DELIVERABLE 4.3.3

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	Concept for low frequency high transmission loss for windows and their casing		
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PP	Restricted to other programme participants (including the Commission Services)	
RE	Restrictec to a group specified by the consortium (including the Commission Services)	
CO	Confidential, only for the members of the consortium (including the Commission Services)	

Nature of Deliverable

R	Report	✓
P	Prototype	
D	Demonstrator	
O	Other	

SEVENTH FRAMEWORK PROGRAMME

This deliverable has been quality checked and approved by CityHush Coordinator *Nils-Åke Nilsson*

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0 EXECUTIVE SUMMARY

0.1 OBJECTIVE OF THE DELIVERABLE

Designing solutions to reduce low frequency airborne noise (such as e.g. noise from exhaust system of buses or from idling diesel engines) by measures at the façade windows (increased transmission loss).

0.2 DESCRIPTION OF THE WORK PERFORMED SINCE THE BEGINNING OF THE PROJECT

- Determination of the source spectra of buses and trucks through a measurement campaign near a bus stop in a city centre;
- Definition of criteria for low frequency indoor noise;
- Calculation of the indoor noise levels that occur when a bus is idling at a bus stop or when a bus is departing from a bus stop by means of a noise model;
- Determination of three prediction methods to calculate the sound insulation values of double ventilated façades (DVF);
- Determination of the dimensions of an optimized DVF with high low frequency insulation values;
- Description of the use of an active noise control (ANC) system on double windows.

0.3 MAIN RESULTS ACHIEVED SO FAR

The determination of the dimensions of an optimized DVF with high low frequency insulation values.

0.4 EXPECTED FINAL RESULTS

In the next stage of the project, the designed double ventilated façade will be tested thoroughly in the lab and in practice and will be fine-tuned. The final characteristics and dimensions of the designed double ventilated façade will be determined and the insulation values will be ascertained.

0.5 POTENTIAL IMPACT AND USE[1]

The potential impact of the use of the double ventilated façade is to reduce the low frequency airborne noise inside the buildings.

0.6 PARTNERS INVOLVED AND THEIR CONTRIBUTION

APT is involved in designing and testing the solutions to reduce low frequency noise by measures at the façade windows.

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1 *including the socio-economic impact and the wider societal implications of the project so far*

0.7 CONCLUSIONS

Trucks and buses are major contributors to traffic noise. At low speeds, the engine and exhaust typically produce low frequency noise (LFN) with dominant frequencies between 31,5 Hz en 63 Hz.

Commonly used window types do not perform well when it comes to low frequency sound insulation. Trucks and buses passing by at low speeds and at close proximity to building façades therefore generate noise inside the building with a high low frequency content.

In the CityHush project, windows with a high low frequency sound insulation are developed to reduce the LFN inside the buildings.

The acoustic performance of double windows, more specifically, double ventilated façades (DVF) are investigated. Three prediction methods are described to calculate the sound insulation of DVF's. The three prediction methods have their limitations but for now, these are the best available methods to predict the behaviour of DVF's.

The results from the three prediction methods are compared to the results from a measurement campaign performed on existing DVF's. The results from the three methods lie close together when frequencies above 100 Hz are considered. It depends on the DVF to see which method gives the results that are closest to the measured results.

For frequencies below 100 Hz, the predictions could not be compared to the measurements because there were no measurement results below 100 Hz. Below 100 Hz, there are sometimes big differences between the three prediction methods. As long as the three methods cannot be validated by more measurements, the three methods should be used together to predict the performance of a DVF.

In order to have a sound insulation as high as possible for the lower frequencies (around 31,5 Hz and 63 Hz), a parametric study showed that the optimised DVF is as follows:

- Inner façade: 6-12-8 mm;
- Cavity depth: 1300 mm;
- Outer façade: 12 mm;
- A_{cavity} = S.

With this façade, insulation values in the lower frequencies that theoretically are around 20 dB higher than those obtained with a 6 mm single pane glazing.

In the months M13 to M24 a prototype of this façade will be tested in the lab or in situ. A parametric study will also be carried out during the tests to determine the influence of all the parameters and to fine-tune the design of the DVF.

The three prediction methods will also be validated and adjusted as soon as the measurement results in the lower frequencies are available.

Another possibility to increase the transmission loss of windows is to use an active noise control (ANC) system.

Investigations show that ANC methods can improve sound transmission loss of double-glazed windows in the low-frequencies. Particularly around the mass-spring-mass resonance frequency of the double-panel system, the sound insulation can be enhanced up to 10 dB for white noise excitation.

In the months M13 to M24, the concept of ANC on double-glazed windows will be investigated further.

Experimental results from previous research projects will be collected and examined. The acoustical performance of the ANC on double-glazing will be evaluated taking into account the high costs of ANC systems.

1 SOURCE SPECTRA BUSES AND TRUCKS

Trucks and buses are major contributors to traffic noise. At speeds lower than ±50 km/h the noise emission of the drive-line (exhaust, engine) of buses and trucks exceeds the tyre-road interaction (rolling noise), see figure 1.1 and 1.2.

The noise produced by the exhaust and by the engine at low rotational speeds, is typically low frequency.

Therefore, for buses and trucks driving at low speeds, the noise emitted has a low frequency content.

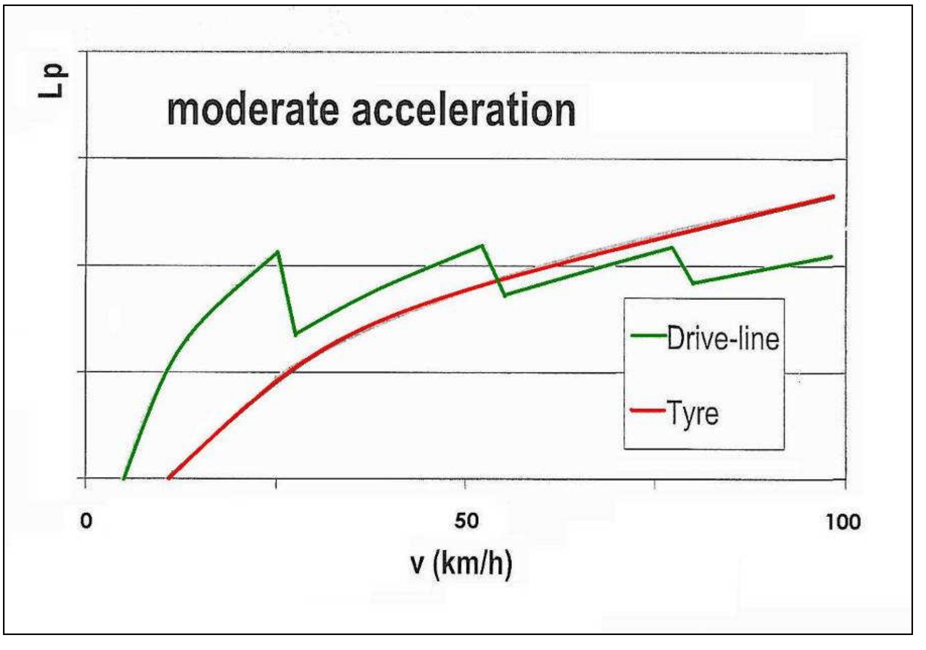


Figure 1.1

Noise level versus speed at moderate acceleration for buses and trucks

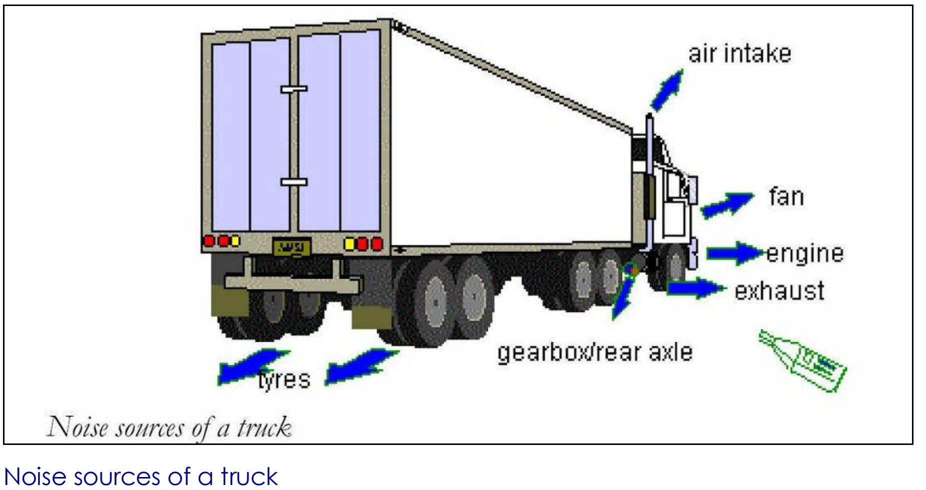


Figure 1.2

Noise sources of a truck

1.1 MEASUREMENT CAMPAIGN

Measurements have been performed near a bus station in a city centre. The city holds a speed restriction of 30 km/h.

Table 1.1 summarises the results from the measurement campaign. In the figures A.1 to A.8 in appendix A, following information is given:

- Figures A.1, A.4, A.7, A.10:
  - Overall level [dB(A)] versus time [s];
  - Maximum level: level [dB(A)] versus third-octave band frequency [Hz];
  - Equivalent level: level [dB(A)] versus third-octave band frequency [Hz];
- Figures A.2, A.5, A.8, A.11:
  - Overall level [dB] versus time [s];
  - Maximum level: level [dB] versus third-octave band frequency [Hz];
  - Equivalent level: level [dB] versus third-octave band frequency [Hz];
- Figures A.3, A.6, A.9, A.12:
  - Third-octave band frequency [Hz] versus time [s] versus level [dB].

Event	Distance from source [m]	Bus speed [km/h]	Equivalent level L_{Aeq} [dB(A)]	Equivalent level L_{eq} [dB]	Maximum level L_{max} [dB]	Dominant frequency [Hz]	Figures
Bus pass-by	14	30	69,9	89,5	96,3	50	A.1 – A.3
Bus idling	14	0	68,4	89,1	90,4	31,5	A.4 – A.6
Bus departure	14	0-30	76,2	98,4	104,3	50-63	A.7 – A.9
Bus arrival + idling + departure	14	0-30	69,7	90,5	102,6	31,5-63	A.10 – A.12

Table 1.1 Results measurement campaign

In the figures with the dB spectra, the dominant frequencies can easily be detected. It can be seen that the dominant frequencies lie between 31,5 and 63 Hz for buses passing by, arriving, idling and departing at bus stops.

2 LOW FREQUENCY NOISE (LFN): INDOOR CRITERIA

Low frequency noise (LFN) can cause more annoyance than predicted from A-weighted noise levels. To evaluate the LFN exposure, two guidelines based on non-weighted noise levels will be used:

- Guideline from the Dutch Association for Noise Annoyance (Nederlandse Stichting Geluidhinder NSG, reference [1]);
- Guideline from the Swedish National Board of Health and Welfare (Socialstyrelsen, reference [2]).

2.1 NSG-GUIDELINE

In the NSG-guideline, audibility is taken as the criterion for the assessment of LF noise: as soon as LFN is audible, it can be annoying.

The reference curve for audibility in this guideline is based on the 90 % hearing threshold for an average group of people between 50 and 60 years old. In this group of people, 90 % will not hear noise below the reference curve; 10 % will be able to hear noise that is (just) below this curve.

The frequency range considered lies between the third-octave bands of 20 and 100 Hz. From measurements in situations with LFN complaints, no audible noise levels at frequencies lower than 20 Hz where found. Frequencies higher than 100 Hz can be assessed with the usual A-weighting.

Frequency [Hz]	20	25	31,5	40	50	63	80	100
Reference curve [dB]	74	62	55	46	39	33	27	22

Table 2.1 NSG-guideline: reference curve

2.2 SWEDISH GUIDELINE

The criteria are given for third-octave bands between 31 and 200 Hz.

Frequency [Hz]	31,5	40	50	63	80	100	125	160	200
Reference curve [dB]	56	49	43	41,5	40	38	36	34	32

Table 2.2 Swedish guideline: reference curve

2.3 COMPARISON GUIDELINES

In figure 2.1, the NSG-guideline and the Swedish guideline are shown (dB-level versus frequency).

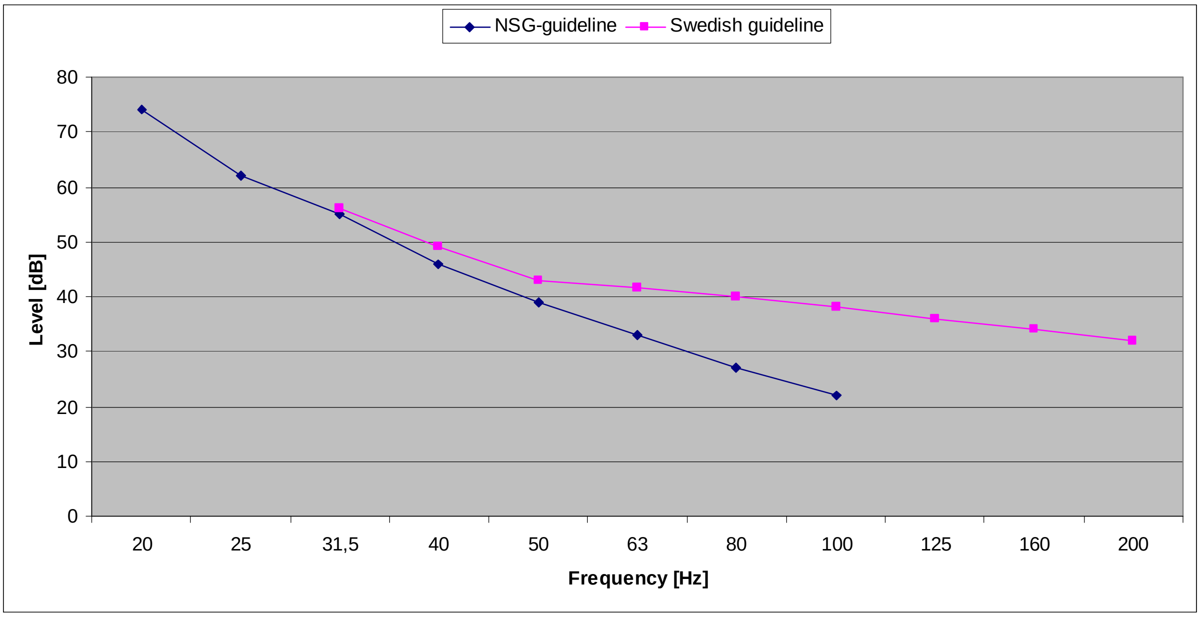


Figure 2.1

Comparison NSG-guideline and Swedish guideline

From the comparison between both guidelines, it can be concluded that the Swedish guideline is less severe than the NSG-guideline.

Both guidelines will be used further on to evaluate indoor noise levels caused by buses driving outdoor.

3 NOISE MODEL BUS STOP

In this paragraph, the results from a noise model from a bus stop in a city centre are presented. The model has been made using the modelling software *IMMI 2010*. The goal of the model is to calculate the indoor noise levels that occur when a bus is idling at a bus stop or when a bus is departing from a bus stop.

3.1 MODEL

The model includes following elements:

– Point source at a height of 0,75 m (ISO 9613);
– Receiver at a distance of 2 m in front of a façade and at a distance of 20 m from the source.

The model uses two source spectra:

– Source spectrum 1: sound power spectrum in dB from maximum level during idling from bus (see §1.1, figure A.5 and figure 3.1);
– Source spectrum 2: sound power spectrum in dB from maximum level during bus departure (see §1.1, figure A.8 and figure 3.1).

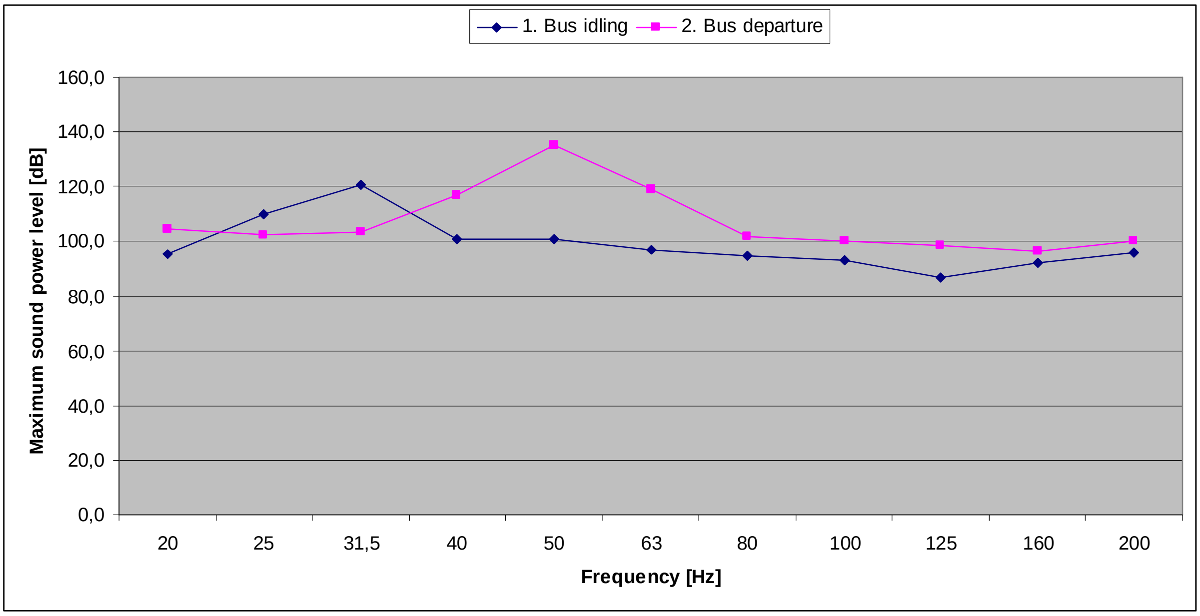


Figure 3.1 Source spectra: bus idling and bus departure

3.2 OUTDOOR NOISE LEVELS

The outdoor noise levels in the receiver position are calculated using the model. The results for the two different source spectra, and for frequencies between 20 and 200 Hz, are given in table 3.1.

	Outdoor noise level [dB]											Overall level	
Frequency [Hz]	20	25	31,5	40	50	63	80	100	125	160	200	[dB]	[dB(A)]
1. Bus idling	66	81	92	71	72	68	66	64	58	63	66	92	70
2. Bus departure	75	73	74	88	106	90	73	71	69	67	71	106	78

Table 3.1 Noise model bus stop: outdoor noise levels

The levels in the table 3.1 are the levels at a distance of 2 m in front of a façade, at a distance of 20 m from the source. The levels include incident and reflected sound against the façade.

3.3 FAÇADE INSULATION

To calculate the indoor noise levels, the insulation values from the façade have to be known. Table 3.2 and figure 3.2 show the insulation values (R_W) from commonly used windows in a city centre:

- Single pane glazing: 6 mm glass;
- Double pane glazing: 6 mm glass – 12 mm air void – 6 mm glass;
- Double pane glazing: 6 mm glass – 20 mm air void – 10 mm glass.

	Insulation values R [dB]											Overall level R_w
Frequency [Hz]	20	25	31,5	40	50	63	80	100	125	160	200	[dB]
6	9	10	11	13	15	16	17	18	20	21	23	31
6-12-6	12	13	15	16	17	18	20	21	21	21	17	35
6-20-10	14	16	18	19	20	21	21	22	20	23	29	38

Table 3.2 Window insulation values: R

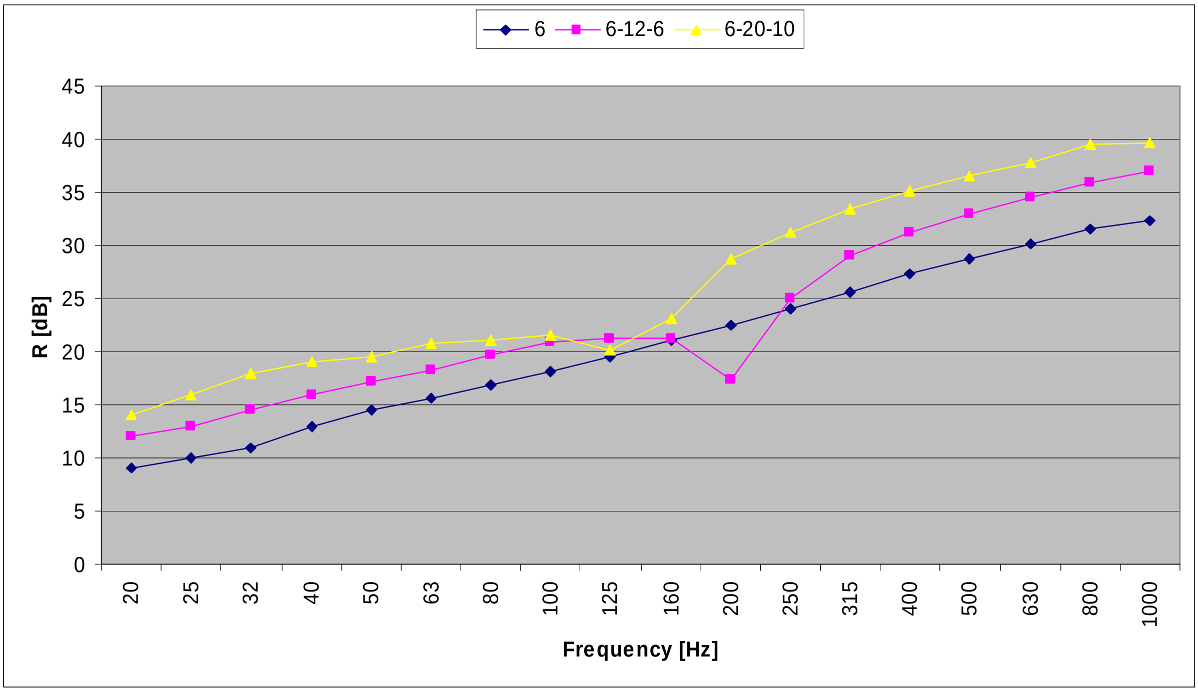


Figure 3.2 Window insulation values: R [dB]

3.4 INDOOR NOISE LEVELS

With the model, the outdoor noise levels in front of a façade are calculated. Now, the indoor noise levels can be calculated from the outdoor noise levels and the insulation values.

