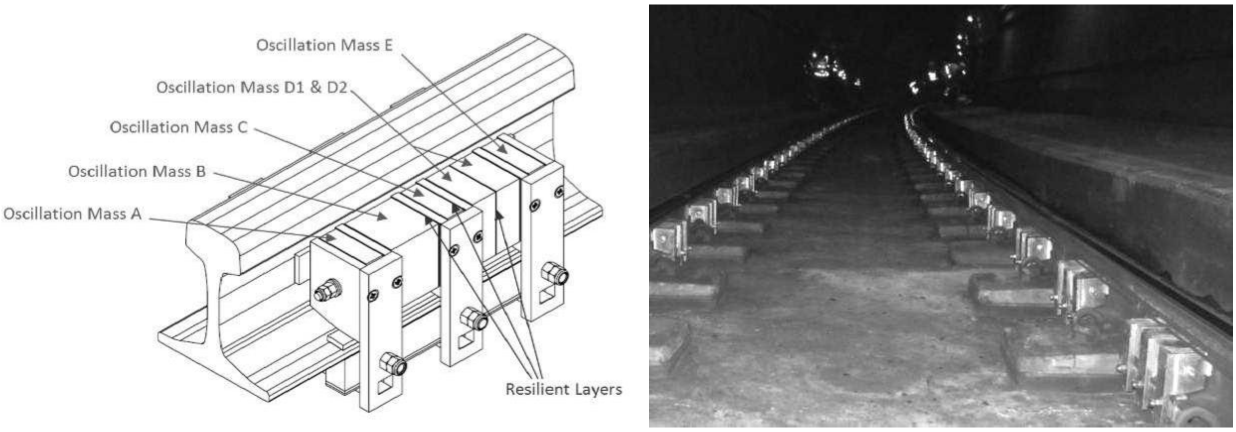

Figure 1 – (a) Rail damper isometric view, (b) dampers installed at the testing site

3 SALOON NOISE REDUCTION

In-saloon noise measurement was conducted at the trailer car of a non-passenger control train with a microphone installed at 1.2m above floor level. PA was switched off throughout the measurement. The dB(A) noise level reduction is depicted in Figure 1, each measurement is the average of 3 train pass-bys. Saloon noise level time history is shown in Figure 2.

Table 1 – Average saloon noise level

Measurement Date	Time after Damper Installation	Months from Last Grinding	Noise Reduction, dB(A)
22/07/2010	Before Installation	4 months	N/A
26/07/2010	1 Day	4 months	2.7
11/08/2010	2 Weeks	4 months	2.8
25/01/2011	6 Months	2 months	2.5
24/06/2011	11 Months	7 months	1.7

