The growth of vibro-acoustical properties of volume based timber buildings during the construction phase

Rikard Öqvist (1), Fredrik Ljunggren (1) and Anders Ågren (1)

(1) Luleå University of Technology, Division of sound and vibrations, S-971 87 Luleå, Sweden

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ABSTRACT

Variations in sound insulation are a problem for lightweight constructions, since it demands a high safety margin to the legal requirements on acoustical performance, if the variations are large. The building costs can be lowered if these variations can be characterised and identified. This paper describes an investigation of how the vibro-acoustical properties of nominally identical dwellings change during the construction phases. The objective is to find out whether acoustical deviations in the field can be traced to the earlier stages of construction. It also gives an indication of how the variations grow during the process. Throughout the investigation, all measurements were made on the same building elements. The building technique under study is a lightweight timber system consisting of industrially produced prefabricated volumes. Acceleration level measurements have been performed in the factory on building elements at different stages of completion; plates attached to beams, floor with gypsum board covering, the whole volume without floor parquet and the finished volume. An ISO tapping machine was used as excitation source and accelerometers were placed along the edges of the floors and across the surface. Field measurements were performed in the finished building. In addition to the analysis of acceleration level, airborne and impact sound insulation were measured in situ. Acoustical deviations were found for frequencies above 400 Hz, but these could not be traced back to the earlier construction stages.

INTRODUCTION

Industrialised building is a concept which is heading for the future in the modern timber building industry. Prefabricated building elements are transported to the construction site where they are easily assembled to form complete buildings. The higher the degree of prefabrication, the less time is needed on the construction site. By producing complete volumes in the factory, a very high degree of prefabrication is possible. These volumes typically constitute a single room apartment or a room in a larger apartment. It is also possible to join two volumes to create larger rooms. One of the biggest advantages with industrialised building compared to traditional on-site manufacturing is that the construction takes place under controlled conditions in a factory. Since many of the uncertainties normally associated with field construction can be avoided, industrialised building has potential to achieve good reproducibility of acoustical properties. However, field studies have shown large variations between nominally identical dwellings [1, 2]. Uncertainties in acoustical performance increase the cost as the constructor has to use a higher safety margin to the legal requirements. An increased knowledge about the variations in sound insulation can lead to lowered costs and increased sound quality for the tenants. Some probable causes are workmanship [3-5] and measurement uncertainty [6, 7], but in order to control the variations an in-depth study of the growth of the variations is necessary. The building elements are constructed in production lines. For example, one production line constructs the floors while another one constructs the walls etc. These production lines then converge, and the building elements are mounted as volumes, which then move along on parallel assembly lines. As the volume is moving on the assembly line, the interior is filled and painted, electrical wiring is installed, parquet floors, cupboards and closets are installed and so on, stepwise bringing the volume closer to a complete apartment or room, ready for shipping at the end of the line. Each of these steps in the production and assembly lines represents a stage of completion for the volume. The present study focuses on the floor, which is the most important building element in determining the impact sound insulation. To minimise structure borne sound transfer, the floor and ceiling are constructed as two separate parts with an insulating strip in between. The construction under study is illustrated in figure 1.

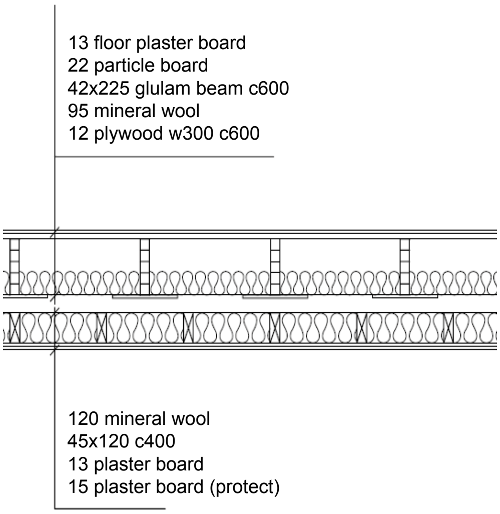


Figure 1. Separate floor and ceiling in a volume construction

The controlled manufacturing of the volume system makes it possible to follow individual building elements throughout the construction process and analyse the growth of their vibro-acoustical properties. The objective of this investigation is to find out if it is possible to trace acoustical properties and deviations in the completed building back to earlier stages of construction. It will also give an indication of how the variations grow during the process.