Following formula is used to calculate the indoor noise levels:

$$R = L_{out} - L_{in} + 10\log\left(\frac{4 \cdot S}{A}\right) \quad (3.1)$$

Assume $4S/A = 1{,}1$:

$$L_{in} = L_{out} - R + 0{,}3 \quad (3.2)$$

The indoor noise levels for 3 different types of window insulations are given in table 3.3 for buses idling and in table 3.4 for buses departing:

	1. Bus idling – indoor noise level [dB]											Overall level	
Frequency [Hz]	20	25	31,5	40	50	63	80	100	125	160	200	[dB]	[dB(A)]
6	57	71	81	59	57	53	49	46	38	42	44	81	44
6-12-6	54	68	77	56	55	50	46	43	37	42	49	78	43
6-20-10	52	65	74	53	52	47	45	42	38	40	38	74	38

Table 3.3 Noise model bus stop: 1.Bus idling – indoor noise levels

	2. Bus departure – indoor noise level [dB]											Overall level	
Frequency [Hz]	20	25	31,5	40	50	63	80	100	125	160	200	[dB]	[dB(A)]
6	67	63	64	75	91	75	56	53	50	47	48	92	62
6-12-6	64	60	60	72	89	72	53	50	49	47	54	89	59
6-20-10	62	57	57	69	86	70	52	49	50	45	42	87	57

Table 3.4 Noise model bus stop: 2.Bus departure – indoor noise levels

The indoor noise levels in dB are compared to the NSG-guideline and the Swedish guideline in following figures 3.3 (bus idling) and 3.4 (bus departing).

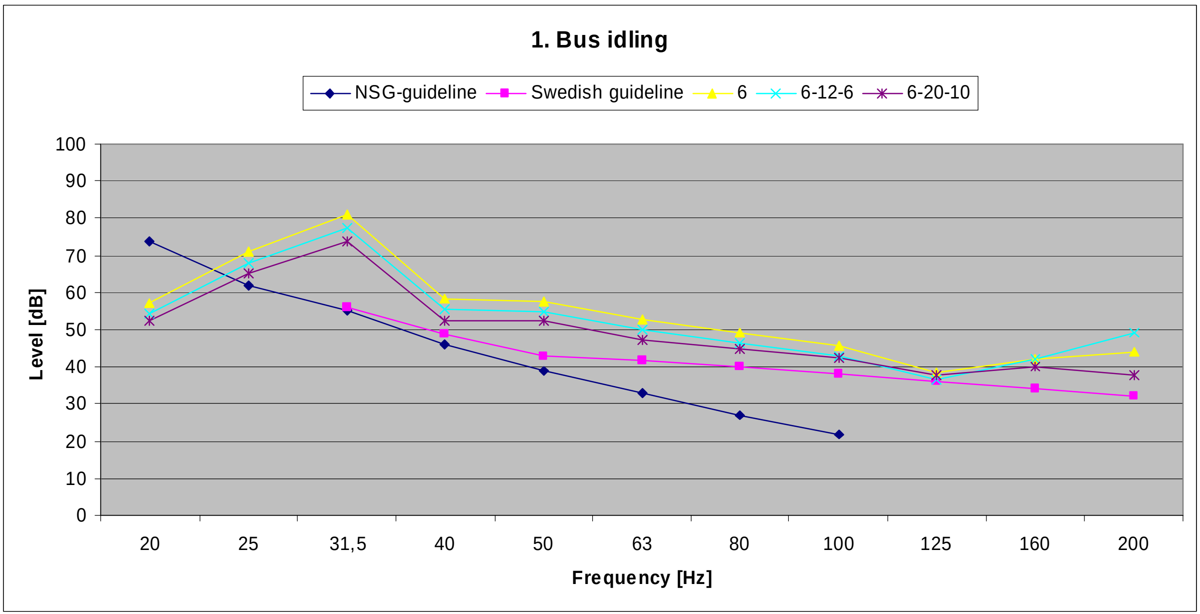


Figure 3.3

Noise model bus stop: 1.Bus idling – indoor noise levels compared to NSG-guideline and Swedish guideline

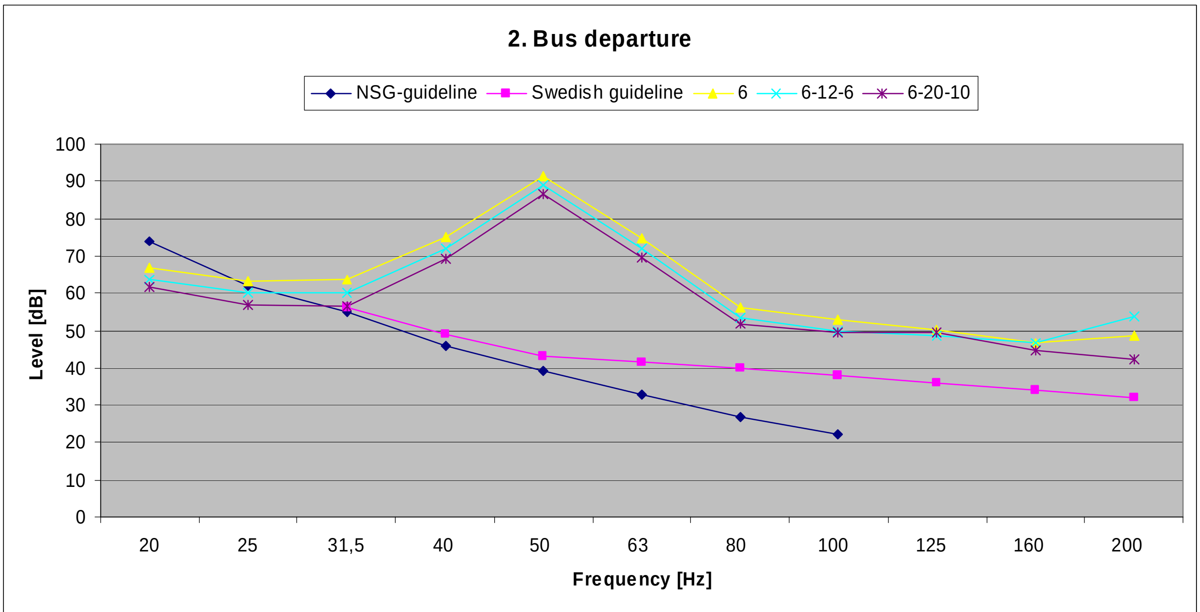


Figure 3.4

Noise model bus stop: 2.Bus departure – indoor noise levels compared to NSG-guideline and Swedish guideline

From both figures it can clearly be seen that, at the dominant frequencies of 31,5 Hz and 50 Hz, both guidelines for low frequency noise (LFN) are largely exceeded.

In the following chapter, solutions will be developed to lower the low frequency noise content indoors: concepts will be designed for windows with a high low frequency transmission loss.

4 CONCEPT FOR LOW FREQUENCY HIGH TRANSMISSION LOSS FOR WINDOWS

4.1 DOUBLE WINDOWS

4.1.1 Theory double wall

In many cases it is desirable to achieve a high sound insulation in walls with low weight. In this context, double walls are used. These walls consist of two cavity walls with a layer of air or a flexible layer in between them.

The model for a double wall system is based on the dynamic equilibrium of two plates connected by a spring system. The modeling of the intermediate layer is that of a coupling by a thin layer of air with normal or oblique incidence.

The resonance frequency f_r for this system is given by:

$$f_r = \frac{60}{\cos\theta \cdot \sqrt{d}} \sqrt{\frac{1}{m''_1} + \frac{1}{m''_2}} \tag{4.1}$$

where f_R resonance frequency [Hz]
- d cavity width [m]
- m''_1 mass of plate 1 [kg/m²]
- m''_2 mass of plate 2 [kg/m²]
- θ angle of incidence [°]
- R sound insulation [dB]

The model gives two areas in which different equations for the sound insulation R are valid:

$f << f_r(\theta)$

$$R = 20 \cdot \log \frac{\omega \cdot \left(m''_1 + m''_2\right) \cdot \cos\theta}{2 \cdot \rho \cdot c} \tag{4.2}$$

The sound insulation corresponds to the mass law in accordance with the total wall weight $m''_1 + m''_2$.

For $\boldsymbol{f = f_r}$ the sound insulation is limited. When $m''_1 = m''_2$, the sound insulation is zero.

f >> $f_r(\theta)$

$$R = 20 \cdot \log \frac{\omega \cdot m_1'' \cdot \cos\theta}{2 \cdot \rho \cdot c} + 20 \cdot \log \frac{\omega \cdot m_2'' \cdot \cos\theta}{2 \cdot \rho \cdot c} + 20 \cdot \log \frac{2 \cdot \omega \cdot d \cdot \cos\theta}{c} \quad (4.3)$$

Due to cavity resonances, the maximum value is limited to:

$$R = 20 \cdot \log \frac{\omega \cdot m_1'' \cdot \cos\theta}{2 \cdot \rho \cdot c} + 20 \cdot \log \frac{\omega \cdot m_2'' \cdot \cos\theta}{2 \cdot \rho \cdot c} + 6 \quad (4.4)$$

The transition between these last two formulas is located at $f_r = \frac{c}{4 \cdot d}$ for an angle of 45 °.

For omnidirectional incident sound, following formulas can be used:

$$f_{r,45°} = \frac{90}{\sqrt{d}} \sqrt{\frac{1}{m_1''} + \frac{1}{m_2''}} \quad \text{(incidence at 45 ° as an average)} \quad (4.5)$$

f << $f_{r,45°}$

$$R_{omni} = 20 \cdot \log \frac{\omega \cdot (m_1'' + m_2'')}{2 \cdot \rho \cdot c} - 5 \quad (4.6)$$

f >> $f_{r,45°}$ and f < $\frac{c}{4 \cdot d}$

$$R_{omni} = R_{omni}(m_1'' + m_2'', f_{r,45°}) + 60 \cdot \log\left(\frac{f}{f_{r,45°}}\right) \quad (4.7)$$

f > $\frac{c}{4 \cdot d}$

$$R_{omni} = R_{1,omni} + R_{2,omni} + 6 \quad (4.8)$$

This model is presented in figure 4.1.

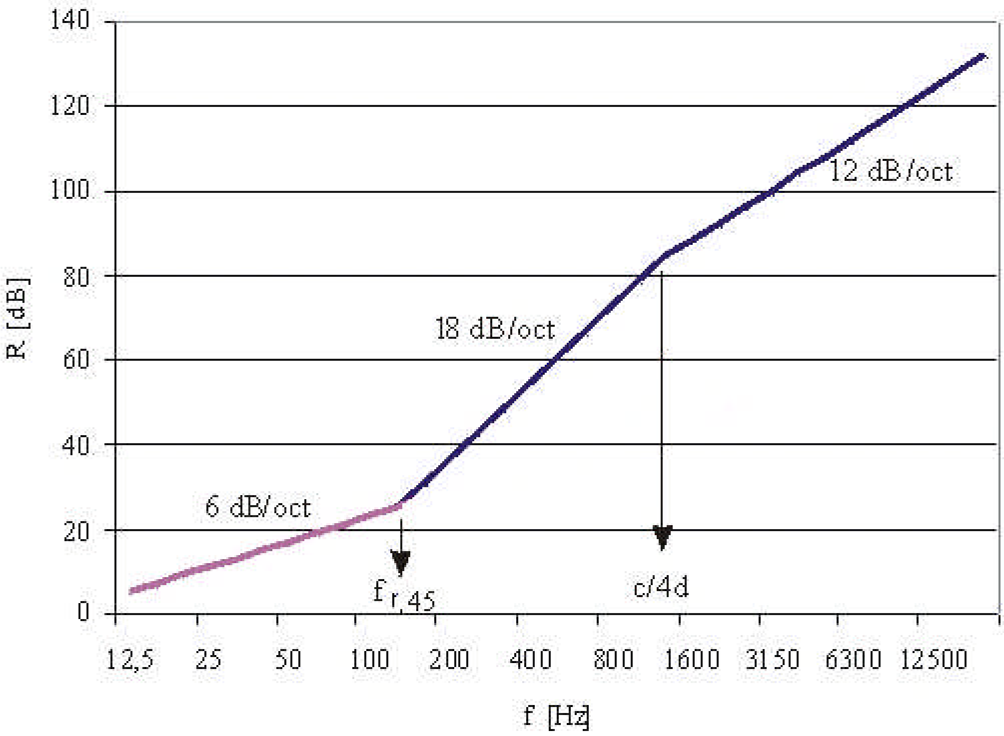


Figure 4.1

Model double wall insulation (reference [3])

To increase the low frequency sound insulation of double walls, and thus double windows, the resonance frequency must be held as low as possible, by:

- Increasing the cavity width d;
- Increasing the mass of the plates m''_1 and m''_2.

Double windows with special gasses in the cavity give improvement in the mid- and high frequencies. Laminated glass windows are an improvement for the coincidence dip. Special gasses and laminated glass therefore do not improve the low frequency sound insulation.

4.1.2 Dimensions double window

In this section the dimensions of a double window will be determined using the theory from the previous chapter so that the resonance frequency lies below 31,5 and 63 Hz. These are the dominant frequencies for buses passing by, arriving, idling and departing at bus stops (see chapter 1).

The resonance frequency for normal incidence:

$$f_{r,\perp} = \frac{60}{\sqrt{d}}\sqrt{\frac{1}{m_1''}+\frac{1}{m_2''}} \tag{4.9}$$

The resonance frequency for omnidirectional incidence (incidence at 45 ° as an average):

$$f_{r,45^\circ} = \frac{90}{\sqrt{d}}\sqrt{\frac{1}{m_1''}+\frac{1}{m_2''}} \tag{4.10}$$

In table 4.1, the possible dimensions are given:

f_r [Hz]	m''_1 [kg/m²]	t_1 [mm]	d [mm]	m''_2 [kg/m²]	t_2 [mm]	$f_{r,\perp}$ [Hz]	$f_{r,45°}$ [Hz]
31,5	25	10	2800	25	10	10	15
	50	20	1400	50	20	10	15
63	25	10	460	25	10	25	38
	50	20	230	50	20	25	38

Table 4.1 Double windows: possible dimensions

4.2 VENTILATED DOUBLE FAÇADES (VDF)

4.2.1 Concept

A ventilated double façade (VDF) can be defined as a traditional single façade doubled inside or outside by a second, essentially glazed façade. Each of these two façades is commonly called a skin. A ventilated cavity, having a width which can range from several centimetres to several metres for the widest accessible cavities, is located between these two skins. Up to now, VDF are mainly used in office buildings.

Due to the presence of a second façade, double ventilated façades have acoustical performances that most of the time cannot be realized by the use of traditional single façades. The acoustical performances of DVF can be at the basis of decision to use this kind of façade in a building. The acoustical performances are however very dependant on the type of façade and to which degree these façades are airtight or not.

Three main criteria can be introduced to classify the VDF

1. The type of ventilation;
2. The partitioning of the façade;
3. The modes of ventilation of the cavity.

1. The type of ventilation

The type of ventilation refers to the driving forces at the origin of the ventilation of the cavity located between the two glazed façades. Each VDF concept is characterised by only a single type of ventilation. One must distinguish between the three following types of ventilation:

1. Natural ventilation;
2. Mechanical ventilation;
3. Hybrid ventilation: compromise between natural and mechanical ventilation.

2. The partitioning of the façade;

The partitioning of the cavity tells how the cavity between the two glazed façades is physically divided.

A first distinction must be made between windows and façades. On the one hand there are ventilated double windows (see figure 4.2), and on the other ventilated double façades (see figure 4.3).

Figure 4.2
Example of a ventilated double window (reference [4])

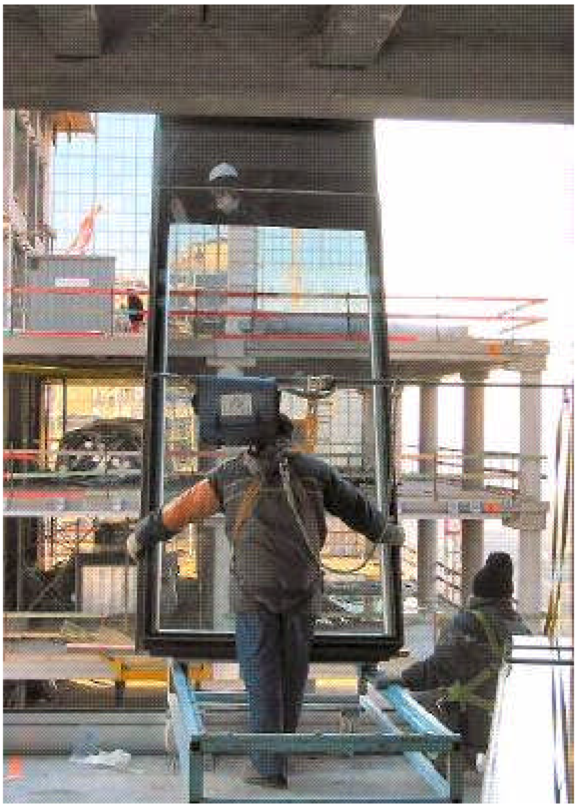


Figure 4.3
Example of a ventilated double façade (reference [4])

Within the ventilated double façades, numerous possibilities of partitioning are imaginable and an additional classification can be created. One observes that the partitioning solutions implemented in practice can be classified as follows:

- Ventilated double window
- Ventilated double façade
  - Partitioned by storey
    - With juxtaposed modules
    - Corridor type
  - Shaft-box type
  - Multi-storey type
  - Multi-storey louver type

The ventilated double window

A façade equipped with a ventilated double window is characterised by a window doubled inside or outside by a single glazing or by a second window. From the partitioning perspective, it is a window with functions as a filling element in a wall.

The ventilated double façade partitioned by storey with juxtaposed modules.

In this type of façade, the cavity is physically delimited (horizontally and vertically) by the module of the façade which imposes its dimensions on the cavity. The façade module has a height limited to one storey as illustrated in figure 4.4.

Figure 4.4

Example of a ventilated double façade partitioned by storey with juxtaposed modules (reference [4])

The corridor-type ventilated double façades partitioned by storey

Corridor type ventilated double façades partitioned by storey are characterized by a large cavity in which it is generally possible to walk. While the cavity is physically partitioned at the level of each storey (the cavities of each storey are independent of one another), it is not limited vertically, and generally extends across several offices or even an entire floor.

The shaft-box ventilated double façade

The objective of this partitioning is to encourage natural ventilation by adapting the partitioning of the façade. This type of façade and partitioning is applied only in naturally ventilated double façades. This type of façade is in fact composed of an alternation of juxtaposed façade modules partitioned by storey and vertical ventilation ducts set up in the cavity which extend over several floors. Each façade module is connected to one of these vertical ducts.

The multi-storey ventilated double façade

Multi-storey ventilated double façades are characterised by a cavity which is not partitioned either horizontally or vertically, the space between the two glazed façades therefore forming one large volume, see figure 4.5. In some cases, the cavity can run all around the building without partitioning.

It should be noted that the façades of this type have excellent acoustical performances with regard to outdoor noise. This characteristic can be the reason for applying this particular type of façade.

Figure 4.5

Example of a multi-storey ventilated double façade (reference [4])

The multi-storey louver naturally ventilated double façade

The multi-storey louver naturally ventilated double façade is very similar to a multi-storey ventilated double façade. Its cavity is not partitioned either horizontally or vertically and therefore forms one large volume. Metal floors are installed at the level of each storey in order to allow access to it, essentially for reasons of cleaning and maintenance.

The difference between this type of façade and the multi-storey façade lies in the fact that the outdoor façade is composed exclusively of pivoting louvers rather than a traditional monolithic façade. The outside façade is not airtight, even when the louvers have all been put in closed position.