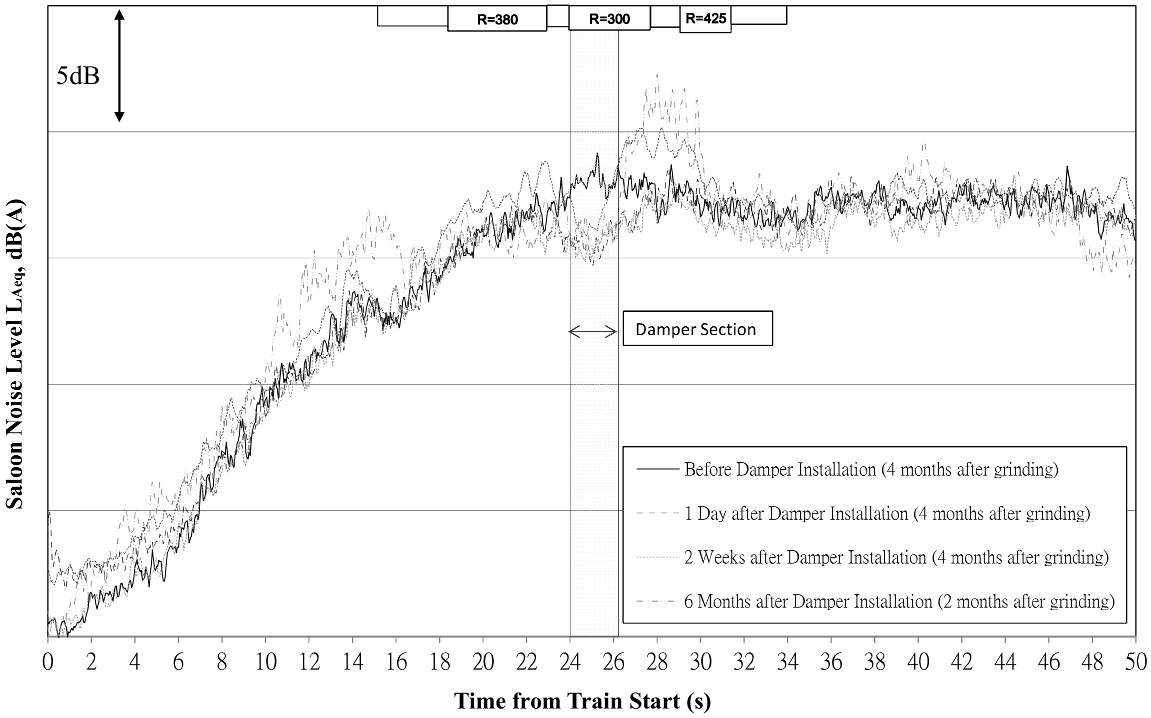

Figure 2 – Saloon noise level time history

Except the measurement in the 11 month after damper installation, which was affected by rail corrugation, the saloon noise level was reduced by around 3dB(A) at the middle of damper installed section as comparing to that before damper installation. Due to highly reverberant environment inside the tunnel, noise level in the middle of the damper section was significantly affected by the noise outside the damper section. With a sufficiently long section of rail dampers, saloon noise reduction is anticipated to be around 4dB(A).

Figure 3 plots the saloon noise spectrum averaged over 0.5s when the control car passes through the middle of the damper section. The major reduction is at mid frequency (600-1200Hz). In the 6th month, the noise levels between 125 and 315Hz were 3–8dB lower than before. In the 11th month, the noise levels at 250-400Hz frequency band were higher than others by 2-6dB. It was due to the rail corrugation growth found on the rail with wavelengths of 50-80mm, corresponding to 250-400Hz for 72km/h running speed.

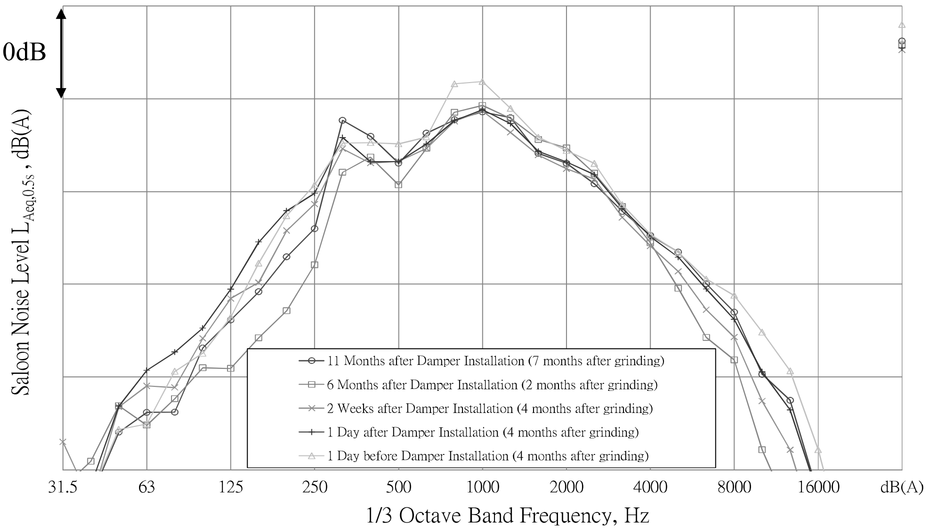

Figure 3 – In-saloon noise spectrum $L_{Aeq\ 0.5s}$ during passage of the middle damper section

4 VIBRATION REDUCTION

Figure 4(a) shows the rail vibration spectrum. Each set of measurement data includes about 20 train passages. Overall vertical and lateral vibration levels were reduced by 7dB(A) and 10dB(A) respectively. Sleeper vibration spectrum is shown in Figure 4(b). The sleeper block has a resonance peak at 300Hz which contributes to significant noise radiation at that frequency. The rail damper has little effect on the sleeper resonance.

The vertical vibration time history at 800Hz, the vertical pinned-pinned resonance, is given in Figure 5. Due to higher track decay rate after damper installation, the rail vibration level drops by 40-50dB between two bogies. The rail becomes localized point sources at the wheel contact points.

