Air intake acoustic radiation on an internal combustion engine. Numerical and Experimental analysis at component state.

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Abstract: According to recent engine development, powertrain tests tend to be reduced.
Thus manufacturers and suppliers have to improve their design and validation tools on component stage, in order to save time during the project and to avoid further acoustic issues on powertrain.
As the NVH air intake contribution to the overall engine noise is not negligible, it’s consequently necessary to manage the airborne acoustic excitation as well as the radial acoustic transfer of the components.
This paper focuses on the acoustic transfer function.
PSA and MECAPLAST – involved in this approach – set out the virtual and experimental analysis that can be performed on plastic components charged with acoustic sources induced by the turbocharger. CTTM (Centre de Transfert de Technologie du Mans) has also been involved into that project to put into evidence advantages from intensimetry methodology. This paper shows how numerical and physical approaches have been developed to reach the NVH targets. In this way, Fluid-Structure methodology has been built to simulate physical phenomenon, and a NVH measurement protocol – taking into account airflow, temperature and pressure- has been established.
Therefore on component stage, NVH contribution and frequency range induced by intake line radiation can be confidently identified. It fully responds to the common objectives of OEM and supplier.

Keywords: Automotive, radial radiation noise, inlet / outlet turbocharger

1. Introduction

This paper is dedicated to turbocharged engine intake line acoustic radiation (low & high pressure).
As the recent engine development plans reduce the number of powertrain tests, manufacturers & suppliers have to improve our conception and validation tools on component state, to save time during the project and to avoid further powertrain acoustic issues.

Intake line are currently plastic components charged by acoustic sources flow (from turbocharger) & by vibrations. The global contribution of this components’ radiation (examples: Air Filter, Duct, Resonator, Muffler) is not negligible. For example, on a 1.6L PSA diesel engine, the ratio of the intake air system radiation compared to the global engine noise (in full load) is almost 15% (it depends on the engine speed).

Figure 1 : 1,6L PSA diesel engine – exhaust side

The radial radiation has to be considered, from the whole external skin of the component exposed to the acoustic excitation (like turbocharger hiss or pulsation).

PSA approach is to control this contribution by managing:
- First, the airborne acoustic excitation,
- Second, the radial acoustic transfer function of components, to achieve an acceptable NVH synthesis.

The first point need manufacturer and supplier collaboration in order to improve the knowledge, to converge on a need contract, and to perform measurements of the sources.

The second point is the technical item of this paper.
Manufacturer (PSA) & supplier (MECAPLAST) – involved in this approach – explain in this paper what has been set up, as component analysis – virtual & experimental – which will be further applied during the three project phases of specification, design and validation.

2. Component description

According to the previous identification of the full engine contribution acoustic sources, most of intake line phenomenon defined are induced by the turbocharger excitation : whining, whoosh, whistling,... The frequency range with highest radiated levels depends on the turbocharger (supplier, stage, strategy, ..) as well as its different connected parts. Generally, [800Hz 4kHz] is considered, with extension until 8kHz for some applications.

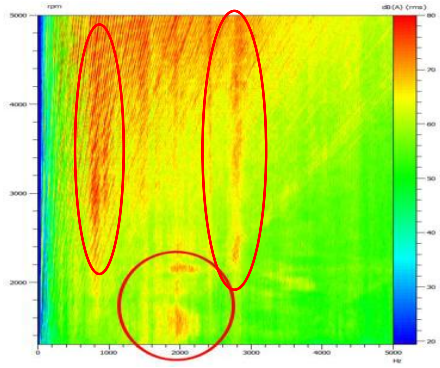

Figure 2 : extract data from Mecaplast benchmarking [0-5kHz] – [1000-5000rpm]

As these parts should receive the most severe airborne excitation, study has focused on components directly connected -before or after- on the charger :

- Inlet turbo pipe + air filter box
- Outlet turbo pipe + intermediate pipe

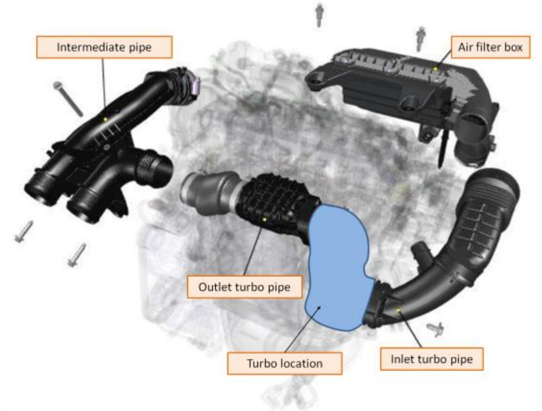

Figure 3 : Surrounding turbo pipes/parts

This paper presents analysis that have been done on outlet turbocharger parts: one of them on figure 4.