3. The modes of ventilation of the cavity

The ventilation mode refers to the origin and the destination of the air circulating in the ventilated cavity. One must distinguish between the following five ventilation modes, see figure 4.6:

1. Outdoor air curtain
2. Indoor air curtain
3. Air supply
4. Air exhaust
5. Buffer zone

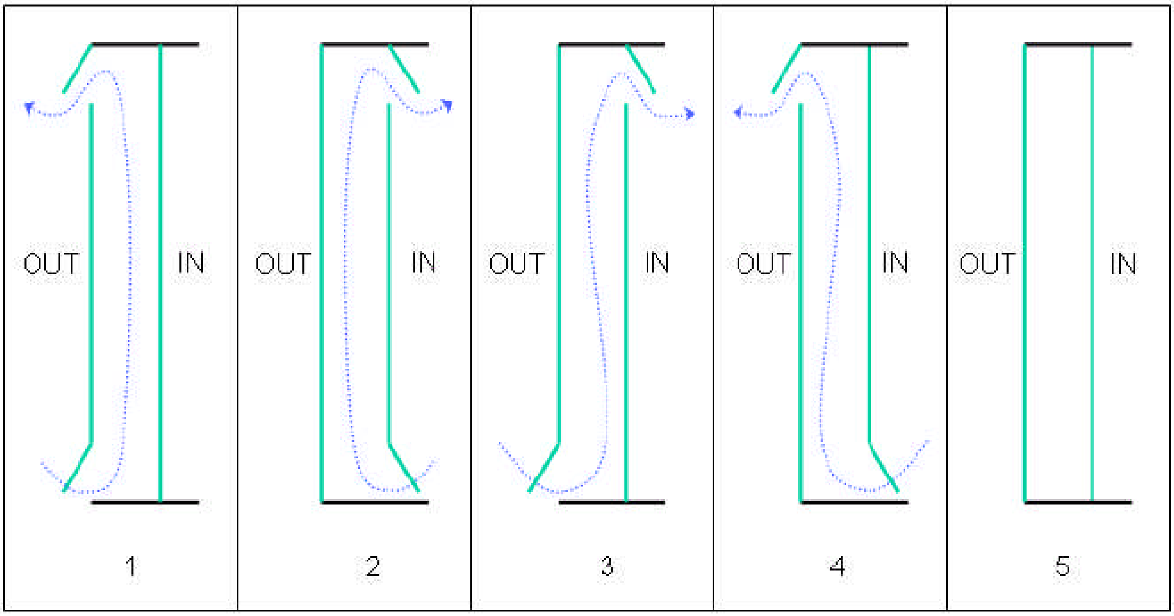


Figure 4.6

The five ventilation modes (reference [4])

4.2.2 Acoustical measurements on DVF

Test method

The test method to realize in situ measurements of the acoustical façade insulation is described in the European standard EN ISO 140-5 (1995). The measurement method uses a loudspeaker outside of the building, generating a standardized noise (white noise). The acoustical façade insulation ($D_{ls,2m,n}$ or $D_{ls,2m,nT}$) is then function of the (spectral) difference between the noise pressure level measured at two meters of the outside façade and the noise level measured inside the building. A correction indicator is added to this difference to take into account the absorption or the reverberation time inside the building.

The way of expressing the spectral result by a single value indicator ($D_{ls,2m,n,w}$ or $D_{ls,2m,nT,w}$) is described in the European Standard EN ISO 717-1 (1996) and is expressed in dB (decibel). The standard used frequency range lies between 100 Hz and 3150 Hz. Two other correction indicators are also calculated (C and C_{tr}) that have to be added to the value $D_{ls,2m,n,w}$ or $D_{ls,2m,nT,w}$ depending on the type of the outside noise that is present (C corresponding to mid and high frequency noise and C_{tr} to (slow) traffic noise (low frequency)).

Measurement results

Below one can find several acoustical measurement results from a number of measurement campaigns performed by the BBRI within the framework of the Active façade project (financed by the Ministry of Economic Affairs in Belgium). The insulation spectra and the single value indicator are displayed.

Measurement campaign DVF 1 (climate façade) (reference [5])

The tested façade is a ventilated double façade partitioned by storey with juxtaposed modules with an indoor air curtain. The façade element of the measured room includes two modules (2 x 1,5 m width) composed of a glass outer and inner façade. The glass inner façade is hinged and can be opened. In the closed state the inner façade has at the bottom a ventilation slit of 1,5 cm in height over the entire width of the module (the air in the room is extracted via the slit into the cavity and upwards via the false ceiling). The inner façade is only opened for maintenance reasons.

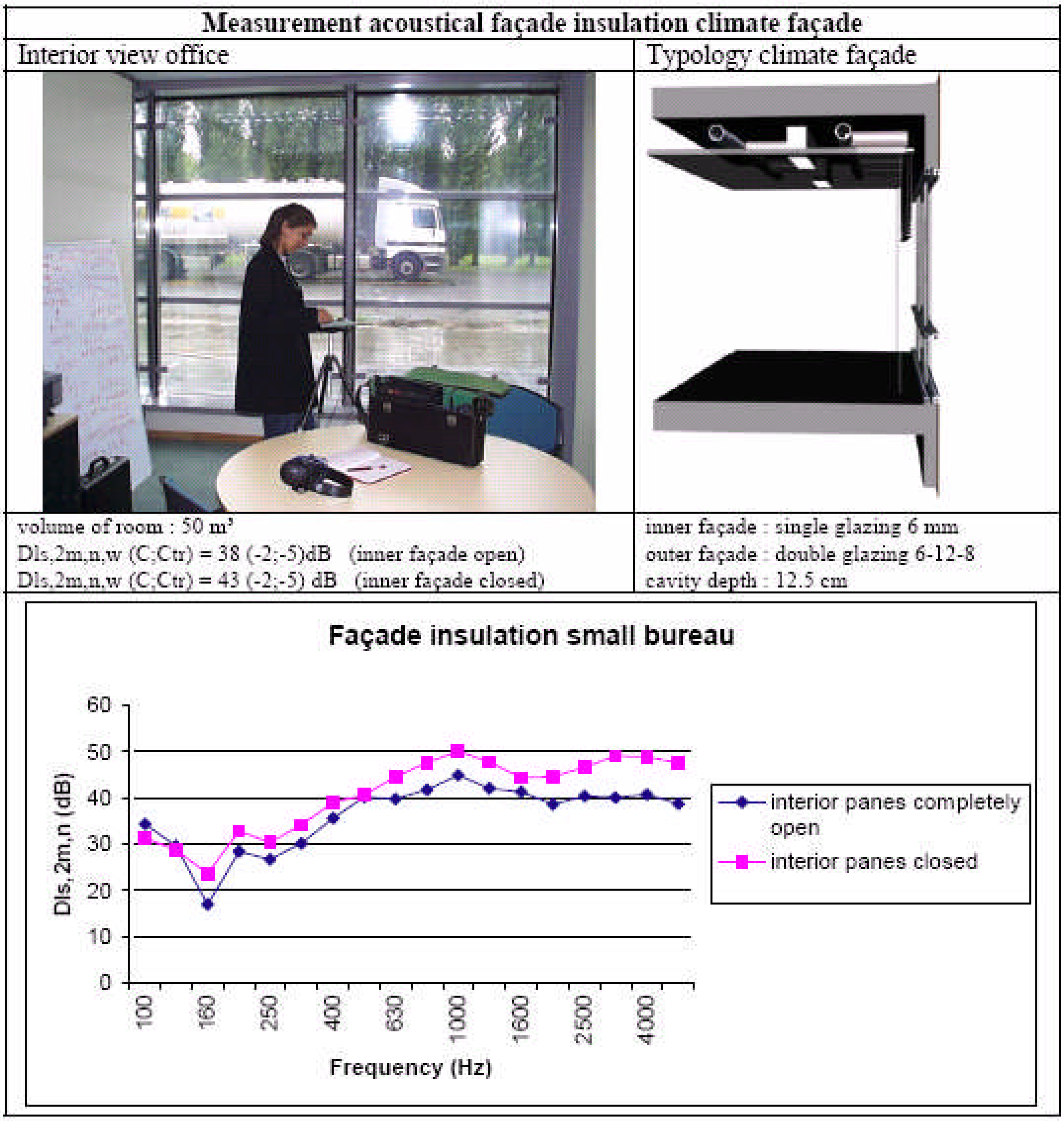
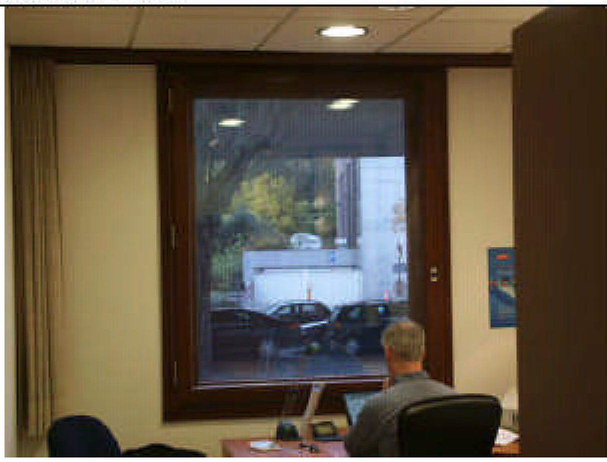
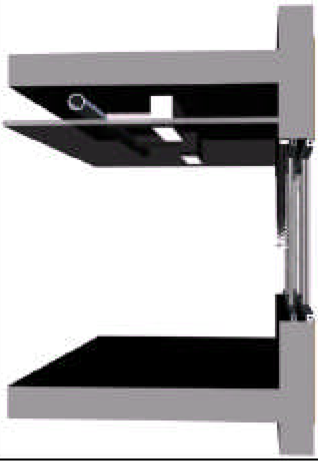


Figure 4.7

Measurement campaign 1 (reference [5])

Measurement campaign DVF 2 (double window) (reference [5])

The façade which separates the room from the street side contains a double window. Both windows can be opened. In the measurement campaign a comparison was made between the situation with both windows closed and the situation where the inner window stands completely open. In the completely closed state the inner window has along the bottom a ventilation slit (extraction via the cavity upwards) with a height of 1,5 cm over the entire width of the window (1,35 m).

Measurement acoustical façade insulation double window	
Interior view office	Typology Double window
	
volume of room : 47 m³ Dls,2m,n,w (C;Ctr) = 41 (-3;-5) dB (inner window open) Dls,2m,n,w (C;Ctr) = 47 (-2;-5) dB (inner window closed)	inner window: 10 mm single glazing outer window: 6-12-8 cavity depth: 7 cm

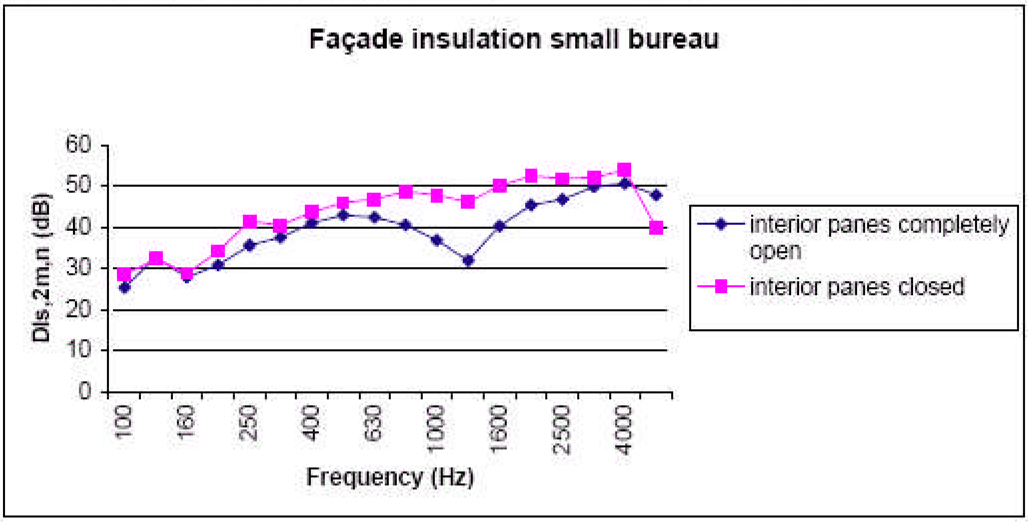


Figure 4.8

Measurement campaign 2 (reference [5])

Measurement campaign DVF 3 (double façade) (reference [5])

The tested façade is a corridor-type ventilated double façade partitioned by storey. The measurements concern the façade insulation of a meeting room on the first storey. All windows were completely closed.

Measurement acoustical façade insulation double façade	
Interior view cavity	Typology double façade
	
Volume of room: 93.1 m³ Dls,2m,nT,w (C;Ctr) = 50 (-1;-5) dB	inner façade: double glazing : 8-12-6 outer façade: single glazing : 6mm cavity depth: 130 cm

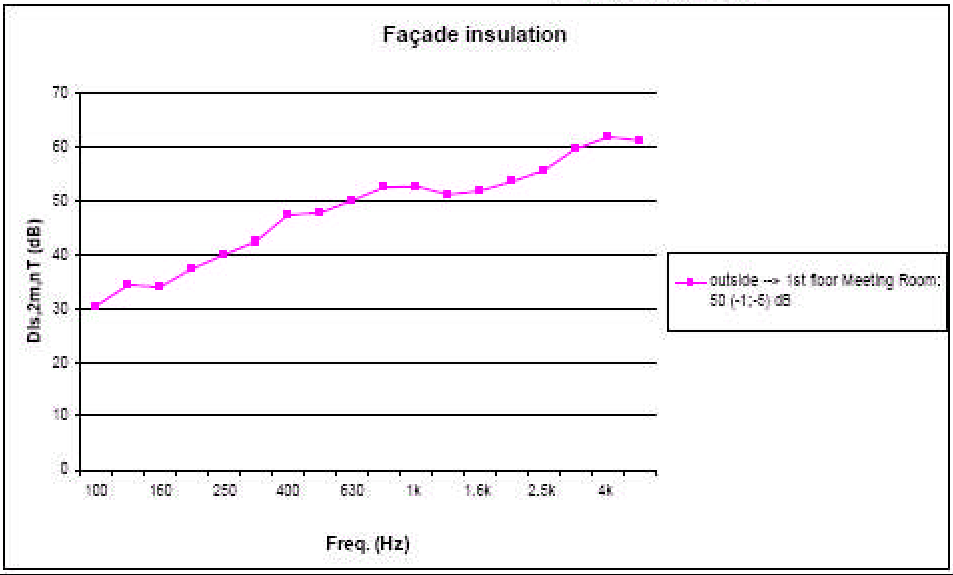


Figure 4.9 Measurement campaign 3 (reference [5])

A summary of the results is given in table 4.2:

Façade type	Façade composition			$D_{ls,2m,n(T),w}$ ($C;C_{tr}$)
	Indoor	Air cavity	Outdoor	
DVF 1 – Ventilated double façade partitioned by storey with juxta-posed modules	6	12,5 cm	6-12-8	43 (-2;-5)
DVF 2 – Double window	10	7 cm	6-12-8	47 (-2;-5)
DVF 3 – Corridor-type ventilated double façade partitioned by storey	8-12-6	130 cm	6	50 (-1;-5)

Table 4.2 DVF: summary of measurement results

In comparison, in Belgium the average façade insulation for residential constructions lies at about 35 dB taking into account all façade components. An acoustical insulation level R_W of 45 dB corresponds approximately to a wall composition of 14 cm of brick (180 kg/m²).

There are quite a few parameters which influence the acoustical performances of a DVF. These are: type of façade system / type of glass / size of glazed surfaces / properties of receiving room / openings / cavity depth / resonance of one and two layers / source properties.

4.2.3 Flanking sound or lateral transmission

Lateral transmission of noise via the air cavity (flanking) can occur in some concepts of façade, mainly with a cavity extending over several offices. Due to this flanking of sound the acoustical insulation between rooms (on different floors) situated at the façade side, is lower compared to buildings with the same internal construction but with no cavity (values up to 8 dB), when no special measures are taken to prevent the (airborne) flanking transmission.

4.2.4 Prediction of the acoustical façade insulation

In order to be able to design a DVF that is effective in the frequency range of low speed traffic noise (31,5 Hz – 63 Hz), the acoustical performance of a DVF must be predicted. In this section, three prediction methods will be developed. The predicted results will be compared to the measured results on DVF 1, DVF 2 and DVF 3 from § 4.2.2.

4.2.4.1 Prediction methods

***Prediction method 1: INSUL version 6.3 (*Marshall Day Acoustics)**

INSUL is a program for predicting the sound insulation of walls, floors, ceilings and double or triple windows. Using this software, the façade insulation of the DVF can be predicted. Together with the theory of double walls, a special empirical routine is built into *INSUL* to predict the performance of double or triple glazing. The software states that it should not be used outside following limits: 3 to 6 mm panes and maximum overall width of the assembly 120 mm.

The DVF's are entered into the program as triple glazing.

Prediction method 2: Three chamber model combined with Mass-Spring-Mass law

A possible way to predict the sound insulation of double wall systems is to see the transmission as the sound transmission in which three spaces are involved: the outside, the cavity and the inside. This is an approximation that is only valid when the cavity width is larger than half of the wavelength: f>172/d. For the smaller frequencies the Mass-Spring-Mass model for double constructions has to be applied.

The three chamber model is based on following formulas:

$$R_{12} = L_{out} - L_{cavity} + 10\log\left(\frac{4 \cdot S}{A_{cavity}}\right) \tag{4.11}$$

$$R_{23} = L_{cavity} - L_{in} + 10\log\left(\frac{S}{A_{in}}\right) \tag{4.12}$$

$$R_{tot} = L_{out} - L_{in} + 10\log\left(\frac{4 \cdot S}{A_{in}}\right) \tag{4.13}$$

$$R_{tot} = R_{12} + R_{23} - 10\log\left(\frac{4 \cdot S}{A_{cavity}}\right) \tag{4.14}$$

The insulation values for the separate façades, R_{12} and R_{23}, are calculated using the software *INSUL*.

For the Mass-Spring-Mass transmission with coupling R_{tot} can be approximated by:

$$R_{tot} = \min(R_{12};R_{23}) + 10 \qquad (4.15)$$

The three chamber model can take into account the presence of ventilation slits in the inner façade:

$$R_{\text{with slit}} = -10\log\left(10^{-R_{\text{glass,no slit}}/10} + \frac{S_{slit}}{S_{glass}}\right) \qquad (4.16)$$

For the prediction of the insulation values with the Mass-Spring-Mass method, results closest to the measured results are obtained when the slits are not taken into account.

Prediction method 3: Three chamber model

The predictions will also be made by applying the three chamber model to all frequencies. As mentioned before, the three chambers model is actually an approximation that is only valid when the cavity width is larger than half of the wavelength: f>172/d. Formula (4.11) is also based on the condition of a diffuse or a reverberant sound field in the cavity. For lower frequencies (with bigger wavelengths), this condition will not be met as there will not be enough reflections in the cavity.

In the prediction method 3, the three chambers model is used for all frequencies to determine the difference between the three chambers model and the Mass-Spring-Mass law.

Comparison of measurements and predictions

The three prediction methods have their limitations, as mentioned above, but for now, these are the best available methods to predict the behaviour of DVF's.

With the software *INSUL*, results down to 50 Hz can be calculated, so the lower frequencies (up to 12,5 Hz) have to be extrapolated from the predictions between 50 Hz and 3150 Hz.

The predictions give results expressed as R_w (C;C_{tr}). To be able to compare this parameter to the measured values D_{nT} (C;C_{tr}), following formula is used:

$$R = L_{out} - L_{in} + 10\log\left(\frac{4 \cdot S}{A}\right) \qquad (4.17)$$

$$D_{nT} = L_{out} - L_{in} + 10 \cdot \log\left(\frac{T}{0,5}\right) \tag{4.18}$$

$$D_{nT} = R + 10 \cdot \log\left(\frac{V}{12 \cdot S}\right) \tag{4.19}$$

The single value indicators $D_{nT,w}$ ($C;C_{tr}$) are calculated according to EN ISO 717-1 (1996) for the frequency range of 100-3150 Hz. For the predicted results, the indicators $C;C_{tr}$ are also calculated for the frequency range of 50-3150 Hz so that the results in the lower frequencies are expressed better.

4.2.4.2 Predicted results and comparison to measured results

DVF 1

The composition of the façade is as follows:

- Inner façade: 6 mm
- Cavity depth: 125 mm
- Outer façade: 6-12-8

In the closed state the inner façade has at the bottom a ventilation slit of 1,5 cm in height over the entire width of the module.

The receiver room has a volume of 50 m³ and the surface of the façade is 8,4 m². The amount of absorption in the cavity A_{cavity} is high and equal to the surface of the façade ($A_{cavity} = S$).

The measured and predicted results are given in table 4.3 and figure 4.10.

$D_{nT,w}$ ($C;C_{tr}$)				$D_{nT,w} + C_{tr}$			
Meas.	Meth. 1	Meth. 2	Meth. 3	Meas.	Meth. 1	Meth. 2	Meth. 3
based on 100-3150 Hz							
43 (-2;-5)	44 (-2;-4)	40 (-1;-4)	47 (-2;-6)	38	40	36	41
based on 50-3150 Hz							
-	44 (-2;-10)	40 (-1;-6)	47 (-2;-8)	-	34	34	39

Table 4.3 Measured and predicted results DVF 1

When the results are compared over the full frequency spectrum (see figure 4.10), method 1 predicts results that are the closest to the measured results. When only the frequencies below 250 Hz are considered, the results from the three methods are comparable.

When the comparison is based one the single value indicator $D_{nT,w}$, it can be seen that method 1 gives a result that is only 1 dB higher than the measured result. The predicted results for $D_{nT,w}$ + C_{tr} are comparable for the three methods and differ 2 to 3 dB from the measured result.

In figure 4.10 one can see that there is a big difference between the three prediction methods for frequencies below 100 Hz. Since the measurements were only carried out as from 100 Hz, the predictions cannot be compared to the measurements.