METHOD

A series of acceleration level measurements have been made in three nominally identical timber volumes at different stages of completion. The floor was excited by an ISO tapping machine and the response was measured in the frequency range 50-3150 Hz with an averaging time of 15 seconds. Double-sided adhesive tape was used to mount the accelerometers on the floors. The measurement setup is illustrated in figure 2, and was used in all measurements. A total of 20 measurement positions were selected with 5 on the short edge, 5 on the long edge and 10 positions randomly placed on the surface. The corresponding measurement results are referred to as “Width”, “Length” and “Surface”. The data were analysed by averaging the results in each of these three groups. A total of six different completion stages were measured. Each stage of completion represents a significant structure-acoustical change in the volumes. Throughout this paper, the three volumes will be referred to as 206D, 306D and 406D, which were their corresponding identification numbers.

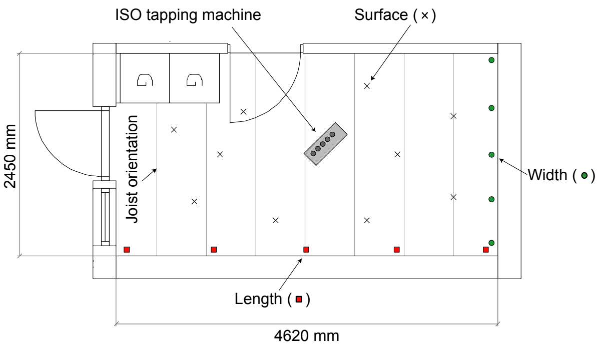


Figure 2. The measurement setup and definition of terms

Plates on beams

The floors were measured at the beginning of the production line, where the floors are placed on tables with rollers, see figure 3. In this measurement stage the floor consists of wooden plates on beams. Floor elements were quickly produced and it was important to complete the measurements as quickly as possible, before the workers glued the gypsum boards. Each measurement represented a small, but disturbing delay in the production. The construction schedule was therefore adapted so that the floors of the three volumes were built in direct succession to ease and speed up the measurement procedure.

Figure 3. The simple floors with plates on beams were measured in the production line, on tables with rollers

Floor with gypsum board

At this stage of completion, gypsum boards had been glued to the wooden plates and secured by screws when the glue was curing. All floors had been allowed to cure for four days. The securing screws improve the structural connection between the gypsum boards and the floor structure and were therefore removed before the walls and ceiling were attached. The floors were placed on wooden point supports on a large concrete foundation. The measurements were performed with the screws removed.

Volume

When the volumes were assembled, the floors were placed on moving rails on the floor, see figure 4. The volume then moved along on these rails until it was ready for shipping. All subsequent measurements in the factory thus used the rails as support. The floor covering inside the volume was the same as in the previous stage; exposed gypsum boards. The walls are attached from the outside of the flanks, which makes the construction stiffer.

Figure 4. The volumes are supported with moving rails on the floor

Patch of parquet

In the final building, the floor was to be covered with parquet tiling. To assess the energy transferred to the floor construction through the parquet and its resilient layer, a square patch of parquet (1 m^2) was constructed and placed beneath the ISO tapping machine, see figure 5. The accelerometers were placed on the still exposed gypsum boards, inside the volume.

Figure 5. A 1 m^2 square patch of parquet was placed beneath the ISO tapping machine inside the volume

Finished volume

These measurements were performed when the volume was completed and ready for transport to the building site. The floor was covered with parquet tiling and all the installations were in place. The volume had reached the same state of completion it would have in the final building.

Field measurements

The three volumes were transported to the construction site in Nynäshamn, where they were used in a five storey building. The field measurements were performed in unfurnished rooms before the tenants had moved in. Six months had passed since the final measurements in the factory. The acceleration level measurements were complemented by measurements of impact and airborne sound insulation. The volumes were stacked on top of each other at floor numbers 2, 3 and 4 with 1 being the ground floor. Each volume was part of a larger apartment were they served as a small bedroom. The volume at the ground floor was nominally identical to the three under study. All sound insulation measurements were thus performed between nominally identical pairs of rooms, with the floor number being the only known significant difference between them. The measurements of impact and airborne sound insulation were made according to SS-EN ISO 140-4 and SS-EN ISO 140-7 and the data was evaluated according to SS-EN ISO 717-1, SS-EN ISO 717-2 and SS 25267:3 [8-12]. A rotating boom with a rotation time of 60 s was used in two positions. The same measurement and source positions were used in all measurements. The area of the floor separating each dwelling was 11,3 m^2 and the volume of each room was 27,0 m^3.