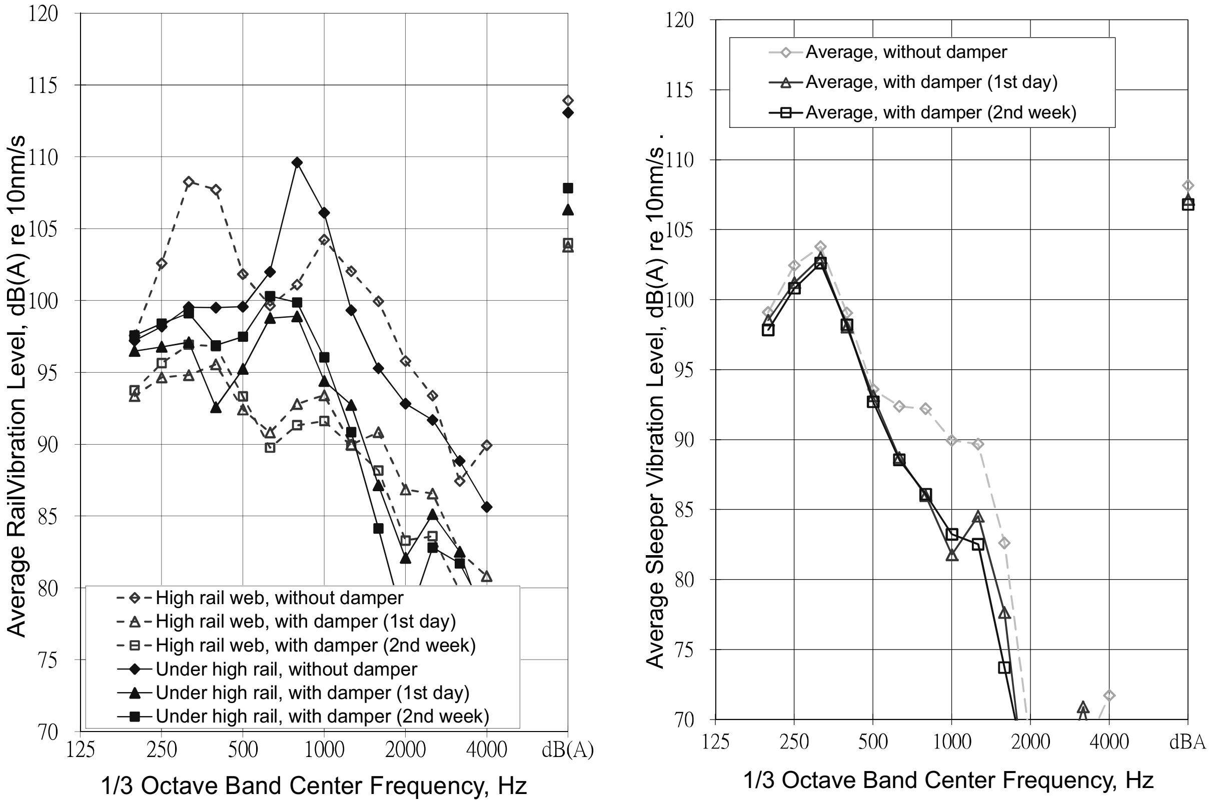

Figure 4 – (a) Average vibration level at high rail, (b) Vibration level at sleeper block

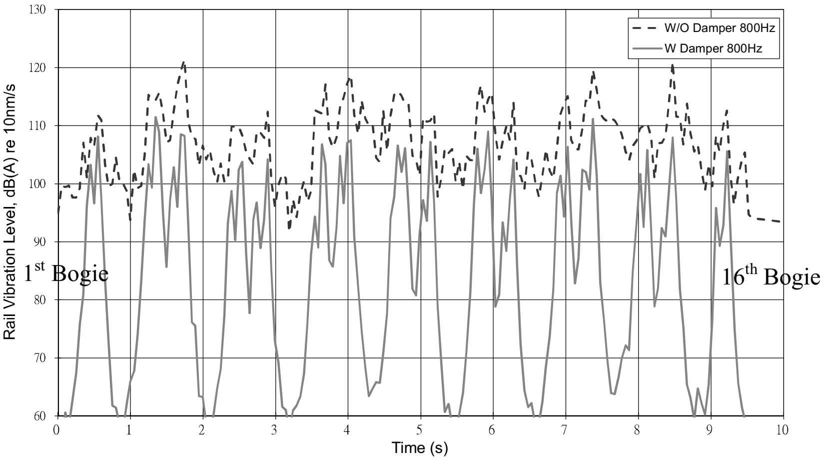

Figure 5 – Vertical vibration time history at 800Hz

5 RAIL CORRUGATION CONTROL

Figure 6 shows the rail roughness at approximately 7 months after grinding at the damper section and the control section without rail dampers. [9] Low rail has significant corrugation at wavelengths of 50-80mm, which corresponds to frequencies of 250-400Hz at 72km/h train speed. Rail roughness at the damper section is found lower than that at the control section, particularly at the corrugation wavelengths of 80mm, 63mm and 50mm, where corrugation was reduced by 72%, 41% and 10% respectively. The overall corrugation growth rate was reduced by 45%, as shown in Table 3 below. Figure 7 illustrates the roughness changed against time to determine the corrugation growth rate at critical frequencies of 50-80mm wavelengths. From 25/01/2011 to 10/06/2011, roughness at 50-80mm wavelengths steadily increased as corrugation developed.