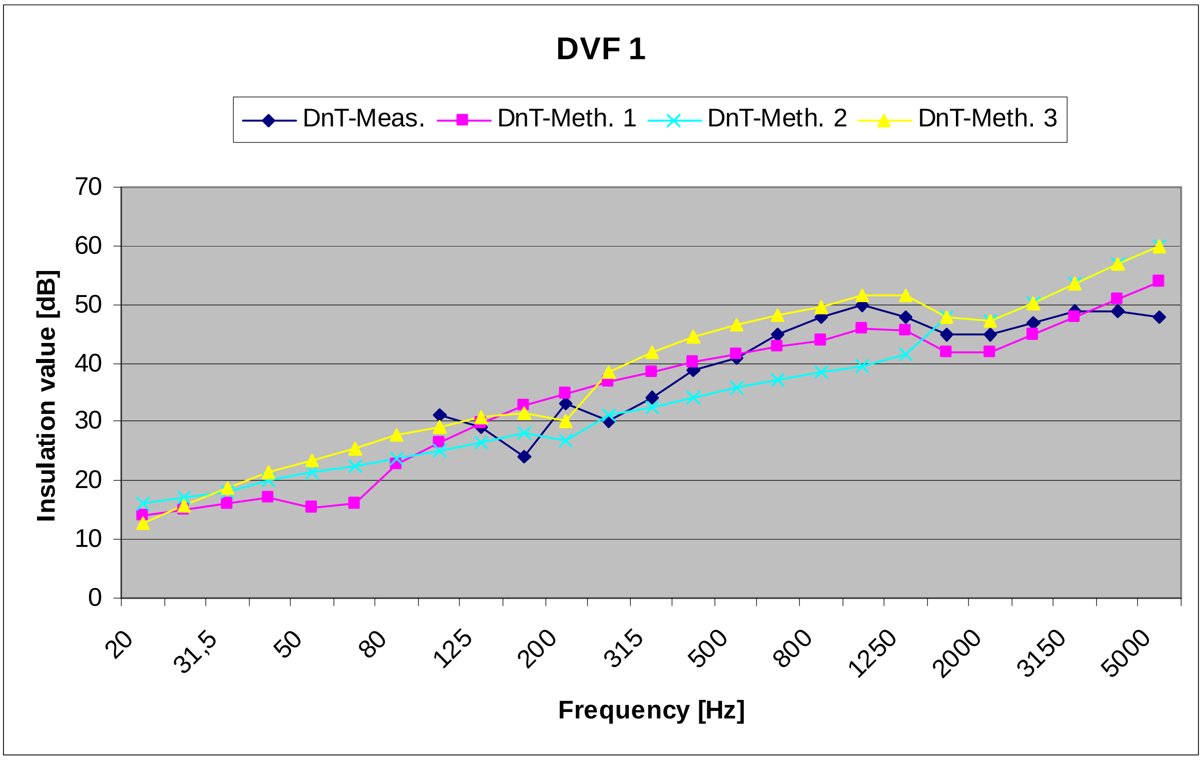


Figure 4.10

Measured and predicted results DVF 1

DVF 2

The composition of the façade is as follows:

- Inner window: 10 mm
- Cavity depth: 70 mm
- Outer window: 6-12-8

In the closed state the inner window has at the bottom a ventilation slit of 1,5 cm in height over the entire width of the module.

The receiver room has a volume of 47 m³ and the surface of the window is 2,0 m². The amount of absorption in the cavity A_{cavity} is low and equal to 0,2 times the surface of the façade (A_{cavity} = 0,2 S).

The measured and predicted results are given in table 4.4 and figure 4.11.

$D_{nT,w}$ ($C;C_{tr}$)				$D_{nT,w} + C_{tr}$			
Meas.	Meth. 1	Meth. 2	Meth. 3	Meas.	Meth. 1	Meth. 2	Meth. 3
based on 100-3150 Hz							
47 (-2;-5)	47 (-1;-3)	47 (-1;-4)	45 (-2;-5)	42	44	43	40
based on 50-3150 Hz							
-	47 (-1;-8)	47 (-1;-5)	45 (-2;-6)	-	39	42	39

Table 4.4 Measured and predicted results DVF 2

For DVF 2 method 1 and 2 give good results compared to the measurements when the whole spectrum in figure 4.11 is considered. For frequencies below 250 Hz, it is method 3 that gives results closest to the measured results.

The single value indicator $D_{nT,w}$ as predicted with methods 1 and 2 is identical to the measured one. The predicted $D_{nT,w} + C_{tr}$ only differs 1 or 2 dB from the measured value for all three methods.

For this DVF, one can see again in figure 4.11 that there is a big difference between the three prediction methods for frequencies below 100 Hz. Since the measurements were only carried out as from 100 Hz, the predictions cannot be compared to the measurements.

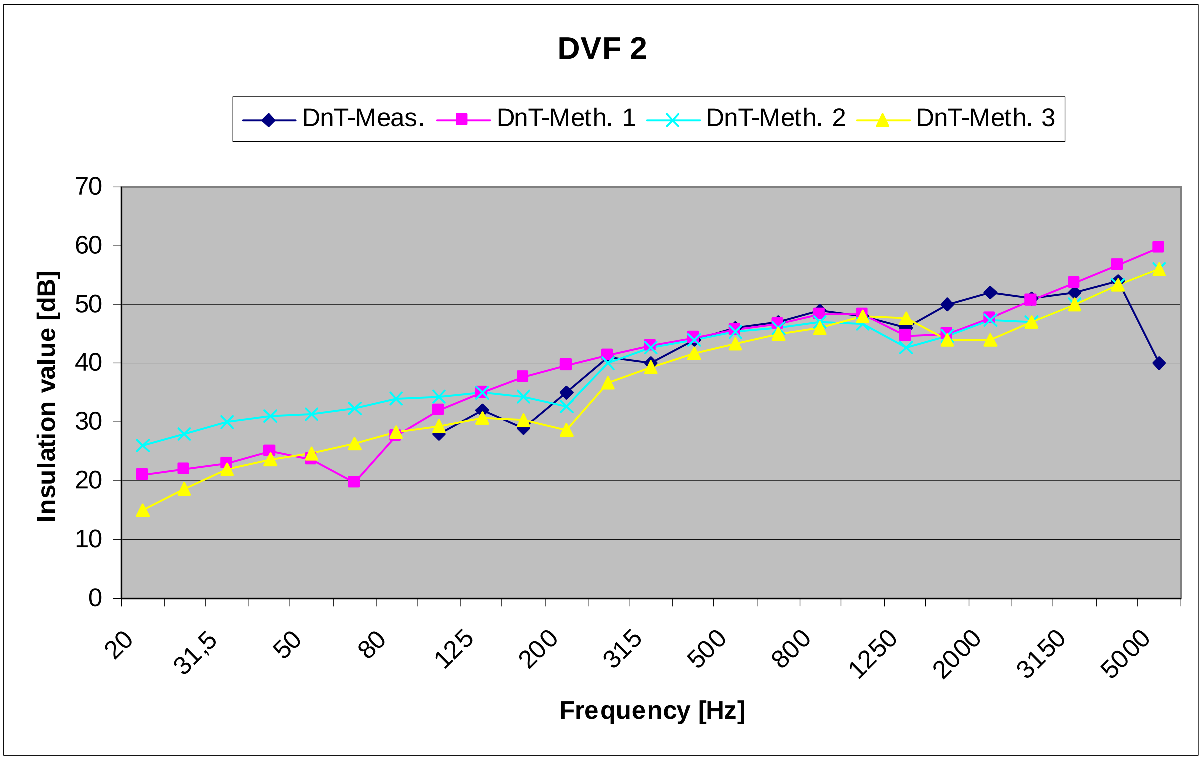


Figure 4.11

Measured and predicted results DVF 2

DVF 3

The composition of the façade is as follows:

- Inner façade: 6-12-8 mm
- Cavity depth: 1300 mm
- Outer façade: 6

The receiver room has a volume of 93,1 m³ and the surface of the façade is about 15,4 m². The amount of absorption in the cavity A_{cavity} is high and equal to the surface of the façade (A_{cavity} = S).

The measured and predicted results are given in table 4.5 and figure 4.12.

$D_{nT,w}$ (C;C_{tr})				$D_{nT,w}$ + C_{tr}			
Meas.	Meth. 1	Meth. 2	Meth. 3	Meas.	Meth. 1	Meth. 2	Meth. 3
based on 100-3150 Hz							
50 (-1;-5)	52 (-1;-4)	51 (-4;-10)	52 (-2;-8)	45	48	41	44
based on 50-3150 Hz							
-	52 (-2;-8)	51 (-5;-13)	52 (-3;-11)	-	44	38	41

Table 4.5 Measured and predicted results DVF 3

Method 1 gives the best results for the whole frequency range, while for frequencies lower than 250 Hz, both methods 1 and 3 lie closely to the measured results.

As for the single value indicator $D_{nT,w}$, the three methods give results that only differ 1 or 2 dB from the measured result. For $D_{nT,w}$ + C_{tr}, it is method 3 that gives the best result (only 1 dB difference with measured result).

For this DVF, one can see again in figure 4.12 that there is a big difference between the three prediction methods for frequencies below 100 Hz. Since the measurements were only carried out as from 100 Hz, the predictions cannot be compared to the measurements.

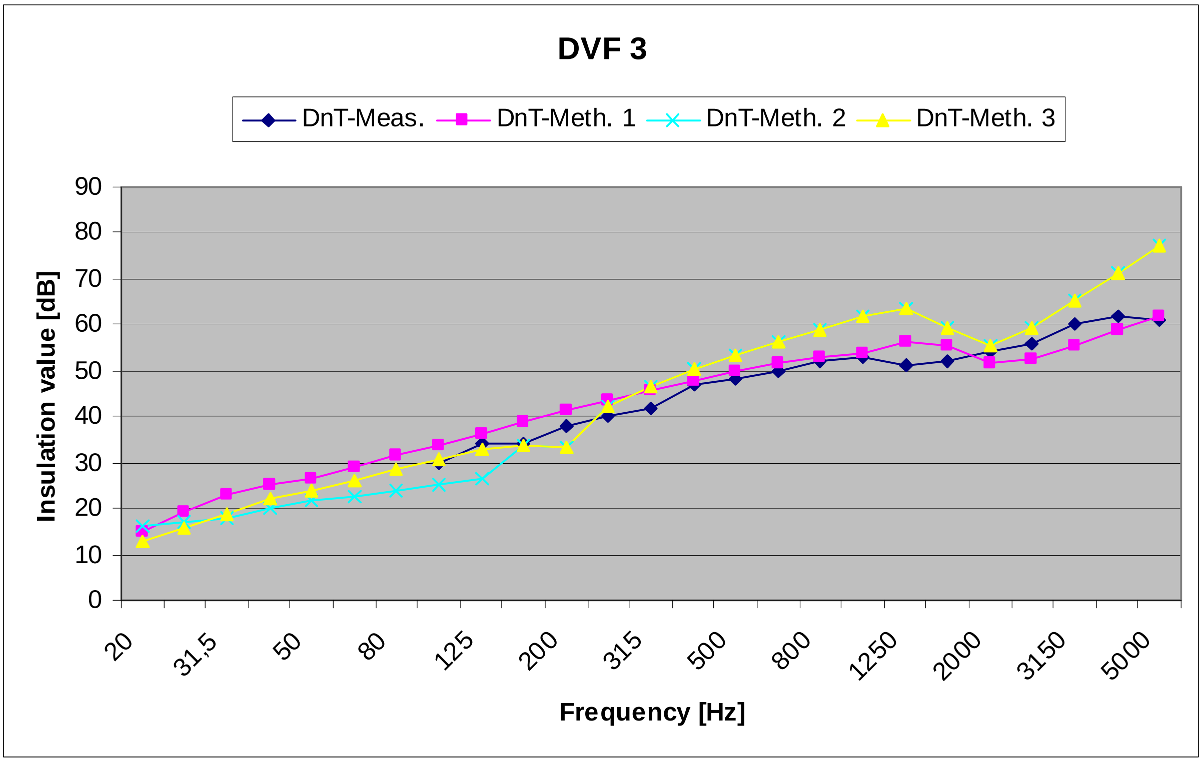


Figure 4.12

Measured and predicted results DVF 3

General conclusion

The results from the three methods lie close together when frequencies above 100 Hz are considered. It depends on the DVF to see which method gives results that are closest to the measured results.

For frequencies below 100 Hz, the predictions could not be compared to the measurements because there were no measurement results below 100 Hz. Below 100 Hz, there are sometimes big differences between the three prediction methods.

As long as the three methods cannot be validated by more measurements, the three methods should be used together to predict the performance of a DVF.

4.2.5 Parametric study on DVF's

To investigate the influence of the different parameters in a DVF, a parametric study will be done. The following parameters are taken into consideration:

- Cavity depth between the inner and the outer façade;
- Thickness of the glass panels in the inner or outer façade;
- Sound absorption in the cavity.

As a basis, the DVF 3 will be used. The original composition of the façade is as follows:

- Inner façade: 6-12-8 mm
- Cavity depth: 1300 mm
- Outer façade: 6
- A_{cavity} = S

4.2.5.1 Variation of cavity depth

The prediction methods 2 and 3 do not take into account the cavity depth. The variation of the cavity depth is therefore only noticeable in the prediction method 1.

The acoustical performance of following DVF's will be predicted:

- DVF 3-A : 6-12-8 / 650 / 6 (resonance frequency = 27 Hz)
- DVF 3: 6-12-8 / 1300 / 6 (resonance frequency = 18 Hz)
- DVF 3-B: 6-12-8 / 2600 / 6 (resonance frequency = 14 Hz)

	$D_{nT,w}$ (C;C_{tr})			$D_{nT,w}$ + C_{tr}		
	Meth. 1	Meth. 2	Meth. 3	Meth. 1	Meth. 2	Meth. 3
	based on 100-3150 Hz					
DVF 3-A	50 (-1;-4)	-	-	46	-	-
DVF 3	52 (-1;-4)	-	-	48	-	-
DVF 3-B	54 (-1;-5)	-	-	49	-	-
	based on 50-3150 Hz					
DVF 3-A	50 (-2;-7)	-	-	43	-	-
DVF 3	52 (-2;-8)	-	-	44	-	-
DVF 3-B	54 (-2;-8)	-	-	46	-	-

Table 4.6 Parametric study: variation of cavity depth

The overal result of raising the cavity depth is an increase of 2 dB per doubling of the cavity depth.

For the lower frequencies (lower than 50 Hz), there is a bigger difference between the three façades. As mentioned before, to obtain a high insulation value at a certain frequency (e.g. 31,5 Hz), the resonance frequency of the façade must be much lower than that frequency. For the façades DVF 3 and DVF 3-B, the resonance frequencies are significantly lower than 31,5 Hz, so for these two façades the predicted insulation values at 31,5 Hz are 4 to 5 dB higher than the insulation value of DVF-A.

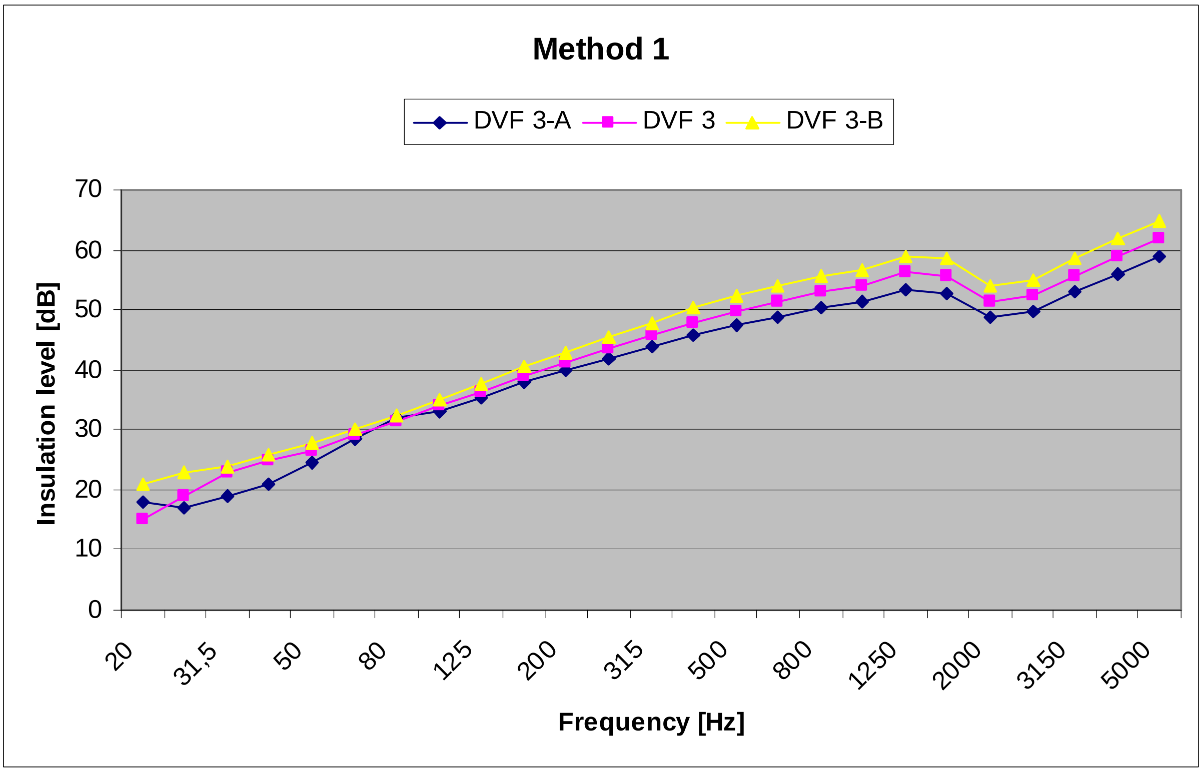


Figure 4.13

Parametric study: variation of cavity depth

4.2.5.2 Variation of thickness of glass plates

The acoustical performance of following DVF's will be predicted:

- DVF 3: 6-12-8 / 1300 / 6
- DVF 3-C : 6-12-8 / 1300 / 6-12-8
- DVF 3-D: 6-12-8 / 1300 / 12
- DVF 3-E: 6-20-10 / 1300 / 6

	$D_{nT,w}$ (C;C_{tr})			$D_{nT,w}$ + C_{tr}		
	Meth. 1	Meth. 2	Meth. 3	Meth. 1	Meth. 2	Meth. 3
	based on 100-3150 Hz					
DVF 3	52 (-1;-4)	51 (-4;-10)	52 (-2;-8)	48	41	44
DVF 3-C	-	54 (-6;-12)	55 (-6;-11)	-	42	44
DVF 3-D	54 (-2;-4)	56 (-5;-11)	57 (-2;-7)	50	45	50
DVF 3-E	52 (-1;-4)	54 (-5;-12)	55 (-3;-9)	48	42	46
	based on 50-3150 Hz					
DVF 3	52 (-2;-8)	51 (-5;-13)	52 (-3;-11)	44	38	41
DVF 3-C	-	54 (-4;-12)	55 (-6;-12)	-	42	43
DVF 3-D	54 (-2;-6)	56 (-6;-14)	57 (-3;-10)	48	42	47
DVF 3-E	52 (-1;-7)	54 (-6;-16)	55 (-4;-12)	45	38	43

Table 4.7 Parametric study: variation of thickness of glass plates

For the frequencies lower than 100 Hz, the three prediction methods give the same conclusions:

- The highest insulation values are obtained with the façades DVF 3-C and DVF 3-D. These façades give an improvement of about 6 dB compared to the façades DVF 3 and DVF 3-E;
- In the lower frequencies, the predicted results for the façades DVF 3-C and DVF 3-D are almost equal;
- In the lower frequencies, the predicted results for the façades DVF 3 and DVF 3-E are almost equal.

If we only look at the single value indicators in table 4.7, these conclusions cannot be taken. So to draw conclusions for the for us interesting low frequency region, we must look at the values per third octave band and not so much at the single value indicators.