Quality control

A second control measurement was made at three different measurement stages (plates on beams, gypsum boards and in a volume). The measurement equipment was completely removed from the object and replaced when the second run was made. This is a basic test of the uncertainty due to the measurement procedure. The background noise vibrations in the factory were measured at several times during the schedule. Silent measurements were performed with the ISO tapping machine turned off, which were then compared with the normal measurements to assess the signal to noise ratio. A test of the influence of the way the floors were supported was made, since the supports differed between the measurement stages. Three different supports were tested; tables with rollers, wooden point supports and isolating strips along the edges. The latter two were placed on a large concrete foundation. The test was conducted on a simple floor with wooden plates on beams. During the field measurements of the airborne and impact sound insulation, the background noise level was measured and corrected for according to [10-11].

Equipment

- BK Pulse six-channel system
- 5 BK 4508 Accelerometers
- BK 2270, single channel with rotating boom
- BK ISO tapping machine
- BK 4224 sound source

RESULTS

The three control measurements in the factory indicated good repeatability with a spread of less than 1 dB in a given 1/3 octave band. The background vibration levels in the factory were well below (>40 dB) the levels measured with the ISO tapping machine. The comparison of different floor supports showed a spread in acceleration level of more than 10 dB in frequency bands lower than 50 Hz. Therefore, the data below 50 Hz was considered too uncertain and was omitted from the analysis. Above 50 Hz the different supports gave similar results, with an average difference between maximum and minimum values of 1,8 dB in a given 1/3 octave band. The field measurements of airborne sound insulation showed an unacceptable signal to noise ratio in the frequency bands 50 and 63 Hz. No problems were found above 80 Hz.

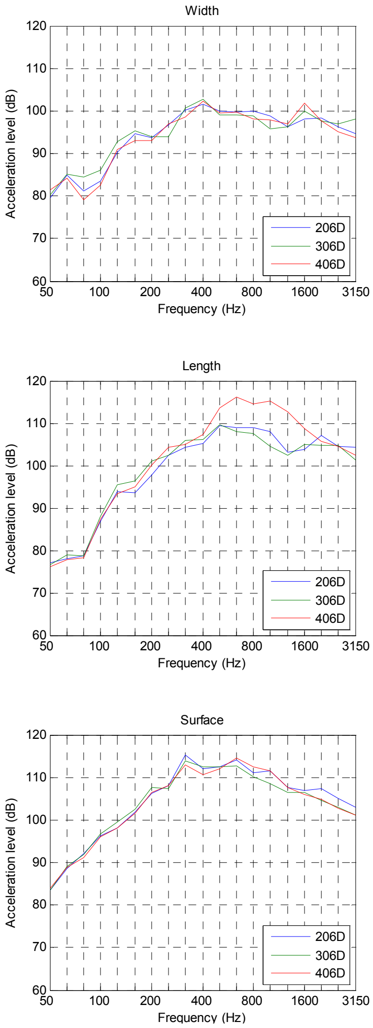


Figure 6. Vibrations on a floor consisting of wooden plates on beams

In the simplest configuration the floors measure similar acceleration levels, see figure 6. The only exception is floor 406D which achieves high acceleration levels on the long side, in the frequency range 400-1600 Hz.