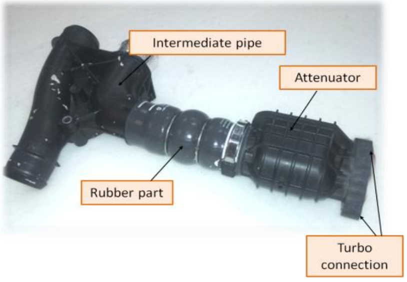

Figure 4 : Outlet turbo pipe

3. Acoustic power

In order to work on component stage, input and output data have to be explicit. Turbocharger airborne power excitation is considered as Wi, and outlet radiated power as Wr. Other acoustic power are describes on the figure 5 hereafter.

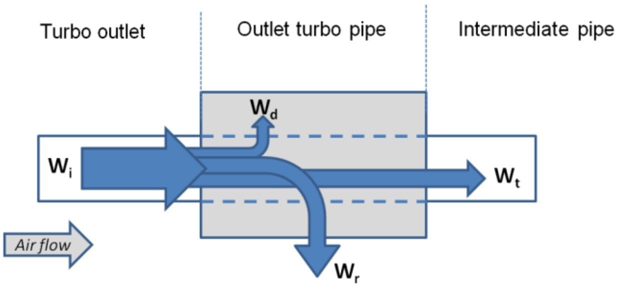

Figure 5 : Acoustic power description

W_i : acoustic power injected into the component (without the reflective part),
W_r : acoustic power radiated by the component,
W_d : acoustic power dissipated through the component,
W_t : acoustic power transmitted

The longitudinal acoustic transfer is noted TLw_T and is defined by the following equation :

$$TLw_T = 10\ Log\left(\frac{W_i}{W_t}\right) \qquad [1]$$

The radial acoustic transfer function is noted TLw_R and is defined by the following equation :

$$TLw_R = 10\ Log\left(\frac{W_i}{W_r}\right) \qquad [2]$$

TLw_R is the transfer that we study in this paper.

3. Virtual component analysis

Different methodologies have been tested to calculate radial acoustic transfer function. As fluid/structure coupling has to be taken into account, two problems must be considered: intern (interaction between air inside the component and the component) & extern (interaction between air outside and the component) problems. According to the impedances involved, both kind of coupling (weak or strong) could be verified.

Calculation conditions

PSA did such calculation on a quite complex component of the 1,6L turbocharged diesel engine - the resonator outlet of the turbocharger. This component is in plastic PA66GF30 (**ρ**s = 1370 kg/m3; Es = 9. 10-9 N/m²; 1% for modal damping) and in the component perimeter of the under pressure air intake system (for this engine, maximum of pressure = 3,8 x Patm).

The air properties are c = 340 m/s and ρa = 1,225 kg/m3, for a modal damping = 1%.

Characteristic size of meshing is 3mm to perform calculations unto 14000Hz.
Figures 6, 7 and 8 represent the following step of numerical methodology.

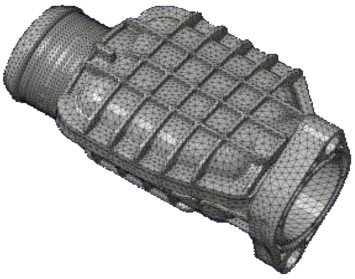

Figure 6 : Finite elements model of the resonator (87396 T10)

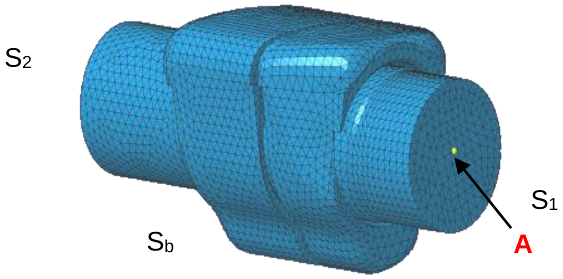

Figure 7: Finite elements model
Internal cavity Va (152042 T10), which is described by velocity and pressure on each point (v, p)

The Finite Elements (FE) calculations are done in two steps:
- a vibro-acoustical Nastran forced Response case (strong coupling);
- a BEM calculation for external radiation (weakly coupling).