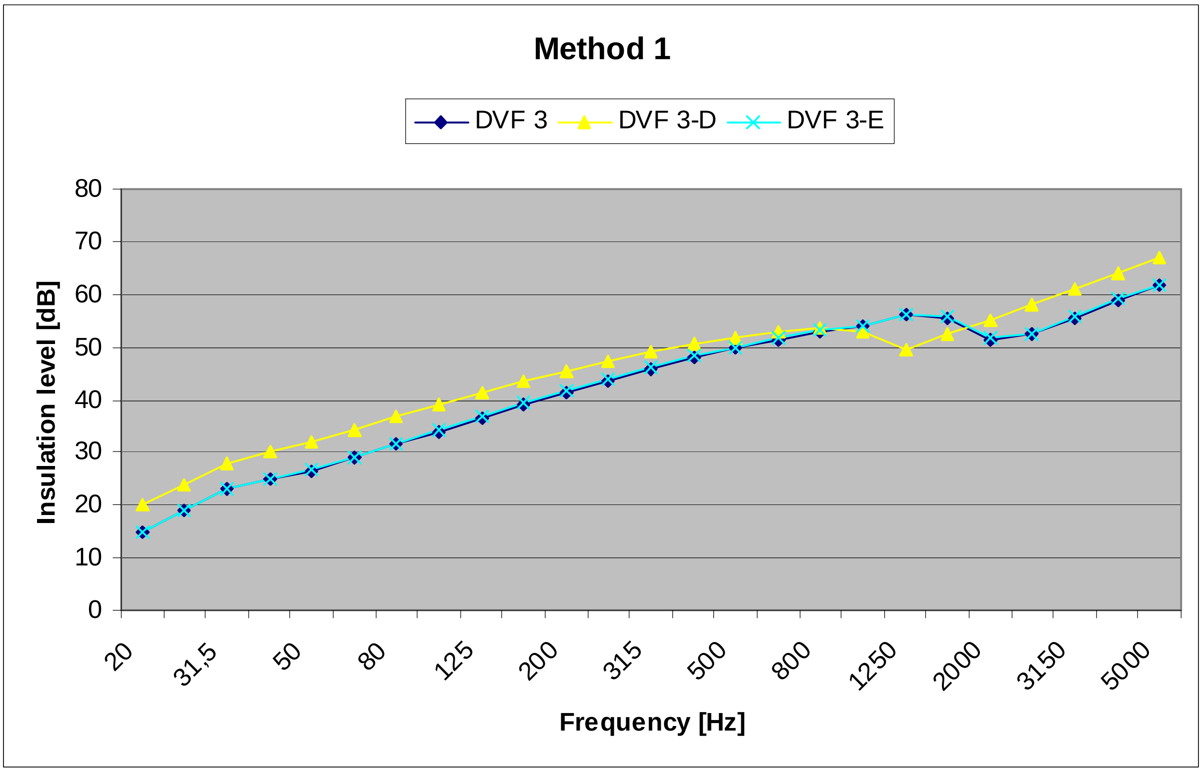


Figure 4.14

Parametric study: variation of thickness of glass plates – method 1

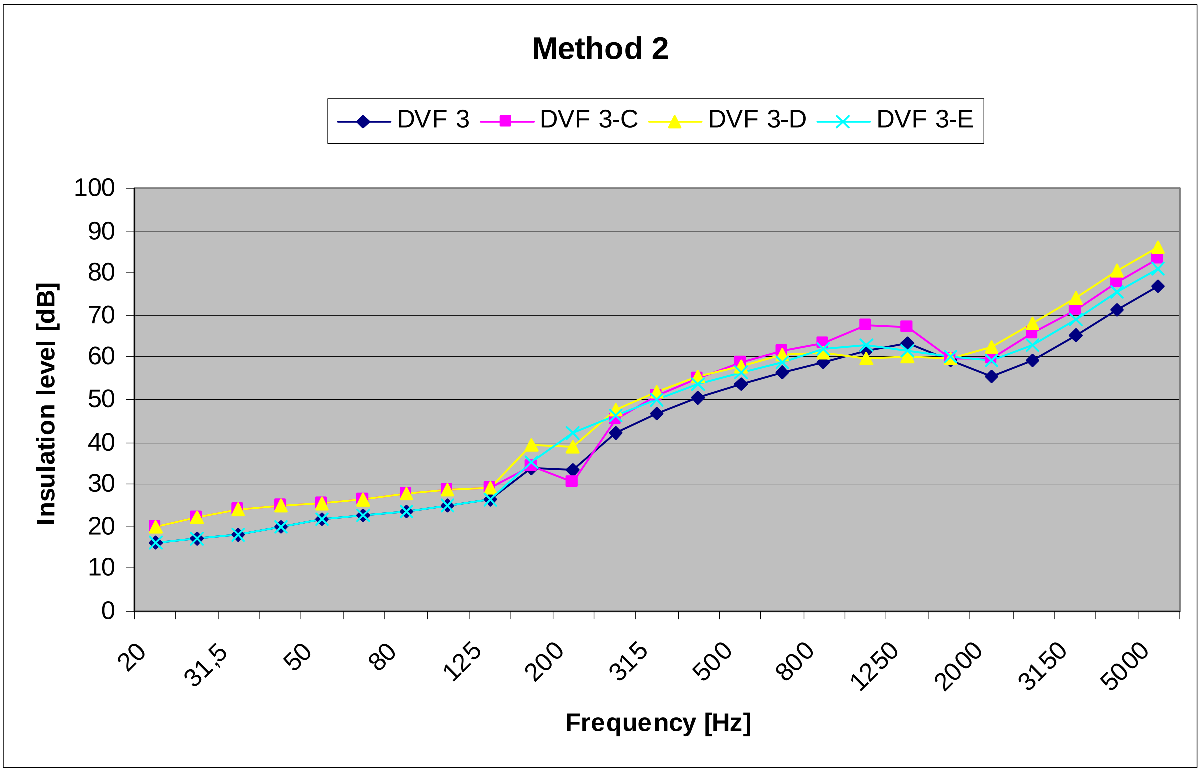


Figure 4.15

Parametric study: variation of thickness of glass plates – method 2

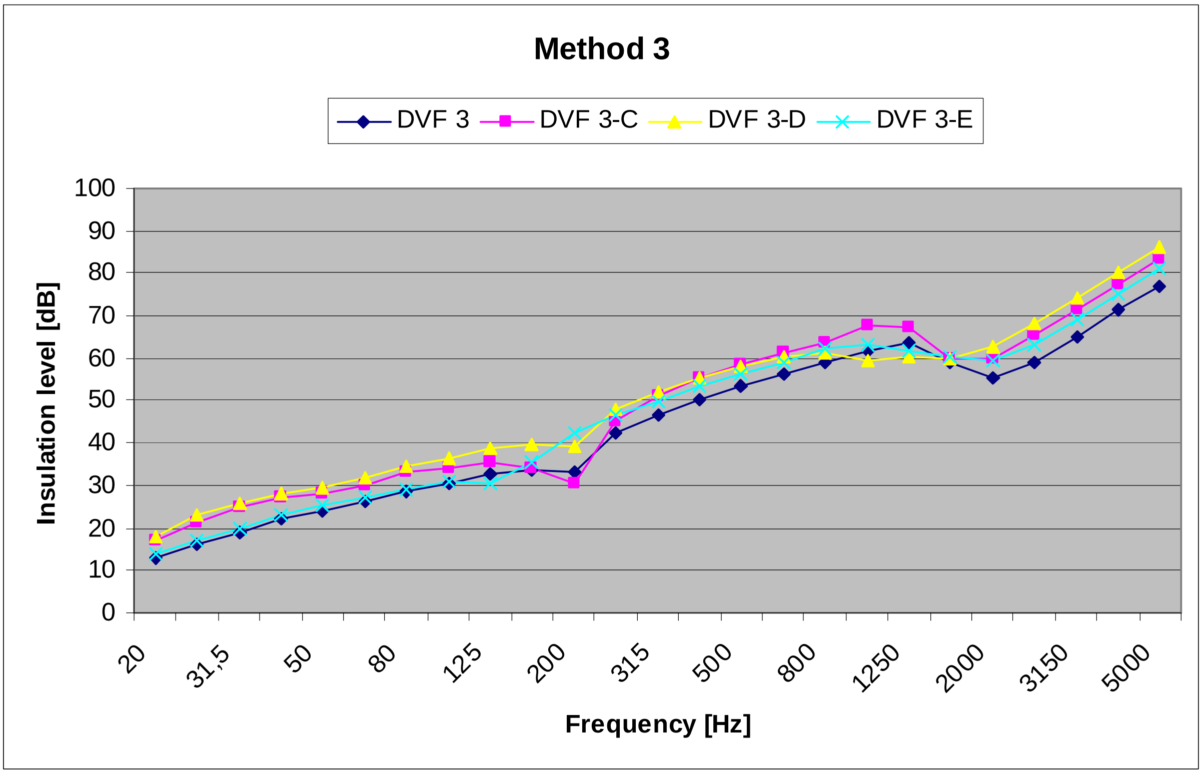


Figure 4.16

Parametric study: variation of thickness of glass plates – method 3

4.2.5.3 Variation of sound absorption in cavity

In the base façade DVF-3, the sound absorption in the cavity is equal to the surface of the glass: A_{cavity} = S. In this section, the variation of the absorption in the cavity will be investigated.

The absorption in the cavity only plays a role in the prediction methods that are based on the three chambers model: method 2 for f>172/d=132 Hz and method 3. Method 1 does not take into account the absorption in the façade.

The acoustical performance of following DVF's will be predicted:

– DVF 3: 6-12-8 / 1300 / 6: A_{cavity} = S
– DVF 3-F : 6-12-8 / 1300 / 6: A_{cavity} = 0,6 S
– DVF 3-G: 6-12-8 / 1300 / 6: A_{cavity} = 0,2 S

	$D_{nT,w}$ (C;C_{tr})			$D_{nT,w}$ + C_{tr}		
	Meth. 1	Meth. 2	Meth. 3	Meth. 1	Meth. 2	Meth. 3
	based on 100-3150 Hz					
DVF 3	-	51 (-4;-10)	52 (-2;-8)	-	41	44
DVF 3-F	-	49 (-3;-9)	50 (-3;-8)	-	40	42
DVF 3-G	-	46 (-3;-8)	45 (-2;-8)	-	38	37
	based on 50-3150 Hz					
DVF 3	-	51 (-5;-13)	52 (-3;-11)	-	38	41
DVF 3-F	-	49 (-4;-11)	50 (-3;-11)	-	38	39
DVF 3-G	-	46 (-4;-10)	45 (-3;-11)	-	36	34

Table 4.8 Parametric study: variation of sound absorption in the cavity

Method 2 only describes the effect of absorption in the cavity for frequencies f>172/d=132 Hz, so for lower frequencies, there is no difference between the three façades DVF 3, DVF 3-F and DVF 3-G.

Method 3 is the only method that shows the effect of increased absorption in the cavity for lower frequencies. There is a difference of 2 dB between the façades DVF 3 and DVF 3-F, and a difference of 7 dB between the façades DVF 3 and DVF 3-G.

Since the effect of absorption in the cavity is considered to be an overall effect in method 3, the same conclusions can be drawn from the single value indicators.

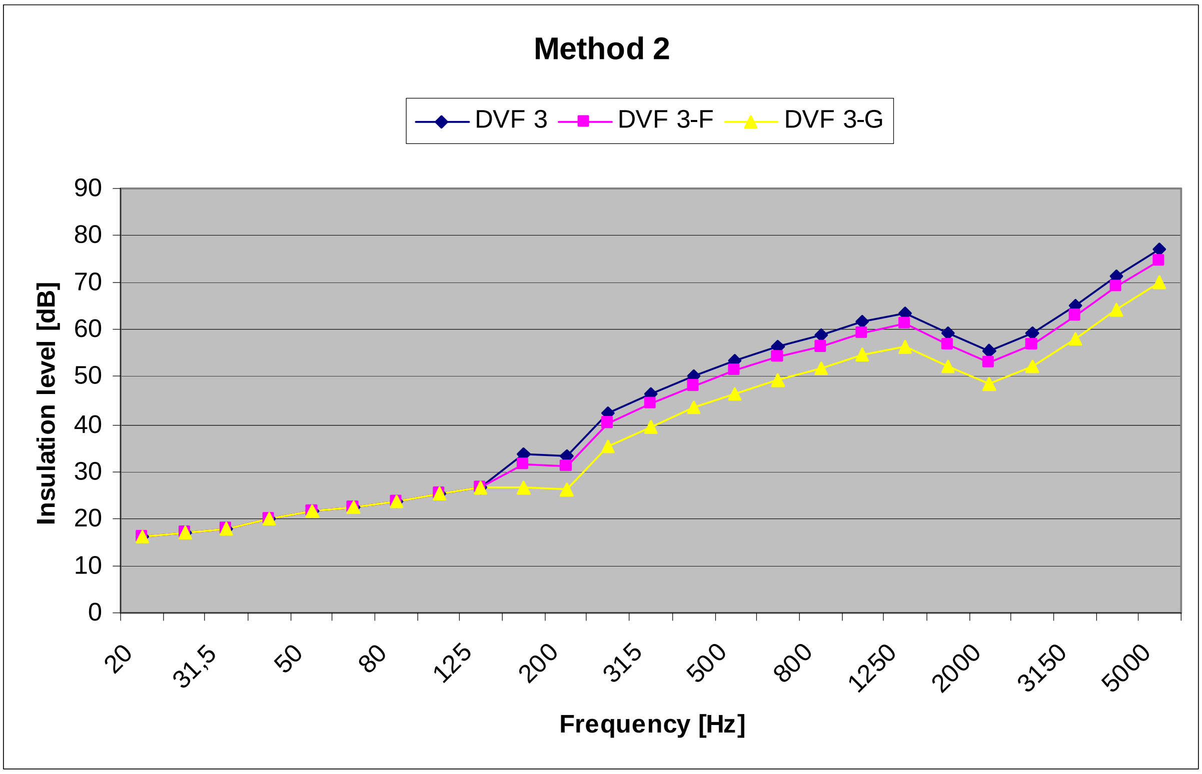


Figure 4.17

Parametric study: variation of sound absorption in the cavity – method 2

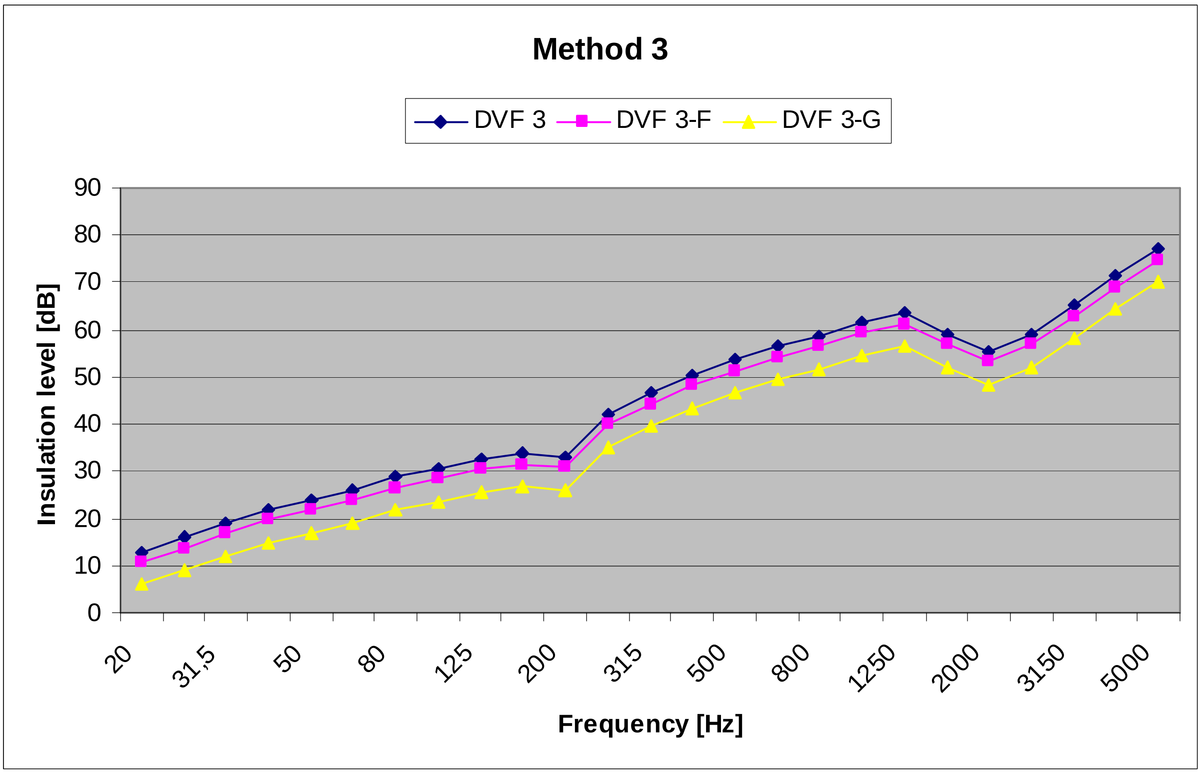


Figure 4.18

Parametric study: variation of sound absorption in the cavity – method 3

4.2.5.4 Optimized DVF

To have a sound insulation as high as possible for the lower frequencies (31,5 Hz and 63 Hz), the parametric study shows that:

1. The cavity depth should at least be 1300 mm;
2. The thickness of the outer glass plate should be increased to 6-12-8 or 12 mm;
3. The absorption in the cavity should be as high as possible (A_{cavity} = S).

The optimized DVF is therefore the façade DVF 3-D:

- Inner façade: 6-12-8 mm;
- Cavity depth: 1300 mm;
- Outer façade: 12 mm;
- A_{cavity} = S.

Figure 4.19 shows the predicted insulation values for this façades using the three prediction methods.

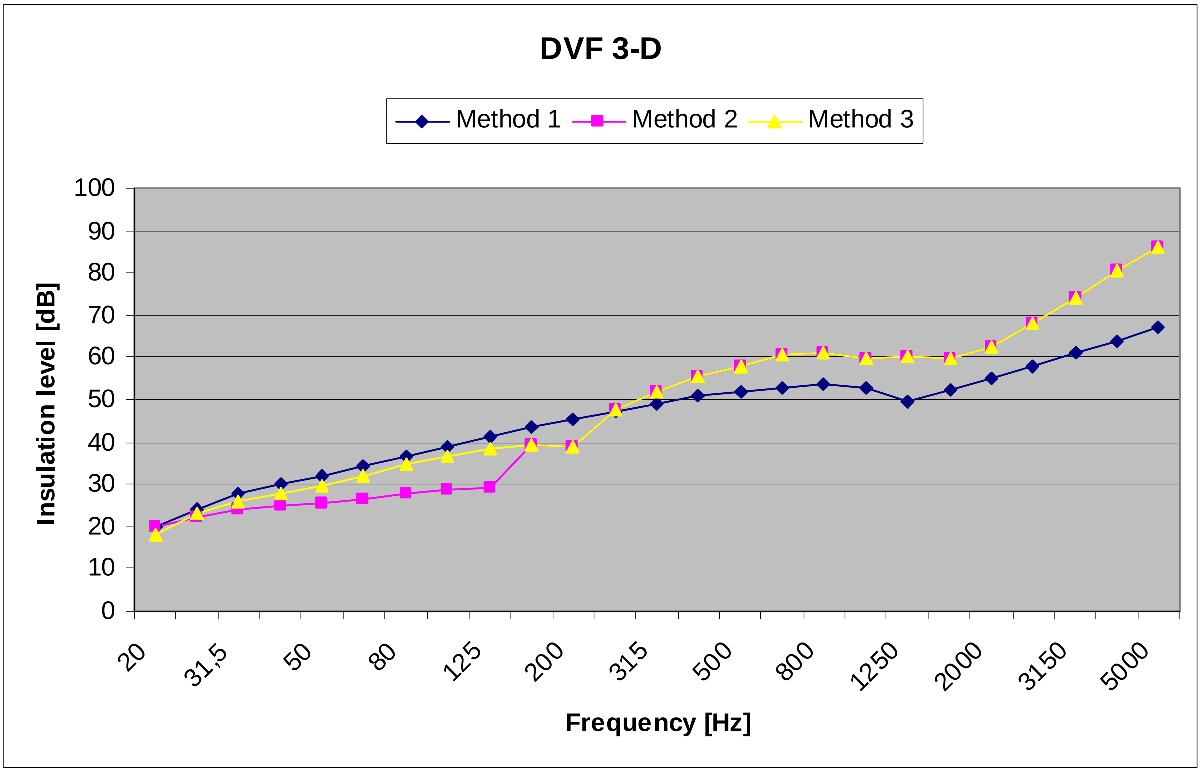


Figure 4.19

Optimized DVF: DVF 3-D

Figure 4.20 compares the results from the prediction method 1 for the DVF 3-D with the insulation values for 6 mm single pane glazing and 6-20-10 mm double glass.

This figure shows that the insulation value of the DVF 3-D is 20 dB higher at 31,5 Hz than 6 mm single pane glazing and 21 dB higher at 63 Hz.