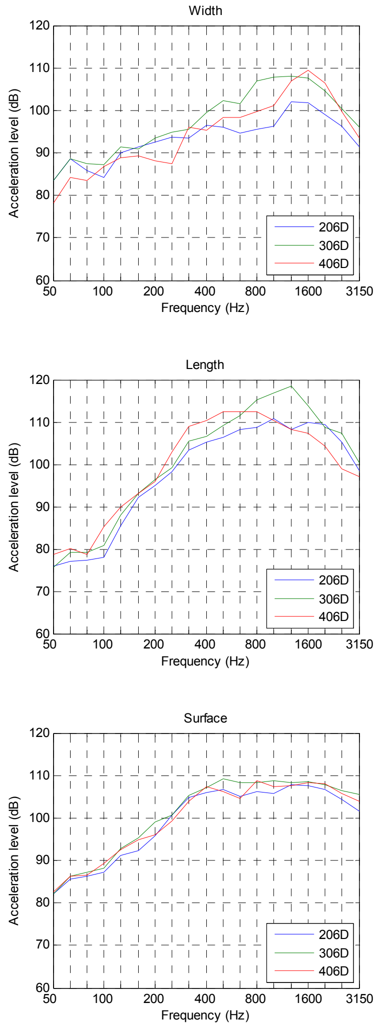


Figure 7. Vibrations on a floor element with glued gypsum boards

When the gypsum boards have been added to the configuration, the complexity of the system has increased. The variation between the floors is larger than in its simplest configuration, see figure 7. The variations are largest on the edges of the floor, with an average deviation of 6,6 dB between maximum and minimum values in the frequency range 400-3150 Hz.

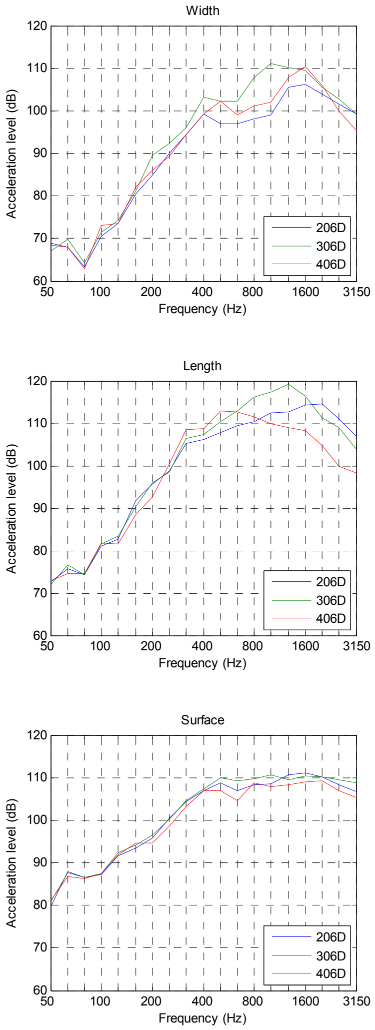


Figure 8. Vibrations on a floor with gypsum boards where the walls and ceiling have been attached to form a volume

The volume stage is similar to the previous stage, except that the edges have been stiffened by the walls and ceiling. Frequencies above 400 Hz have about the same spread as before, see figure 8. The mid and low frequencies (50-315 Hz) however, are here more collected compared to the previous stage.

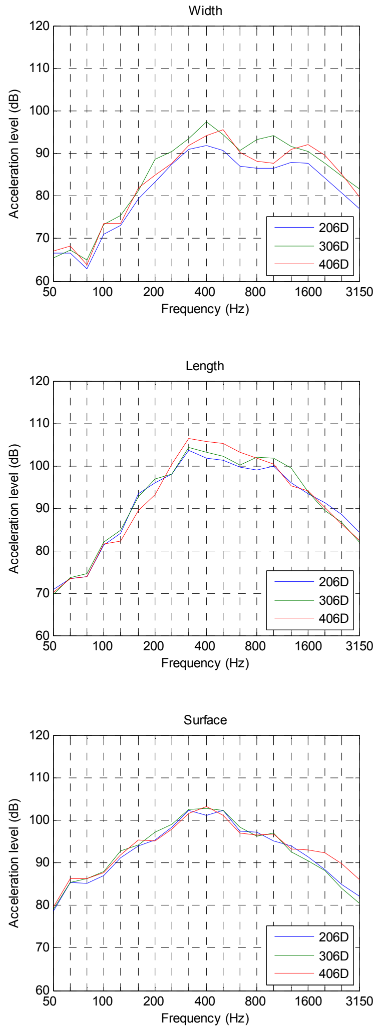


Figure 9. Vibrations with a small patch of parquet placed under the ISO tapping machine on the gypsum floor in a volume

The patch of parquet on a resilient layer acts as an effective isolator of the excitation for frequencies higher than 400 Hz, see figure 9. The highest frequencies were attenuated by more than 20 dB whereas the frequencies below 400 Hz were hardly affected at all.