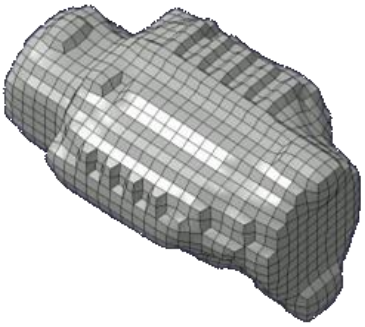

Figure 8: finite elements model of the external wrapper (1618 QUAD4)

The excitation is defined by an acoustic power source at 70 dB (RMS) between 0 and 4000 Hz, put on a point A (in the middle of the surface S_1, eg Figure 7). For that example, calculations are done at ambient temperature, without any flow. Inlet diameter of the duct is 0,02m. With that diameter, the theoretical cut-off frequency is 4978 Hz, meaning that only plane waves can be considered until 4000 Hz.

Fluid pressure field

The steady-state acoustic pressure p at any location (x,y,z) in a bounded domain V_a due to a harmonic external source distribution q at frequency ω = 2πf is governed by the second order Helmholtz equation:

$$p(x,y,z) + k^2 p(x,y,z) = -j\rho a\omega q(x,y,z) \qquad [3]$$

The limit condition on outlet section (S_2) is set anechoic (impedance Z).
The interior coupled vibro-acoustic system is described by two different types of acoustic boundary conditions:

•On S_2: imposed normal impedance ➔ $p = Zv_n$
•On S_b: normal velocity continuity ➔ $v_n = j\omega x_n$

Structural displacement field

The structure is defined by the displacement on each point. Surface S_b is defined as structural surface bounded V_a. Structural displacement ($x_{1(r)}$,$x_{2(r)}$,$x_{n(r)}$), for r ϵ S_b and n the normal direction is defined by :

$$\left(\left[\widehat{L_s}\right] - \omega^2\left[\widehat{M_s}\right]\right)\left\{\begin{matrix} x(r)_1 \\ x(r)_2 \\ x(r)_n \end{matrix}\right. = \left\{\begin{matrix} 0 \\ 0 \\ p(r) * sur\ f \end{matrix}\right. \qquad [4]$$

Where $\left[\widehat{L_s}\right]$ is a matrix governing the elastic and damping forces in the structure and represents inertial parameters of the structure.

Results

Numerical results of TLw_R as given by equation [2] are represented on figure 9. On the frequency range from [800Hz – 4kHz], the overview of that result gives TLw_R values between 20-60dB (pink curve). Weakness points are identified with lowest values of TLw_R.

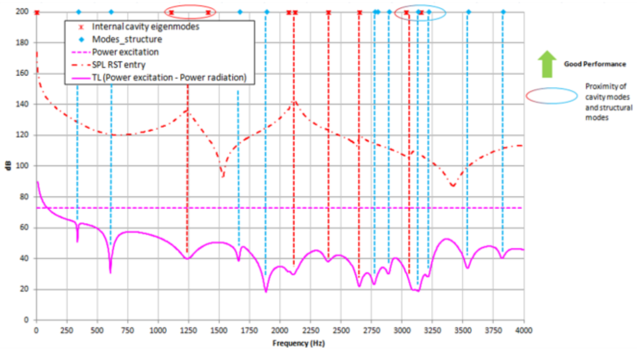

Figure 9: Numerical results:
Level of excitation (W_i); SPL at excitation point A; TLw_R;

On the same figure 9, structural and internal cavity modes are represented (blue and red vertical lines).

Those modes create anti-resonances on TLw_R, and so weakness points.
The red dot curve shows the SPL at the point A.

These results show a coincidence between the TLw_R curve and the structural and acoustics modes. As a consequence the virtual component analysis can help to improve the design and to propose NVH solutions.

4. Experimental component analysis

Different methodologies have been tested to measure radial acoustic transfer function. The main differences concern the radiated acoustic power measurement:

- Reverberating room method / Diffused field
- Intensimetry method / Quiet field

Next to those methodologies, several key factors have been studied :

- Influence of input level
- Influence of air flow
- Influence of pressure
- Influence of temperature

The objective is to define the main influence of these parameters on the radial transfer TLw_R.