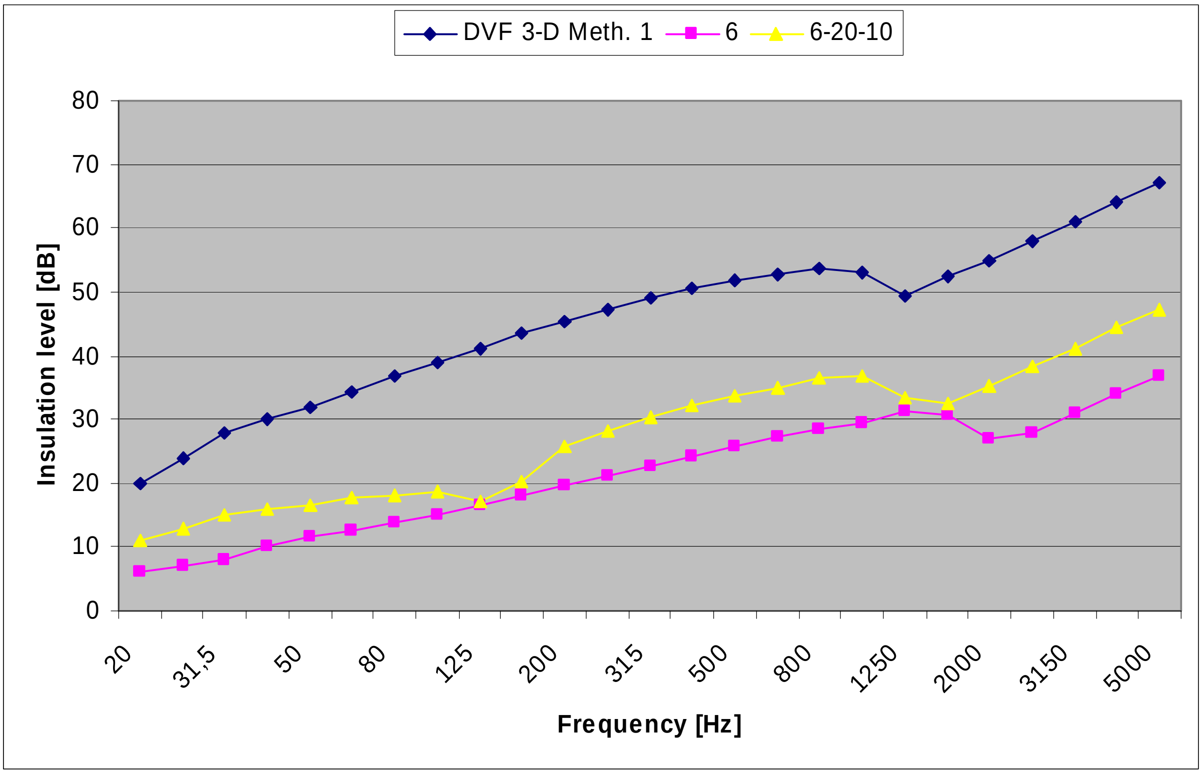


Figure 4.20

DVF 3-D – 6 mm – 6-20-10 mm

4.3 ACTIVE NOISE CONTROL (ANC)

Active noise control (ANC) is using the phenomenon of wave interference: when two waves with the same amplitude and frequency, but phase-reversed, travel in the same direction, they will neutralize each other thanks to destructive interference. The resulting sound is null, the sound energy is transformed into heat. In the simplest form of ANC, a control system drives a speaker to produce a sound field that is the exact mirror-image of the offending sound (the disturbance). The speaker thus cancels the disturbance by means of destructive interference, and the net result is no sound at all.

Investigations show that ANC methods can improve sound transmission loss of double-glazed windows in the low-frequencies (reference [6]). Particularly around the mass-spring-mass resonance frequency of the double-panel system the sound insulation can be enhanced up to 10 dB for white noise excitation.

4.3.1 ANC components

An ANC system consists of the following four major parts:

- Plant: the physical system to be controlled. In the case of the double window this are the glass plates and the cavity;
- Sensors: the vibration sensors, microphones, or other devices that sense the primary disturbance and monitor how well the control system is performing by measuring the remaining error;
- Actuators: the devices that physically do the work of altering the plant response, usually electromechanical devices such as speakers or vibration generators;
- Controller: a signal processor that controls the actuators. It bases its commands on the sensor signals and on some knowledge of the plant's response to the actuators.

Figure 4.21 shows the basic structure of a feedforward ANC system.

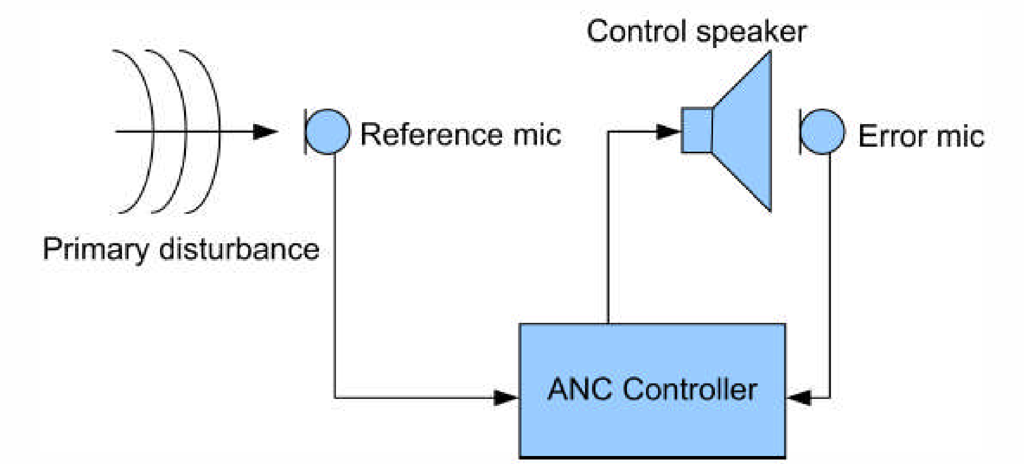


Figure 4.21

Basic structure of a feedforward ANC system

4.3.2 Types of ANC

The active control of a double wall structure can be addressed using either panel control or cavity control.

- Panel control: the radiating panel is equipped with some actuators;
- Cavity control: some volumic sources are located inside the cavity.

4.3.3 ANC approaches

There are two different basic approaches to ANC: feedforward and feedback control.

Feedforward control

These systems depend on a direct measurement of the primary disturbance and on a priori knowledge of the plant transfer function. The approach is known as feedforward compensation because the compensator is not contained within a feedback loop. The advantage of this approach is increased stability since the compensator has no influence on the signal at it's input. Figure 4.22 shows a block diagram of a linear feedforward disturbance cancellation system, where U(s) represents the command input, C(s) represents the compensator, P(s) represents the plant transfer function, D(s) represents the external disturbance and Y(s) represents the system output. G(s) represents the possibility of a linear transformation between the primary disturbance and the estimated value available to the control algorithm. The transfer function from the disturbance input to the system output for the feedforward cancellation algorithm is given in formula (4.20). If the compensator is designed so that $C(s) = -G^{-1}(s) \cdot P^{-1}(s)$, then the overall resulting transfer function equals zero.

$$H(s) = \frac{Y(s)}{D(s)} = 1 + G(s) \cdot C(s) \cdot P(s) \tag{4.20}$$

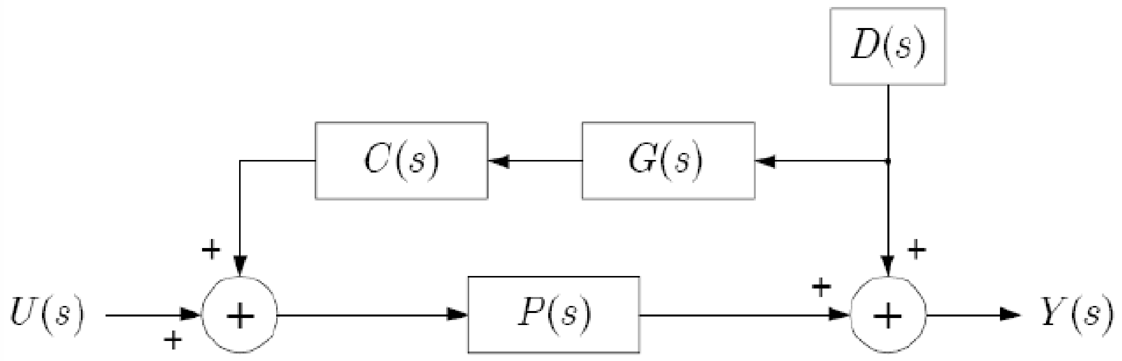


Figure 4.22
Feedforward control

Feedback control

This approach is constantly monitoring the system's output in order to minimize the remaining error. The advantage is that it can compensate dynamic variations in the plant transfer function due to aging, changes in temperature or humidity, etc. The block diagram of a linear feedback control can be seen in figure 4.23. This kind of feedback loop is actually the most common approach to disturbance rejection, by designing the compensator C(s) to minimize the impact of the disturbance D(s) on the closed-loop system output Y(s). For noise cancelling purposes, assume U(s) = 0 as the control signal. In this case, the transfer function from the disturbance input to the closed loop system is given by formula (4.21).

$$H(s) = \frac{Y(s)}{D(s)} = \frac{1}{1 + C(s) \cdot P(s)} \qquad (4.21)$$

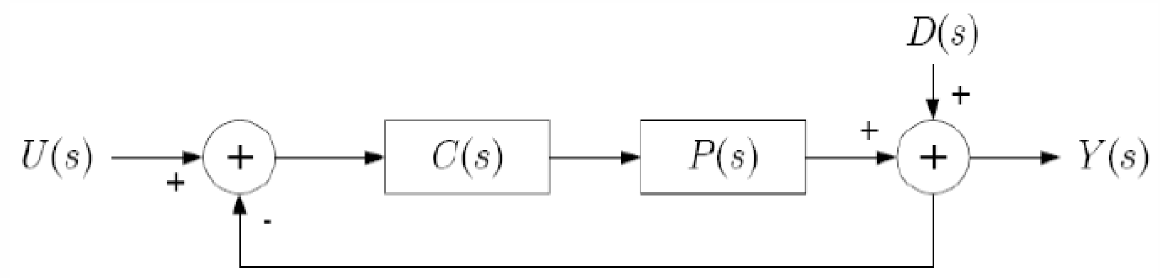


Figure 4.23

Feedback control

4.3.4 Experimental results

Several investigations have been performed concerning ANC in double-glazed windows. This section summarizes the results presented in reference [7] (A. Jakob, M. Möser).

A double glazed window was built, which consists of two 4 mm glass panes with a cavity depth of 40 mm. Figure 4.24 shows the active double glazed window.

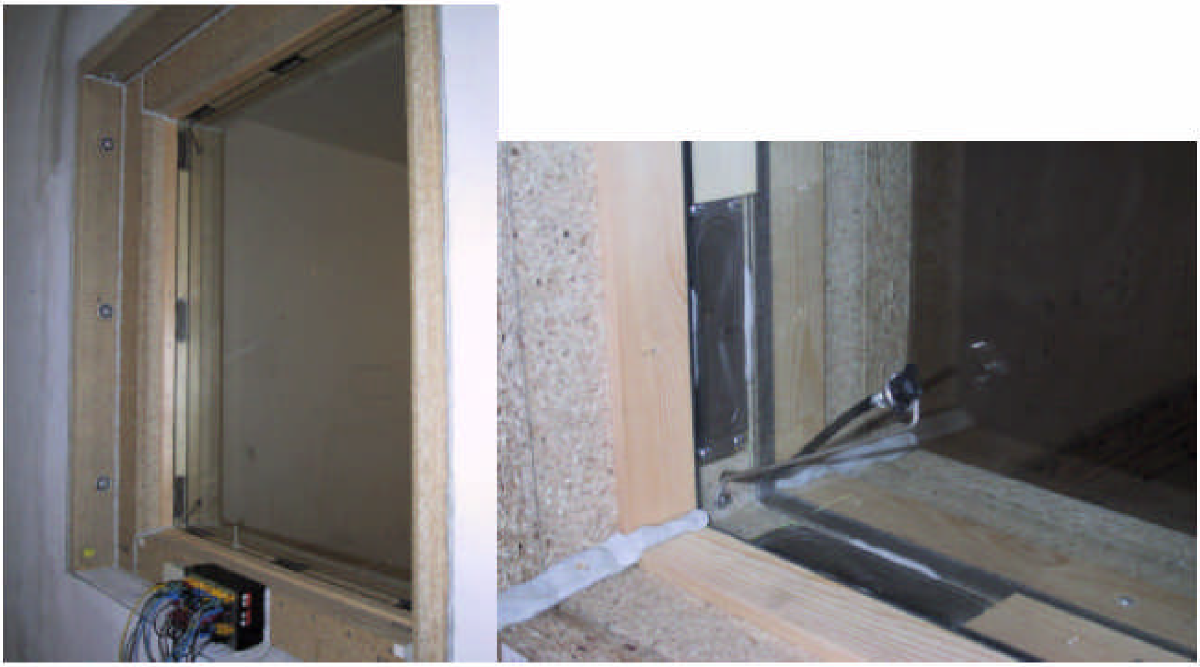


Figure 4.24

Active double glazed window(reference [7])

The mass-spring-mass resonance frequency of the system lies around 125 Hz. Around this frequency active control is most efficiently.

Three loudspeakers were installed at each side of the window frame. Out of these 12 loudspeakers only 9 were used in the experiments presented here. Out of these 9 loudspeakers 3 loudspeakers respectively, belonging to one side respectively, were driven in parallel by one controller output. Four error microphones were installed inside the windows cavity, too, out of which 2 were summed, forming together with the other 2 error microphones 3 error signals. Thus the control system was one with 3 inputs and 3 outputs (3i3o). No additional reference signal was used but a pure feedback scheme with adaptive filters and the multiple error LMS-algorithm.

The loudspeakers have following specifications: power of 2 W, resistance of 16 Ω and a frequency range of 180-17 000 Hz.

In the following measurement results level differences are given between the sound pressure level in the receiving room without and with active control as a mean over time and space: figure 4.25 and 4.26. The achieved results depend strongly on the characteristics of the signal of excitation. In general the algorithm performs better with narrow-band signals with more or less constant signal characteristics, but poorer with broad-band signals and possibly fast changing signal statistics.

For example with the noise source being city-railway, level reductions around the mass-spring-mass resonance frequency of 5,5 dB were yielded.

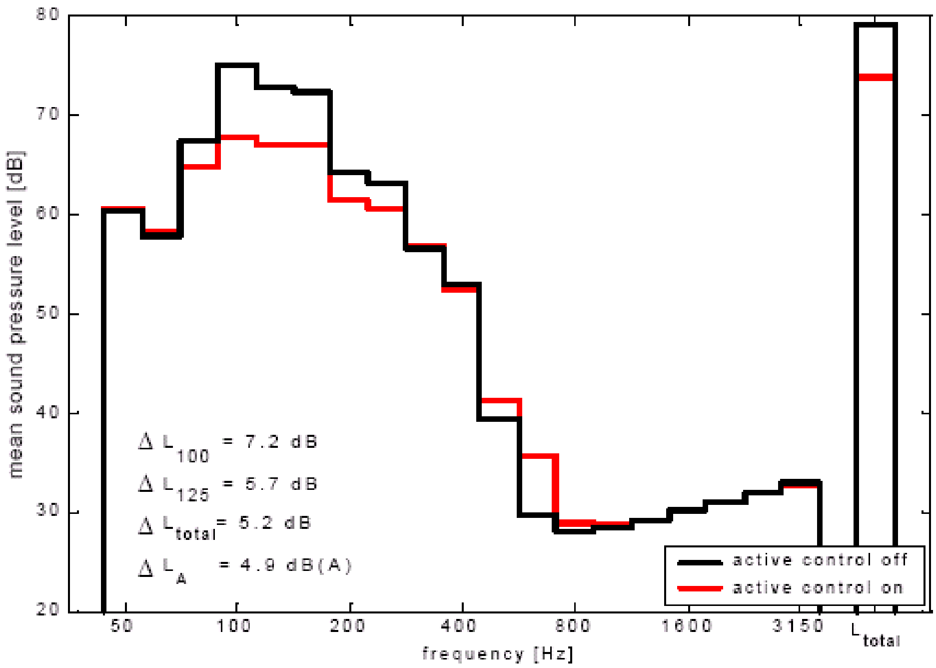


Figure 4.25

Third-octave band mean sound pressure levels measured in the receiving room without and with active control for band-limited white noise excitation (reference [7])

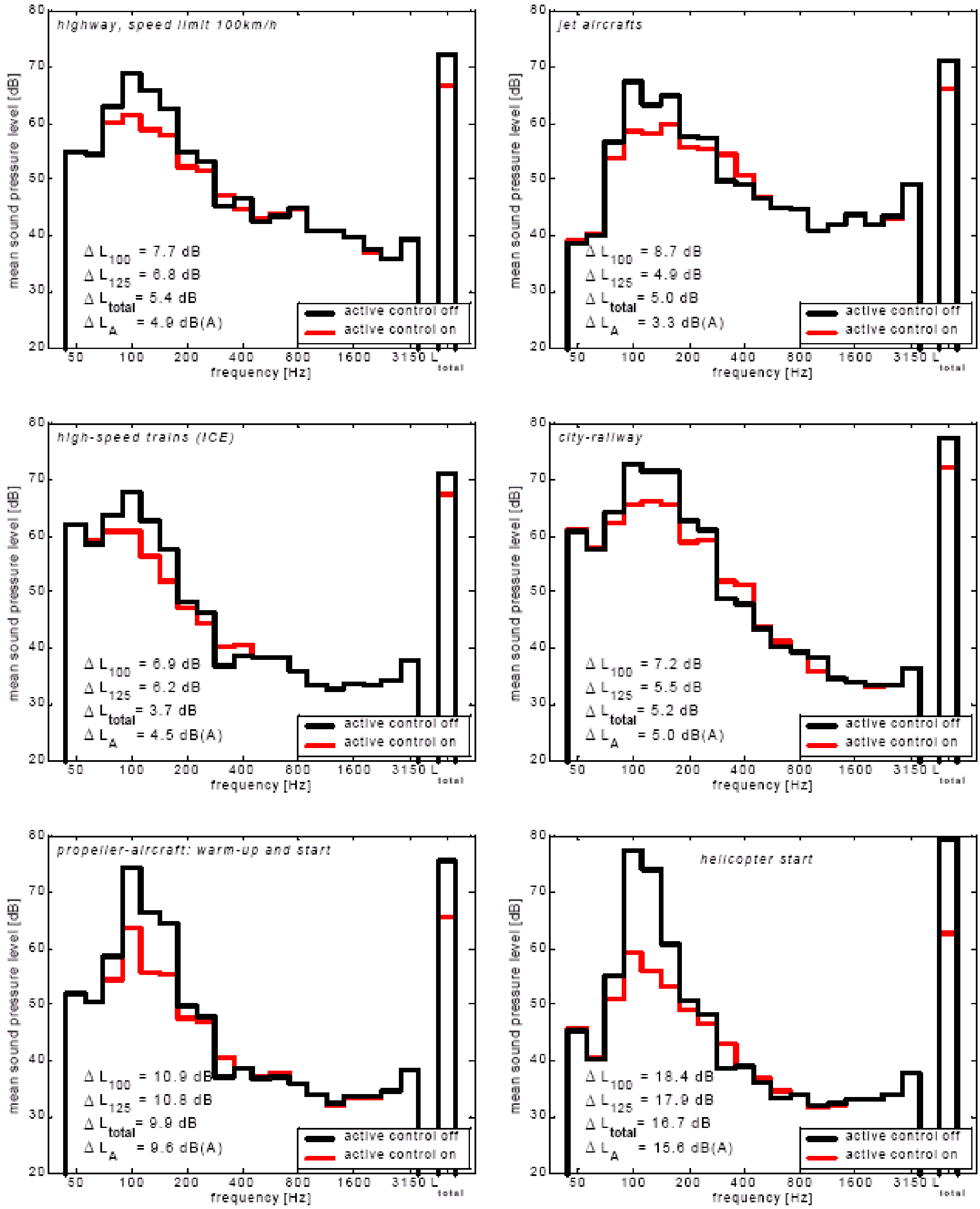


Figure 4.26

Third-octave band mean sound pressure levels measured in the receiving room without and with active control for different traffic noise examples (reference [7])

4.3.5 Conclusion ANC

In the months M13 to M24, the concept of ANC on double-glazed windows will be investigated further.

Experimental results from previous research projects will be collected and examined. The acoustical performance of the ANC on double-glazing will be evaluated taking into account the high costs of ANC systems.

When designing an ANC system, the emphasis will lie on following subjects:

– ANC components: sensors, actuators, controllers;
– Type of ANC: cavity controlled or panel controlled system;
– ANC approach: feedforward or feedback system.

5 CONCLUSIONS

Trucks and buses are major contributors to traffic noise. At low speeds, the engine and exhaust typically produce low frequency noise (LFN) with dominant frequencies between 31,5 Hz en 63 Hz.

Commonly used window types do not perform well when it comes to low frequency sound insulation. Trucks and buses passing by at low speeds and at close proximity to building façades therefore generate noise inside the building with a high low frequency content.

In the CityHush project, windows with a high low frequency sound insulation are developed to reduce the LFN inside the buildings.

The acoustic performance of double windows, more specifically, double ventilated façades (DVF) are investigated. Three prediction methods are described to calculate the sound insulation of DVF's. The three prediction methods have their limitations but for now, these are the best available methods to predict the behaviour of DVF's.

The results from the three prediction methods are compared to the results from a measurement campaign performed on existing DVF's. The results from the three methods lie close together when frequencies above 100 Hz are considered. It depends on the DVF to see which method gives the results that are closest to the measured results.

For frequencies below 100 Hz, the predictions could not be compared to the measurements because there were no measurement results below 100 Hz. Below 100 Hz, there are sometimes big differences between the three prediction methods. As long as the three methods cannot be validated by more measurements, the three methods should be used together to predict the performance of a DVF.

In order to have a sound insulation as high as possible for the lower frequencies (around 31,5 Hz and 63 Hz), a parametric study showed that the optimised DVF is as follows:

- Inner façade: 6-12-8 mm;
- Cavity depth: 1300 mm;
- Outer façade: 12 mm;
- $A_{cavity} = S$.

With this façade, insulation values in the lower frequencies that theoretically are around 20 dB higher than those obtained with a 6 mm single pane glazing.

In the months M13 to M24 a prototype of this façade will be tested in the lab or in situ. A parametric study will also be carried out during the tests to determine the influence of all the parameters and to fine-tune the design of the DVF.

The three prediction methods will also be validated and adjusted as soon as the measurement results in the lower frequencies are available.

Another possibility to increase the transmission loss of windows is to use an active noise control (ANC) system.