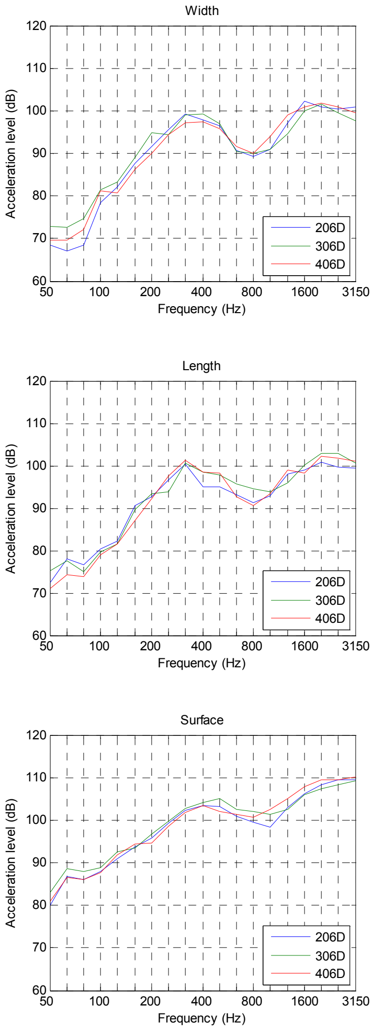


Figure 10. Vibrations in a completed volume with parquet floor, ready for shipping

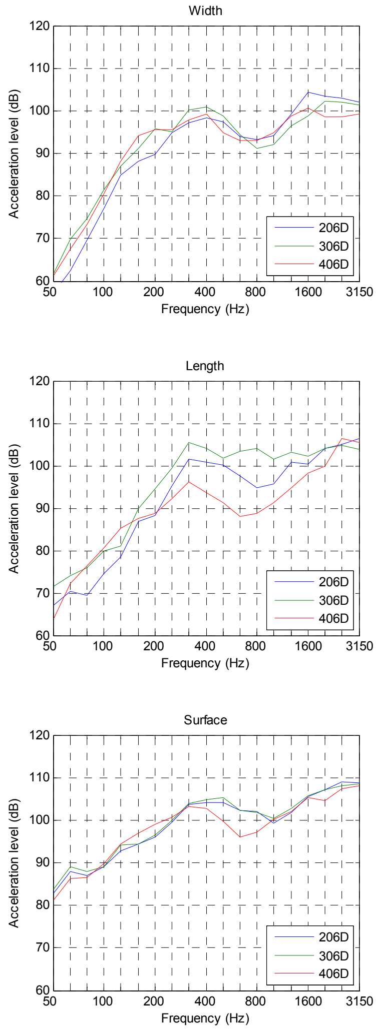


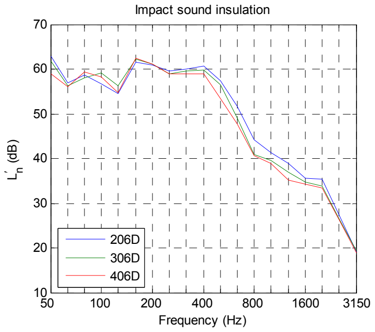
Figure 11. In-situ measurements of vibrations in the finished building

The acceleration levels in the completed volume have a low spread in general, see figure 10. Overall, the results are similar to the patch measurements below 400 Hz. The levels have increased at frequencies higher than 400 Hz, with a substantial increase at the highest frequencies.

The measurement results in the field differ from the previous stage. The variations between the volumes are larger along the flanks and especially on the long side of the floor, see figure 11. A difference exceeding 10 dB can be found between the maximum and minimum values in the frequency range 315-1250 Hz. There are no clear deviations in the impact and airborne sound insulation measurements except that volume 206D has the lowest acoustical performance above 400 Hz, see figure 12. This deviation cannot be identified in the measurements at earlier stages of completion. The single number impact and airborne sound insulation ($L'_{n,w} + C_{I,50\text{–}2500}$ and $R'_w + C_{50\text{–}3150}$) are given in table 1. The volumes achieved similar performance.