Reverberating room method

This test setup is based on PSA standards B32 7123 [1], 01525_10_00112 [3] and on NF EN ISO 7235 [2].
Injected acoustic power, W_i, is measured by using two microphones on input pipe (Figure 10). Hypothesis on plan wave allows to get W_i until pipe cut-off frequency.

$$LW_i = 10 * Log\left(\frac{I}{I_0}\right) \quad [5]$$

With $I = abs\ (S * I_1)$ and $I_1 = \frac{ImgCps}{\rho * \Delta r * w}$

- $I_0 = 10^{-12}$ W;
- $ImgCps$ imaginary side of interspectrum P_1 / P_2
- S = pipe section

Radiated acoustic power by the component, W_r, is measured by using N microphones into reverberating room (Figure 10). Then the mean of absolute pressure measured is calculated (see NF EN ISO 7235)

$$P^2_{moy.} = \frac{\sum_{i=1}^{N} P_i^2}{N} \quad [6]$$

$$L_p = 10 * Log\left(\frac{P^2_{moy.}}{2.10^{-10}}\right) \quad [7]$$

Pressure level is used to determine acoustic power level L_{W_R} :

$$L_{W_R} = L_p + \Delta \quad [8]$$

with

$$\Delta = 10 * Log\ (V) - 10 * Log\ (TR) + 10 * Log\left(1 + \frac{S\ l}{8\ V}\right) + 10 * Log\ (B) - 14$$

- L_{W_R} : Radiated power level (dB ref. $10^{-12}\ W$)
- L_p: pressure level (dB ref. $2.10^{-5}\ Pa$)
- V : reverberating room volume (m^3)
- TR : room reverberating time (s), frequency dependant
- S : room total area (m^2)
- l : length wave (m)
- B : atmospheric pressure (Bar)

Dissipated (W_d) and Transmitted (W_t) acoustic power are studied in that case. As defined into B32 7123, for this test setup, figure 10, intermediate duct is closed at the end.

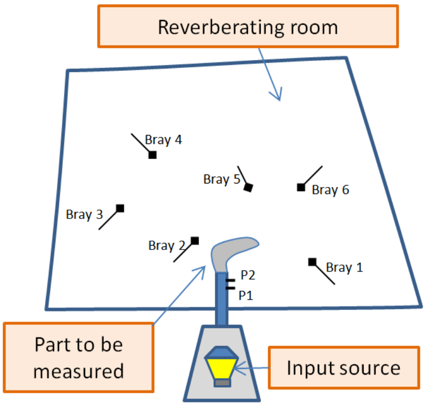

Figure 10: Test setup for reverberating room method

The input source is not included into the reverberating room to avoid any influence on the radiated level of the part that is analysed.

Results

Mecaplast has performed these tests into CRITT M2A reverberating room. This is first necessary to calibrate the system, in order to insure the consistency between Injected acoustic power and radiated acoustic power without any part connected to the pipe source.
In that case, pipe source is opened into the reverberating room. Microphones into that room measure the energy radiated from the source. The 3rd octave comparison between LW_i & LW_R is represented on the figure 11.

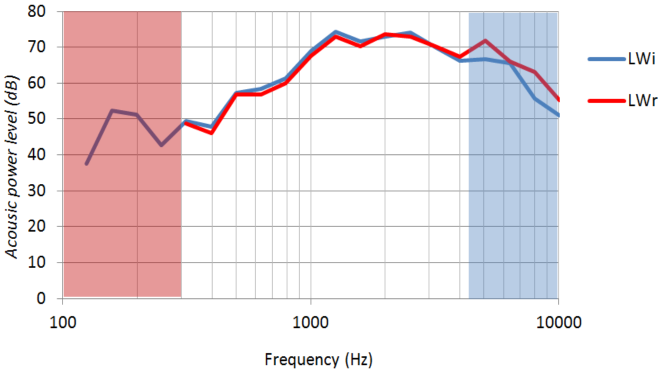

Figure 11: comparison between LW_i & LW_R without part

That shows a good correlation between those acoustic power levels on [315Hz-4kHz]. Red area cannot be considered for LW_R in low frequency, as diffused field conditions are not validated below 300Hz. In high frequency LW_R presents higher levels than LW_i, due to the plan waves hypothesis that is not full field. Thus blue area cannot be considered also for LW_i.