Investigations show that ANC methods can improve sound transmission loss of double-glazed windows in the low-frequencies. Particularly around the mass-spring-mass resonance frequency of the double-panel system, the sound insulation can be enhanced up to 10 dB for white noise excitation.

In the months M13 to M24, the concept of ANC on double-glazed windows will be investigated further.

Experimental results from previous research projects will be collected and examined. The acoustical performance of the ANC on double-glazing will be evaluated taking into account the high costs of ANC systems.

6 REFERENCES

[1] Nederlandse Stichting Geluidhinder., "NSG-Richtlijn Laagfrequent Geluid (in Dutch, Trans: "Guidelines for Low-Frequency Noise")", Nederlandse Stichting Geluidhinder, The Netherlands, (1999).

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[3] G. Vermeir, "Bouwakoestiek", Acco, (2003).

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[6] A. Milosevic, U. Schaufelberger, "Active noise control", University of Applied Sciences Rapperswil HSR, (2005).

[7] A. Jakob, M. Möser, "An actively controlled double-glazed window with small pane distance", Forum Acusticum, (2002).

APPENDIX A: FIGURES MEASUREMENT CAMPAIGN

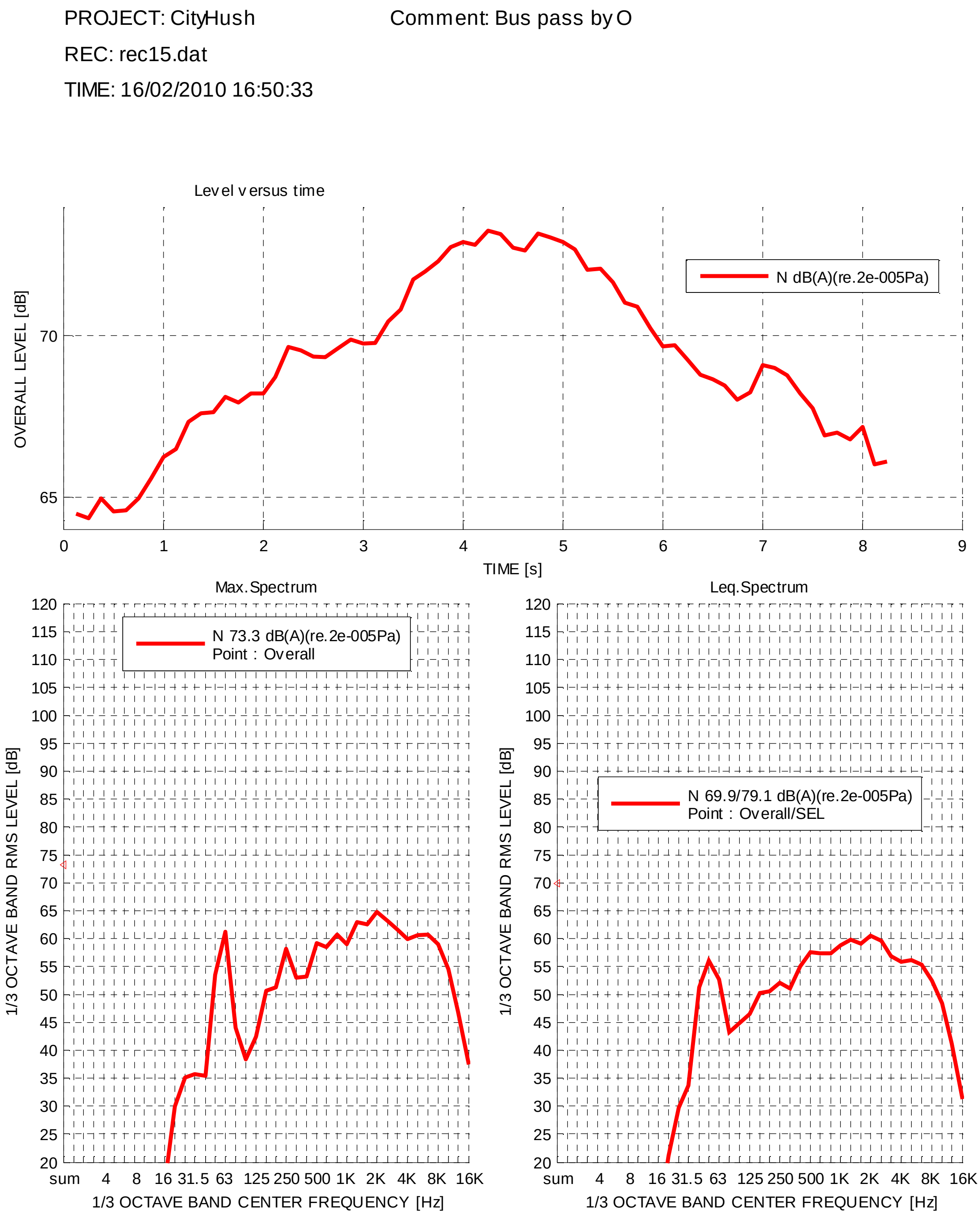

Figure A.1

Bus pass-by

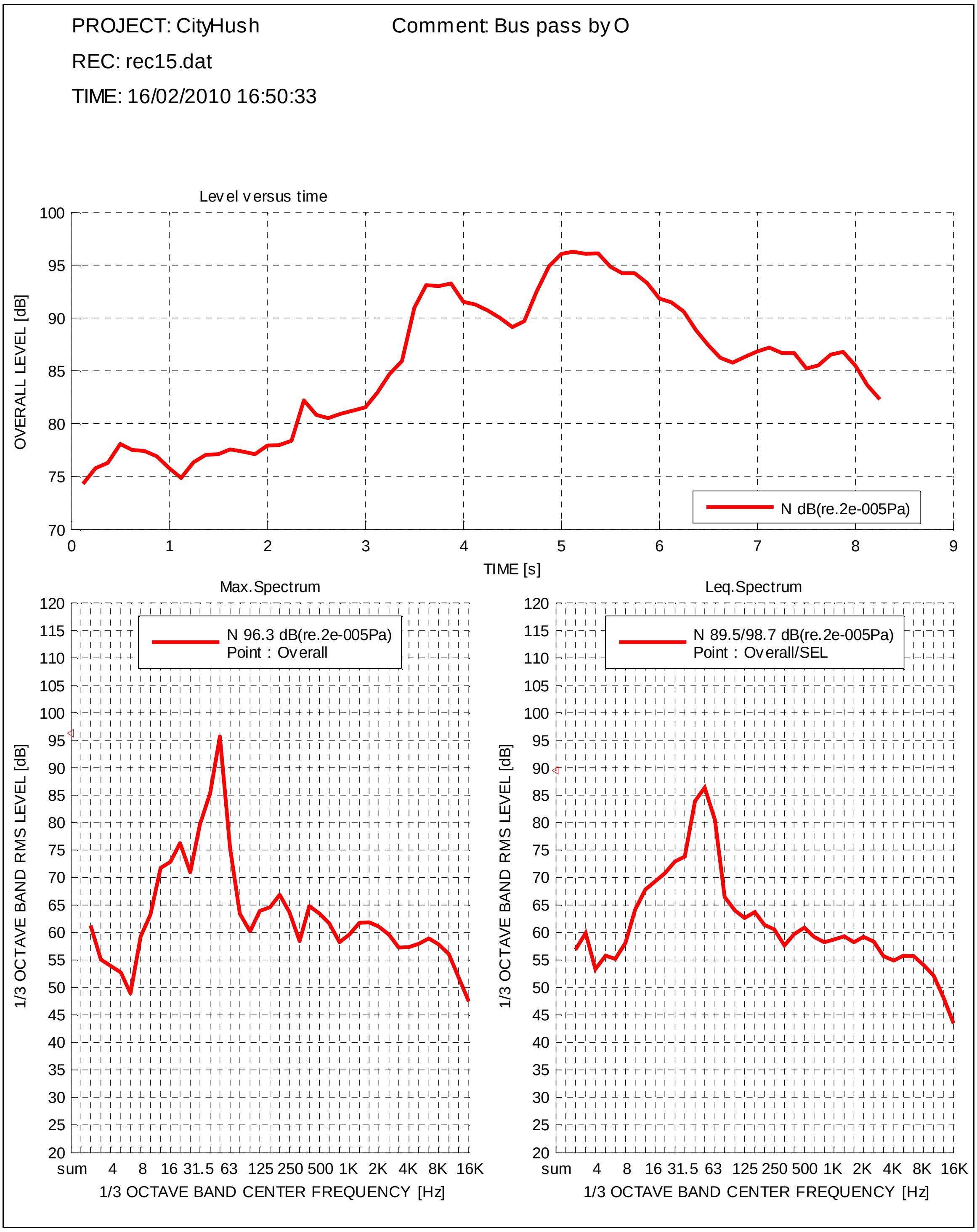

Figure A.2

Bus pass-by

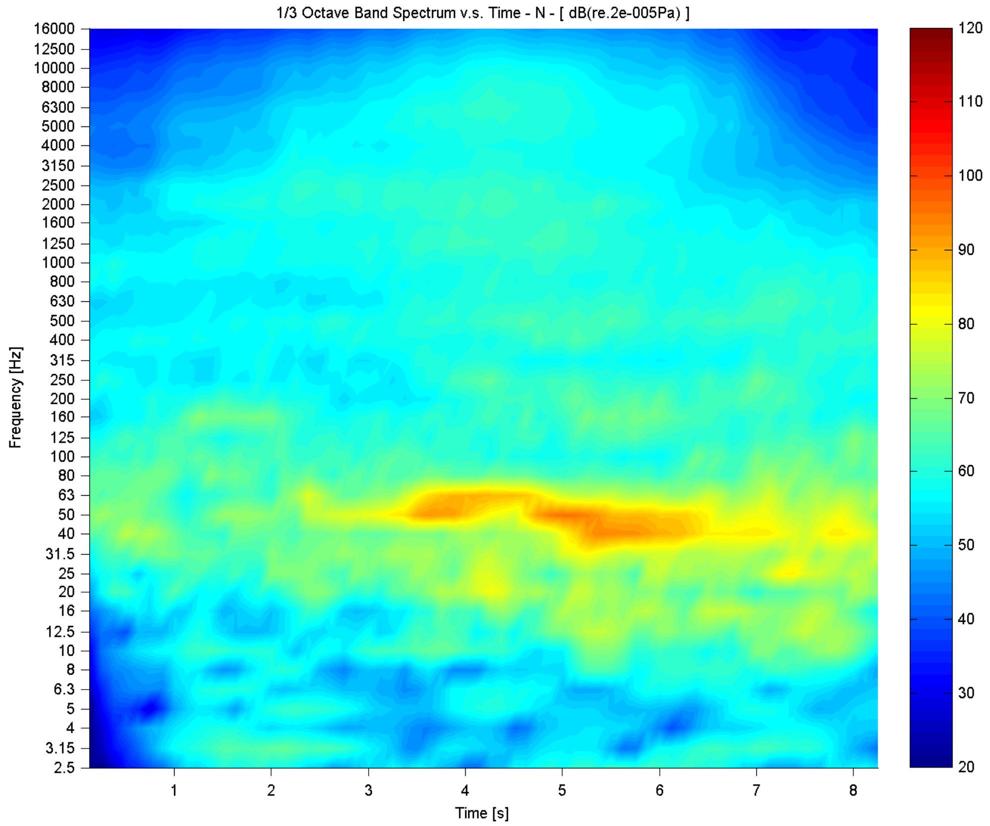

Figure A.3

Bus pass-by

PROJECT: CityHush   Comment: Bus idling O
REC: rec19.dat
TIME: 16/02/2010 16:56:25