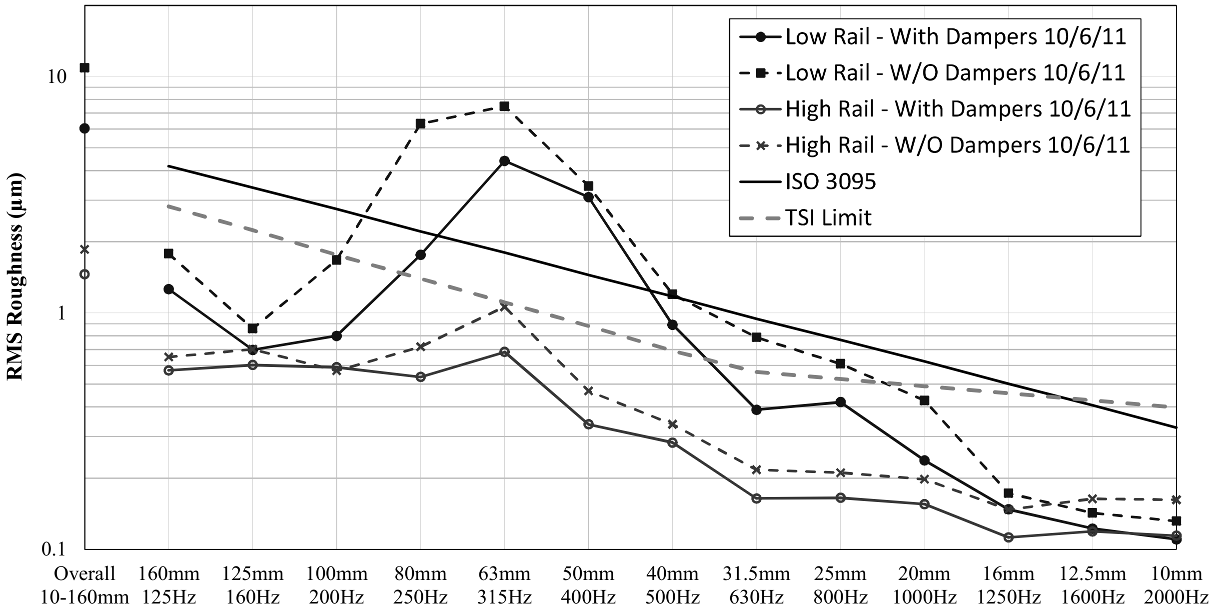

Figure 6 – 1/3 Octave band roughness 7 months after grinding
(frequency in x-axis corresponds to train speed 72km/h)

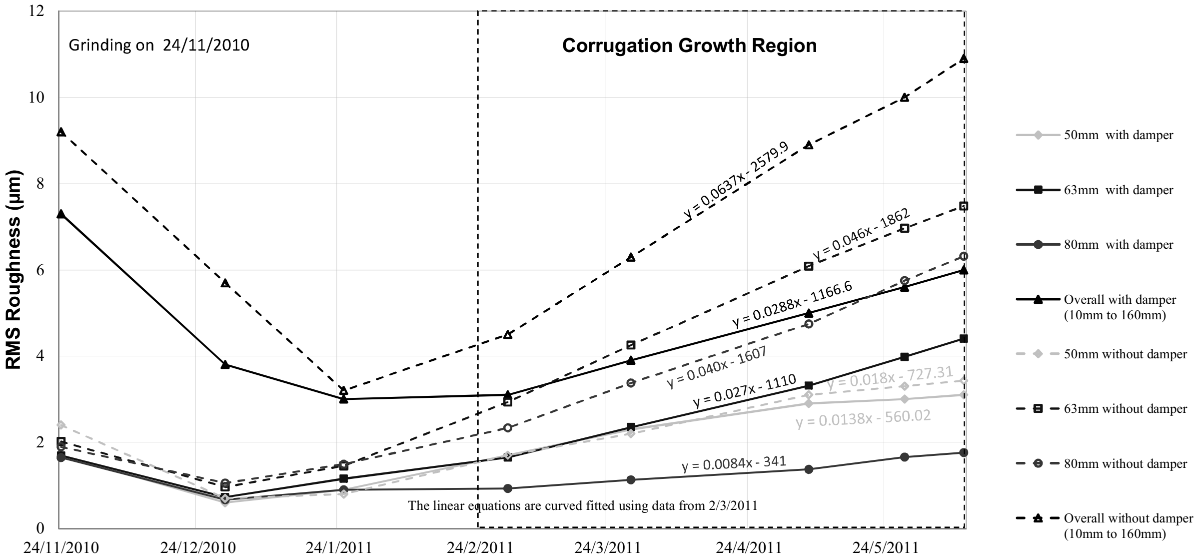

Figure 7 – Roughness at wavelengths of 50mm, 63mm and 80mm from 4/11/2010 to 10/6/2011