During the complete component study, analysis has been performed on two main objectives :

- TLw_R on complete part to get weakness frequency point
- Localization area to get influence of each subsystem.

As the absolute value of TLw_R is to be kept, the studied frequency range is [315Hz-4kHz].

For localization a masking method has been used, after validation of the efficient masking thickness and material. In that case, as LW_i is stable (w/o masking), TLw_R results can be considered until 10kHz, for comparison on the same part.

According to that test setup, TLw_R of the 1,6 outlet charger pipe is given by the figure 12, showing levels between 23-40dB.

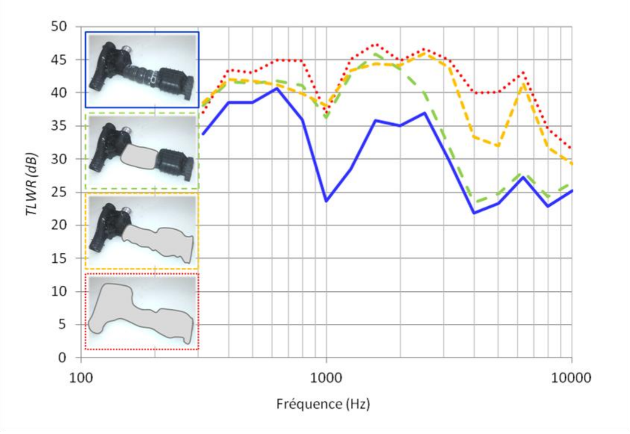

Figure 12: Influence of masking areas on TLw_R

The masking of each main areas allows to detect the part contribution : frequency range and amplitude. Figure 13 presents the % ranking scale, based on distance between base line and full masked part

In this test setup conditions, rubber part has the main contribution on TLw_R until 2kHz. Above 2kHz the attenuator is the main contributor on TLw_R .

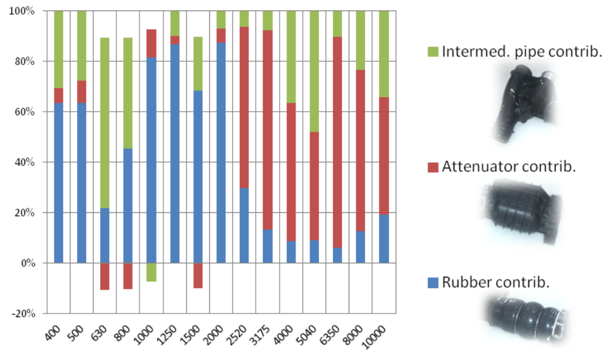

Figure 13: Contribution areas on TLw_R

Intensimetry method

The test setup is based on PSA standard 01525_10_00112 and on internal CTTM procedure. The Figure 14 presents the setup used for measurements with air flow at CTTM. Adaptations have to be done to include pressure and temperature.

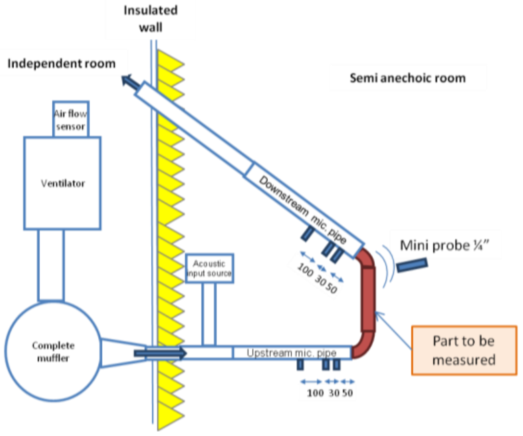

Figure 14: Test setup for intensimetry method

The principle of this method is to measure the injected acoustic power W_i on both sides of the element, and to measure the radiated acoustic power with an intensity probe. The downstream injected acoustic power (reverse to the flow) is considered as an anechoic termination is not present at the outlet.