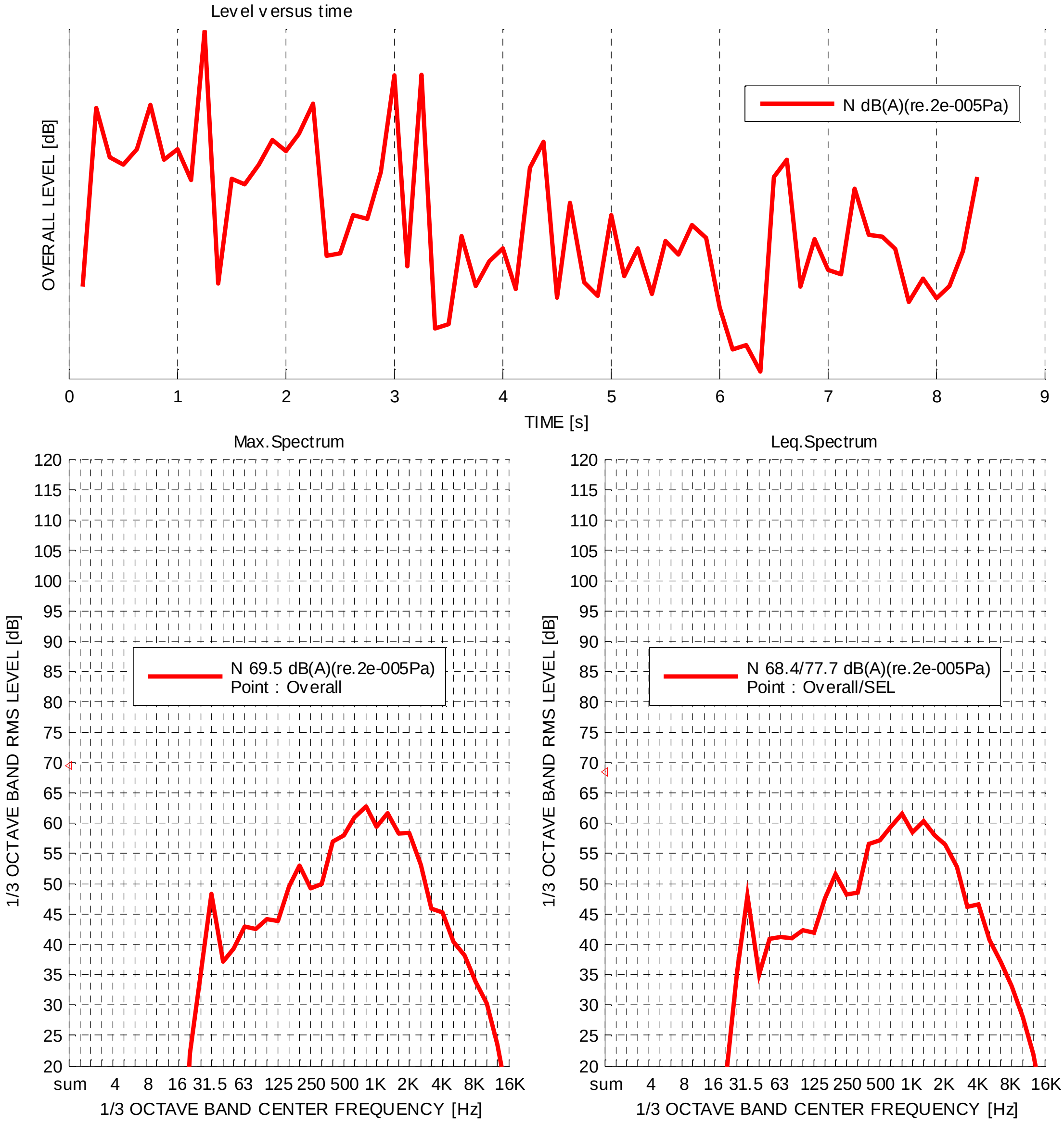

Figure A.4

Bus idling

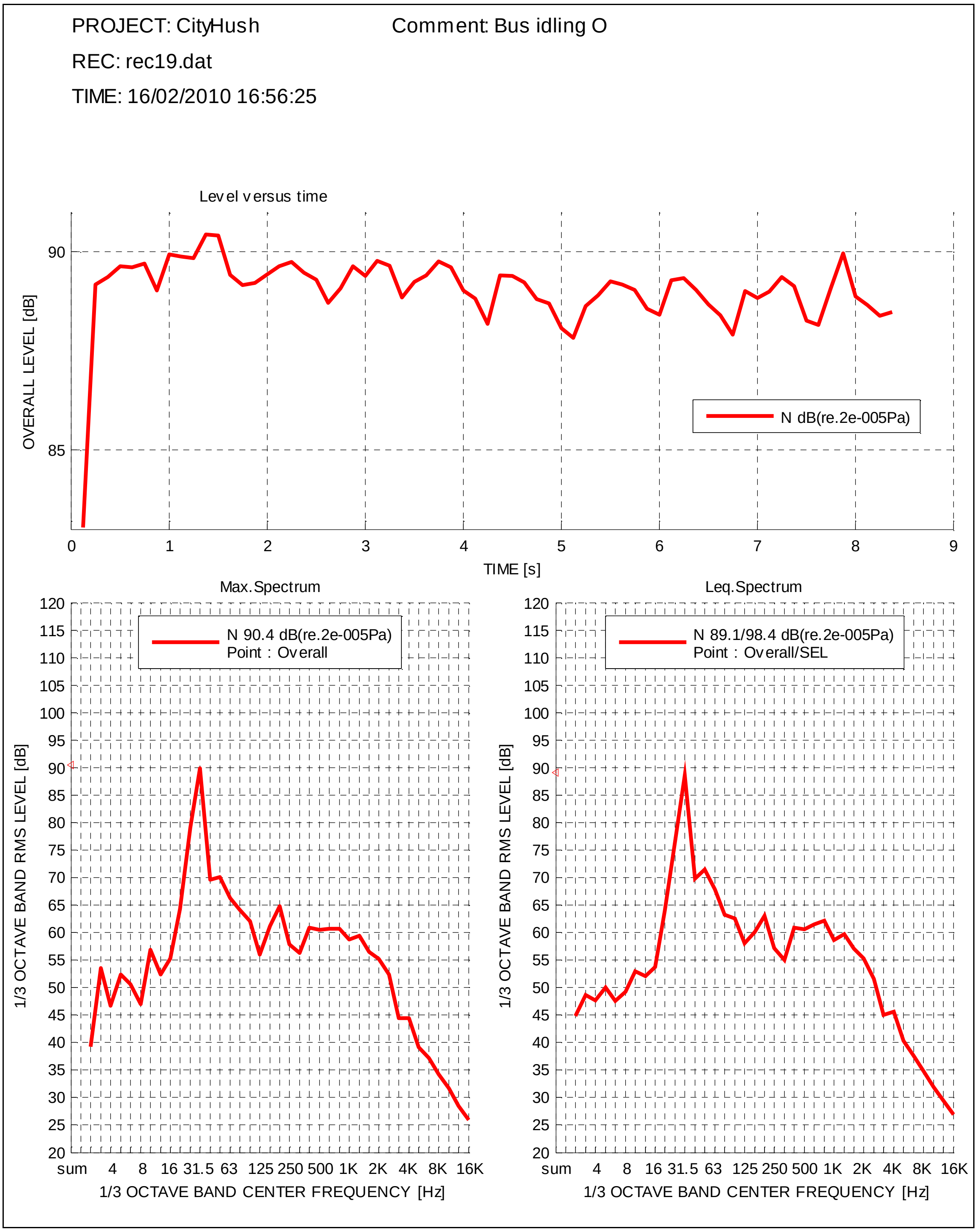

Figure A.5

Bus idling

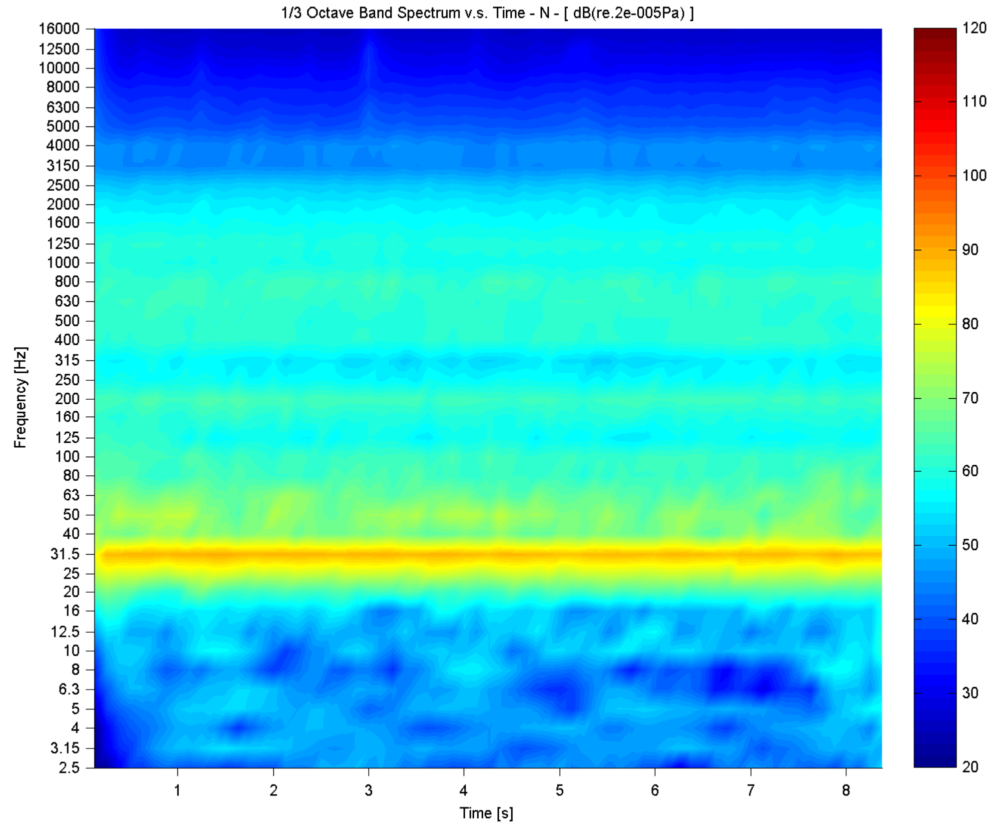

Figure A.6

Bus idling

PROJECT: CityHush Comment: Departure bus O

REC: rec20.dat

TIME: 16/02/2010 16:56:54

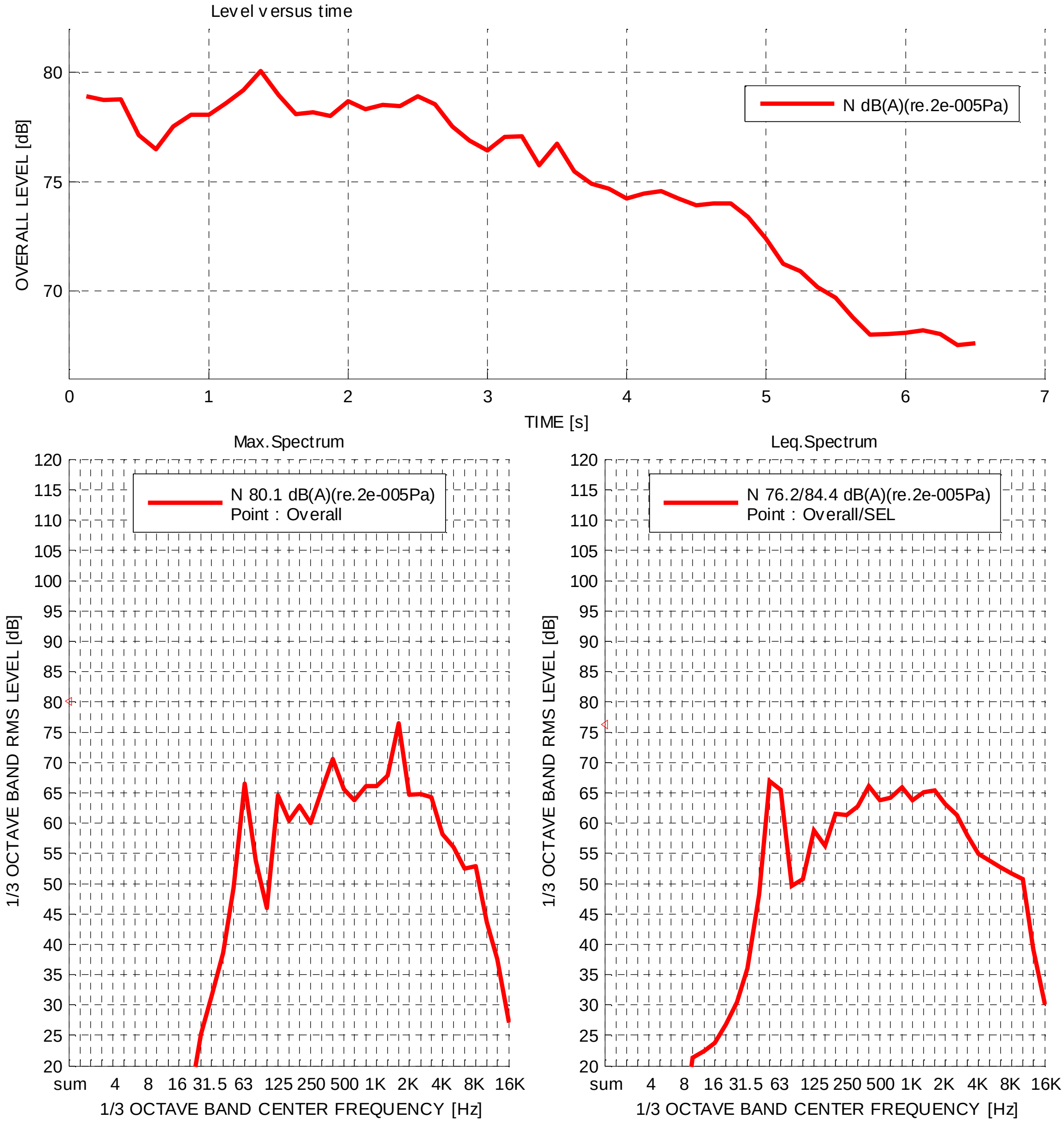

Figure A.7

Bus departure

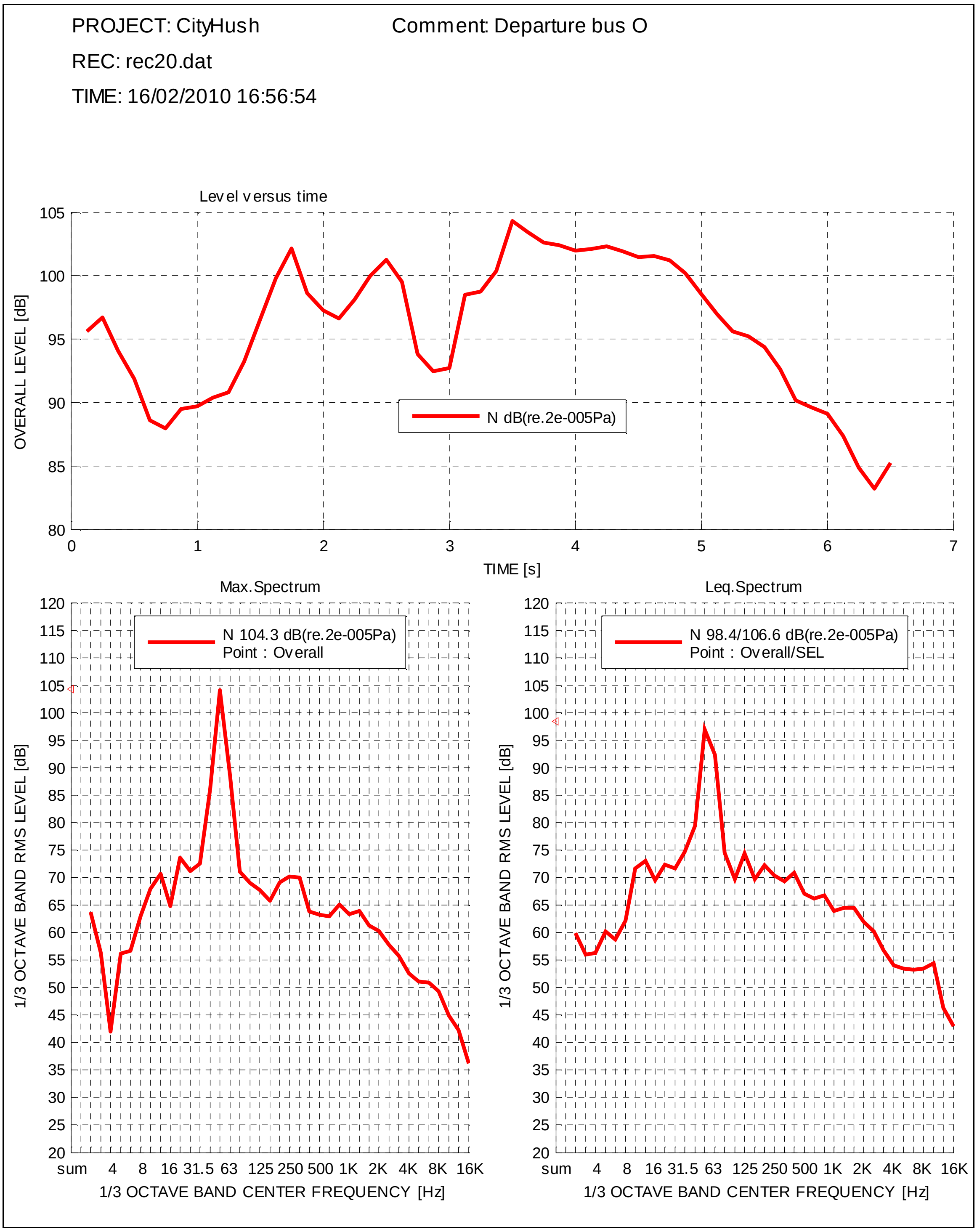

Figure A.8

Bus departure

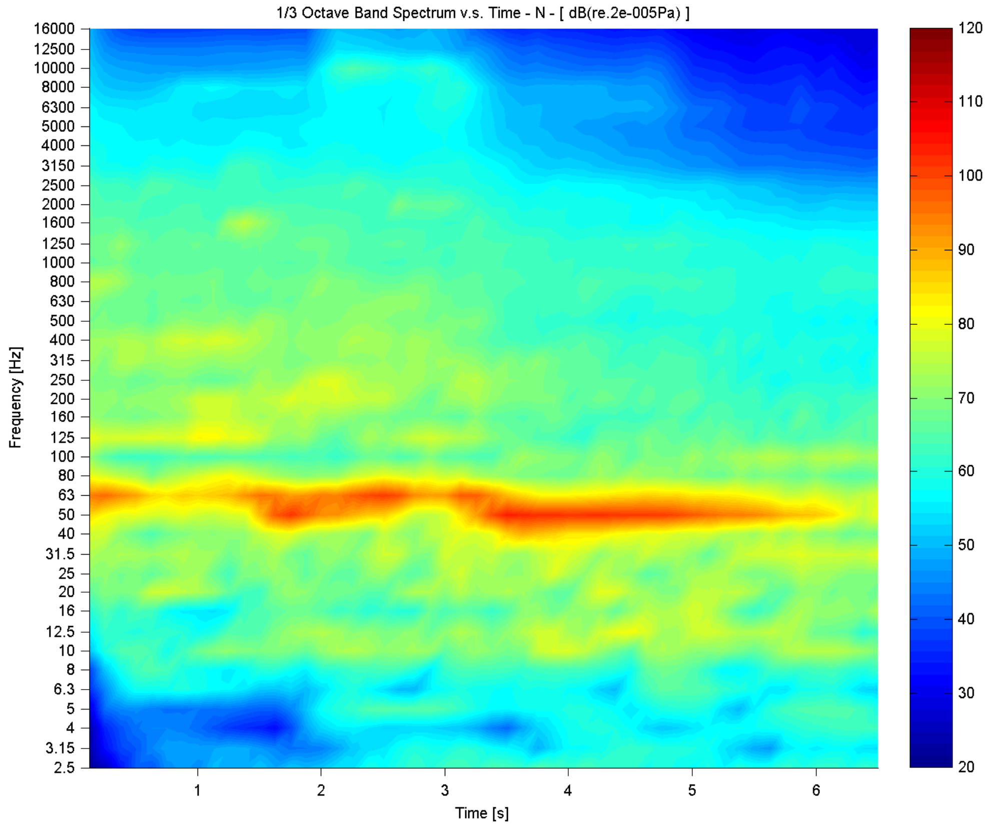

Figure A.9

Bus departure

PROJECT: CityHush
REC: rec11.dat
TIME: 16/02/2010 16:42:15

Comment: Arrival bus + idling + departure O

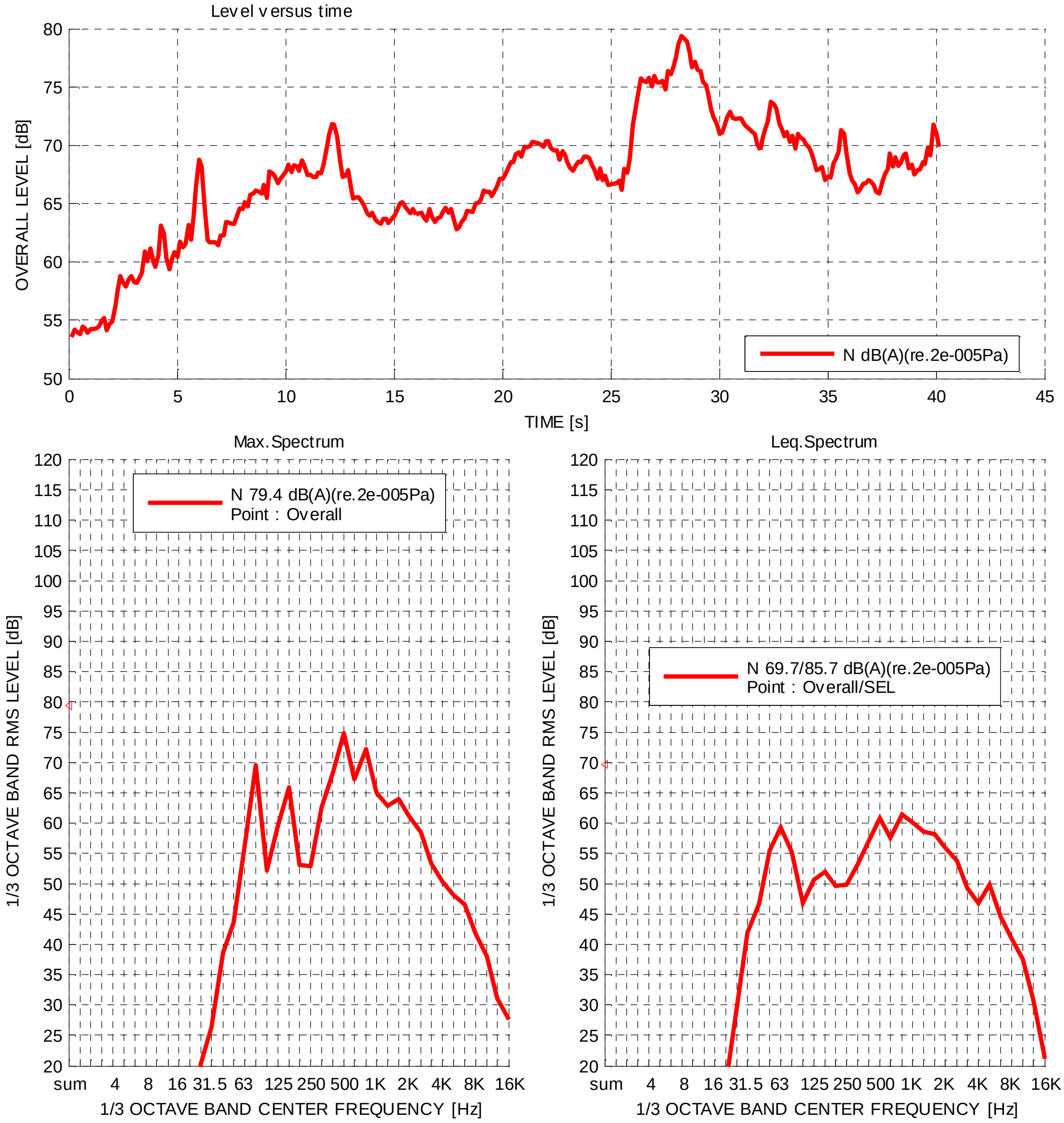

Figure A.10

Bus arrival + idling + departure

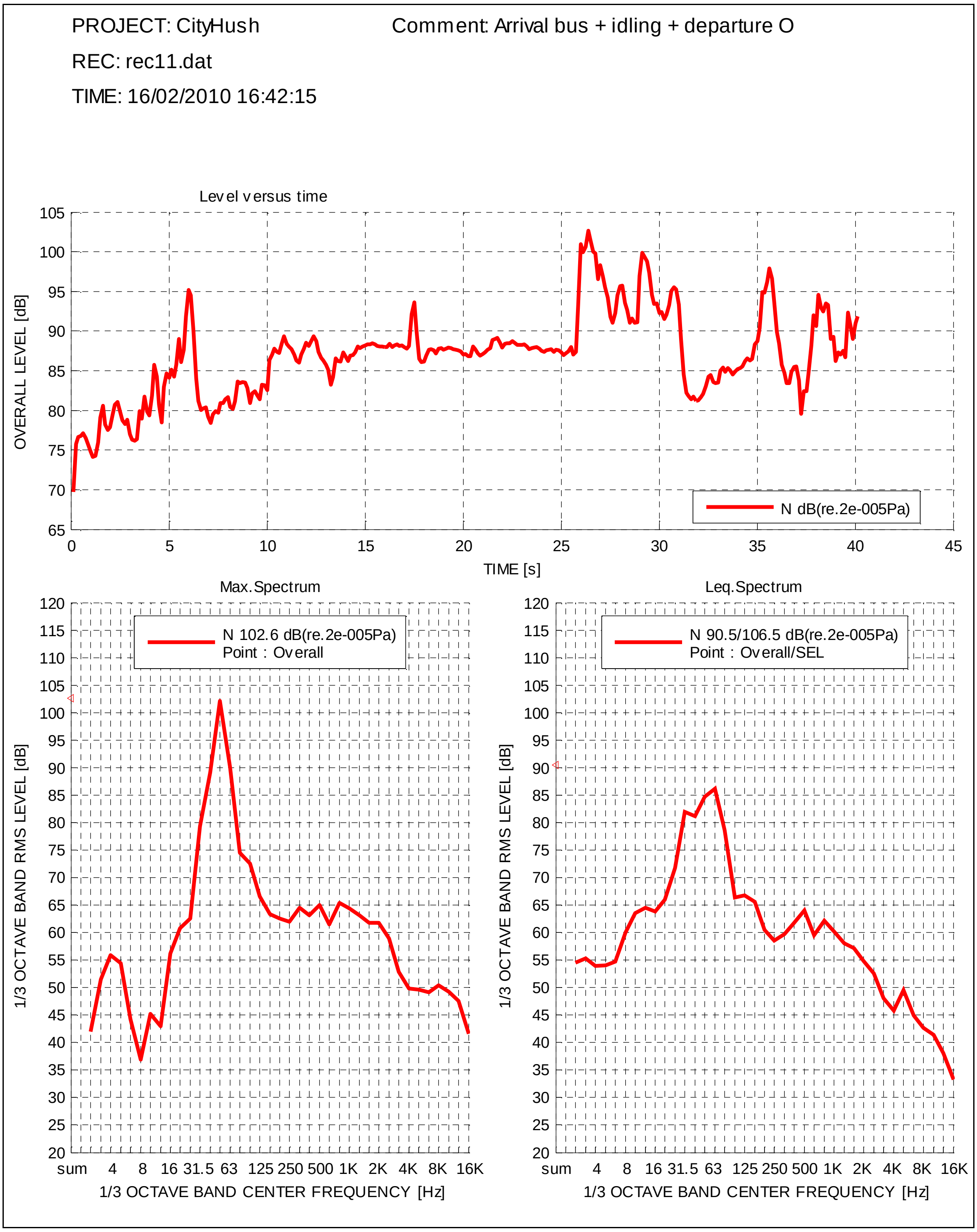

Figure A.11

Bus arrival + idling + departure

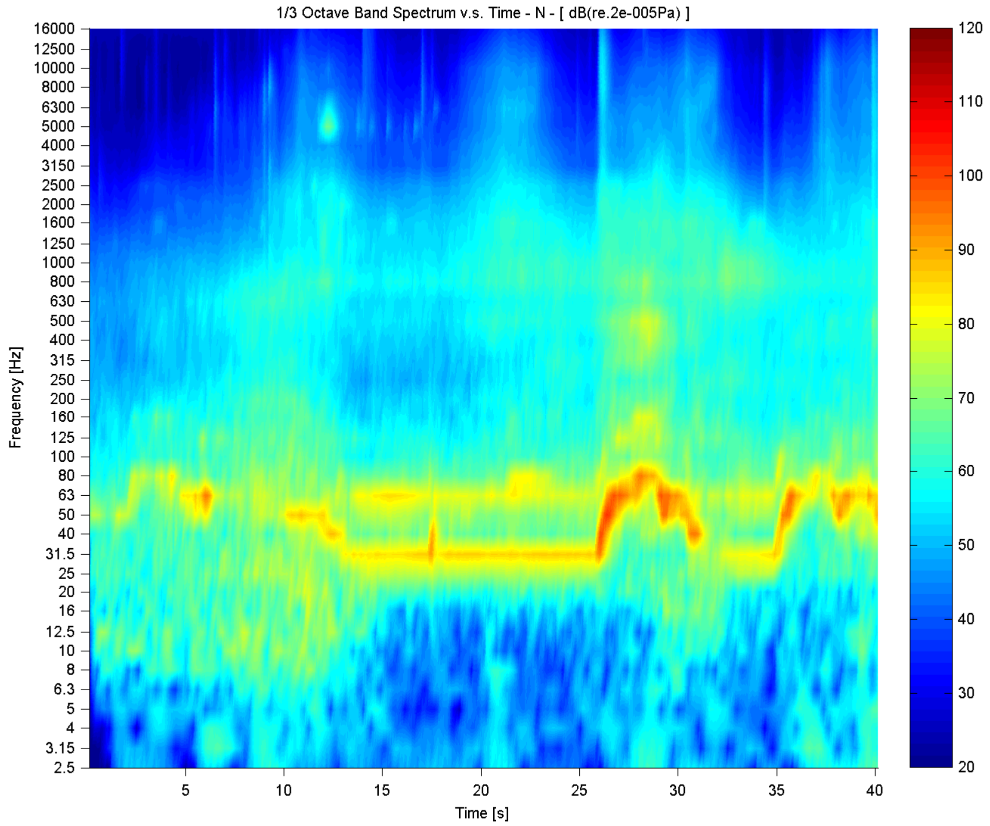

Figure A.12

Bus arrival + idling + departure