Table 1. In-situ measurements of impact and airborne sound insulation in the finished building

Volume	$L'_{n,w} + C_{I,50\text{–}2500}$	$R'_w + C_{50\text{–}3150}$
206D	55	54
306D	55	55
406D	54	54



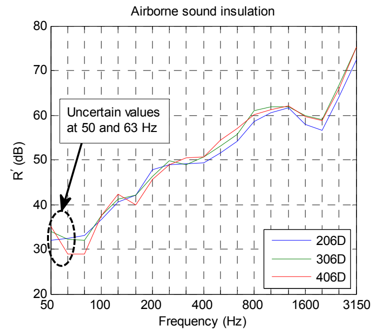


Figure 12. In-situ measurements of impact and airborne sound insulation in 1/3 octave bands

DISCUSSION AND CONCLUSIONS

The control measurement showed similar results which indicate acceptable repeatability of the experiment. Due to time restrictions the floors were not moved and replaced on their corresponding supports which could have resulted in a larger difference between the control measurements. On the other hand, the measurements of different supports also indicated good repeatability above 50 Hz. In all measurements, the variations are larger on the edges of the floor compared to the whole surface average. A contributing factor to this may be that only 5 measurement positions were used on the edges, while the surface average used 10 positions. The problems with the signal to noise ratio in the airborne sound insulation measurements were due to the inability of the sound source to produce sufficient sound pressure levels at the lowest frequencies. The BK 4224 sound source dates back to the time when insulation requirements were specified in the frequency range 100-3150 Hz, and its performance below 100 Hz is thus inadequate nowadays.

During the measurements of plates on beams, the construction schedule was adapted to minimise the negative effects on the production. Since all three floors were produced in direct succession by the same workers, it is likely that the variations in the present study are lower than in a normal situation where the floors would be constructed independently of each other, perhaps by different workers. For the simplest floor configuration, plates on beams, the variations are relatively small. The uncertainty in acoustic performance increases when gypsum boards are added. An important factor regarding the sound insulation is the choice of glue for the gypsum boards. There are specialised glues on the market with acoustically desirable properties. These glues act as a damper between the gypsum boards and the wooden plates. In the present study, basic glue was used.

Some examples of workmanship were identified on the floors with gypsum boards; some securing screws were not removed properly, gypsum boards were assembled differently and in some volumes different glue was used. None of these workmanship issues are relevant for the three volumes in the present study however, as they were strictly supervised during the construction. When the walls and ceiling are attached to the floor, the edges will become stiffer. More energy is transported into the walls and ceiling which makes the acceleration levels decrease on the edges. In the free floor, the same energy is distributed over a smaller structure which should give higher levels. It can be assumed that the decrease in acceleration levels at low frequencies can be attributed to the stiffening caused by the change in the supports.

The acceleration levels are higher when the complete parquet floor has been installed. Acceleration levels above 800 Hz increased drastically compared to the measurements with the patch of parquet, since the measurements in the finished volume were made on a continuous structure. The parquet floor with a resilient layer basically acts as an effective low pass filter with a cut-off frequency of 400 Hz.

The objective of the present study was to find out if it is possible to trace acoustical deviations in the field to the earlier stages of construction. No clear differences and deviations in the field measurements which can be traced back to the earlier stages of construction could be found. For example, volume 206D has the lowest sound insulation in the field above 500 Hz, but deviations in this frequency range found in earlier stages cannot be coupled to that volume. Previous studies of the construction system have shown a decrease in acoustic performance on the lower floors, due to a mismatch in the load-stiffness relationship of the insulation strip used between floors [1-2]. It is possible that this is a contributing factor in the present study too, as the construction is of the same type. Another difference in the field measurements compared to the final factory measurements is that the façade layer had been mounted on the finished building, but in the factory the façade only consisted of gypsum boards.

Something has happened with the volumes in the finished building. The floors measure differently, and the variations in acceleration level along the length of the volume have increased by more than 10 dB. Variations along the short side have also increased, but not by as much. The variations found in $L'_{n,w} + C_{I,50-2500}$ and $R'_w + C_{50-3150}$ are of the same magnitude as what can be expected to be caused by measurement uncertainty. It can be concluded that an investigation of this kind is very hard to arrange and perform. A tremendous amount of work is required to collect enough data to draw statistically significant conclusions. Three volumes are simply a too small population. In general, variations in the acoustical properties are found in the frequency range above 400 Hz. Variations in this frequency range are also apparent in the sound insulation measurements, but it does not affect the values of $L'_{n,w} + C_{I,50-2500}$ and $R'_w + C_{50-3150}$ as they are mainly determined by the low frequency performance.

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