The radial acoustic transfer is defined as:

$$TLw_R\,(dB) = Lw_{inj}(dB) - Lw_r(dB) \qquad [9]$$

Where

$$Lw_{inj}(dB) = 10.\log\left(\frac{W_{inj}}{w_0}\right),\ w_0 = 10^{-12}W \qquad [10]$$

And

$$TLw_r(dB) = 10.\log\left(\frac{W_r}{W_0}\right) \qquad [11]$$

The injected acoustic power, W_i, is measured by using three microphones on upstream and downstream pipes. Plane wave hypothesis allows to get W_i until pipe cutting frequency.

The injected power is calculated as following :

$$w_{inj} = \frac{|P_u^+|^2}{2Z_{cu}} + \frac{|P_d^-|^2}{2Z_{cd}},\ Z_{cu} = \frac{\rho c}{S_u},\ Z_{cd} = \frac{\rho c}{S_d} \qquad [12]$$

with
P_u^+ = the upstream incoming pressure part
P_d^- = the downstream incoming pressure part
-S_u = Upstream section
S_d = Downstream section

The radiated acoustic power by the component, W_r, is measured by using the mini intensimetry probe from CTTM.

Figure 15: Mini intensimetry probe from CTTM

The radiated power W_r is defined by the equation :

$$W_r = I_r * S_r \qquad [13]$$

I_r : intensity measured with probe
S_r : covered area

Measurements with intensimetry probe consist in scanning all around the studied part. Different courses, time durations and operators have been studied in order to validate that protocol and get reliable results.

First results are presented on figure 16, according to the previous setup described, without air flow, at room temperature and atmospheric pressure.

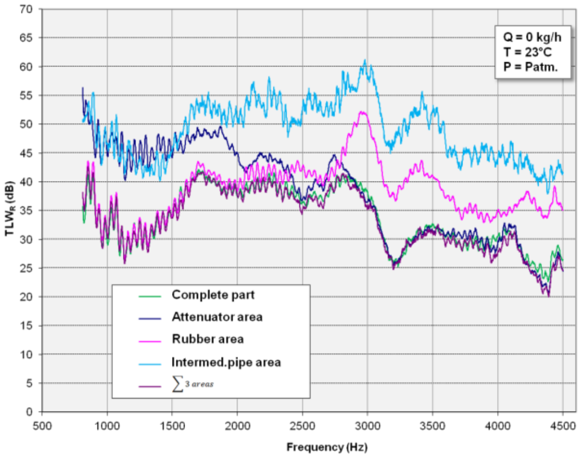

Figure 16: Intensimetry method, TLw_R of complete part & subsystem areas at standard conditions

The acoustic transfer TLw_R of the 1,6 outlet turbocharger pipe is given by the green curve. TLw_R levels are between 20-40dB. Weakness point is identified between 1-1.5kHz.

In order to validate the methodology, a comparison has been performed between the complete component scanning and the addition of part scanning areas (attenuator, rubber and intermediate areas without masking operation). The added parts TLw_R (purple curve) and the full component TLw_R (green curve) present an excellent level comparison. Thus, even if no masking is used, the intensity probe is able to get the lonely radiated power from the intermediate area part evaluated, without being influenced by the surrounding parts radiation.
Indeed, in this test setup conditions, rubber part has the main contribution on TLw_R until 2.3kHz. Above 2.3kHz frequency the attenuator TLw_R is driven by the attenuator. That confirm the previous results with reverberating room methodology.
Let point out that intermediate pipe presents a very high level of TLw_R. That means intermediate pipe is not the area to focus on for improving radiated noise of the whole turbocharger outlet pipe.

Influence of Airflow

The next figure presents the influence of air flow on TLw_R. Involved flow rates are : 100, 250, 400 and 550 kg/h. An effect is visible since 1.2kHz until 3kHz with a TLw_R shift down from 5-8dB and also above 4.5kHz.

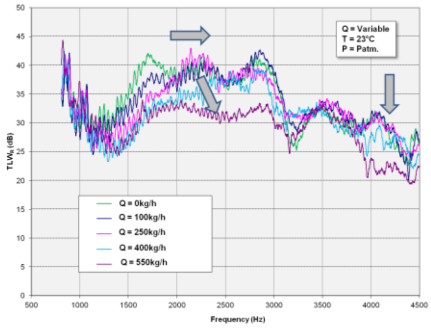

Figure 17: Intensimetry method, TLw_R depending on flow rate Q (kg/h)

Previous investigations lead to say that rubber duct is implied into this effect. To confirm that point, a second part scanning with air flow has been performed. Contribution of part areas is presented on figure 18 that shows the same kind of results as on figure 16.

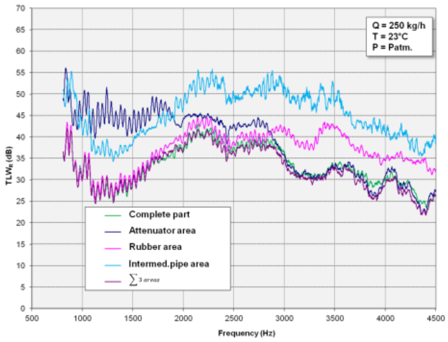

Figure 18: Intensimetry method, TLw_R of complete part & subsystem areas at flow rate Q = 250kg/h

With those information, synthesis on TLw_R contribution with airflow can be started. That is represented on figure 19 where synthesis for flow rates Q_{400} and Q_{550} are estimations.

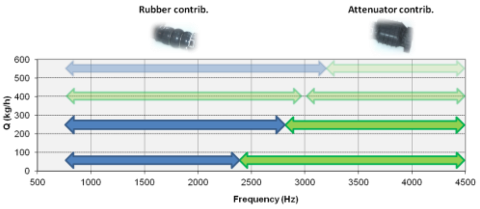

Figure 19: Intensimetry method, TLw_R contribution depending on flow rate Q

Influence of Pressure

To study inside pipe pressure influence, the bench needs to be modified in order to get closed upstream and downstream pipes. At the end of the downstream duct, absorbing materials is inserted to avoid strong reflected waves.

The same approach, as with airflow, has been applied with pressure influence. Two levels of relative pressure are generated : about 0.8 and 1.7 bar. TLw_R results with different pressure levels are represented on figure 20.

Increasing pressure inside turbocharger outlet pipe allows to strongly reinforce TLw_R between 1-1.5kHz. The difference is about 25-35dB. On the other hand, we observe a decrease of TLw_R between 1.5 and 3 kHz.

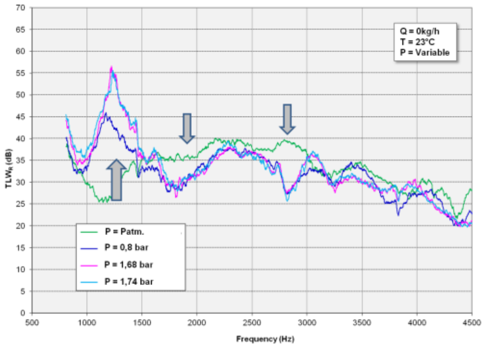

Figure 20: Intensimetry method, TLw_R depending on P

To understand what happened in that condition, the part scanning area has been performed. TLw_R results at 1.7 bar pressure, are presented on figure 21, showing that attenuator area TLw_R is equivalent to the whole component TLw_R .

Consequently, with pressure on this component design, attenuator acoustic radiation is driving TLw_R on the whole frequency range.

That is an important conclusion, as without pressure this frequency range is the weakness point. So without taking into account more realistic parameters, that could induce wrong guide lines, as well as effort and time lost for part improvement.

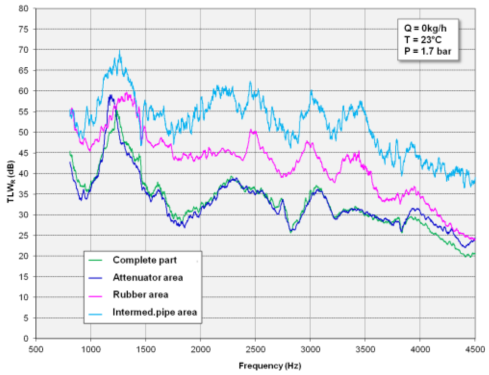

Figure 21: Intensimetry method, TLw_R of complete part & subsystem areas at P = 1.7 bar

Influence of Temperature

To study part temperature influence, the bench needs to be modified in order to allows hot air to get out from downstream pipe. Two temperatures are reached: 160 and 210°C.

Again, the same approach has been applied with temperature influence. TLw_R results with different temperature levels are represented on figure 22.

Increasing part temperature seems to get several shift impacts :

- Decrease by 8dB at the mid frequency range
- Shift on high frequency the max of TLw_R

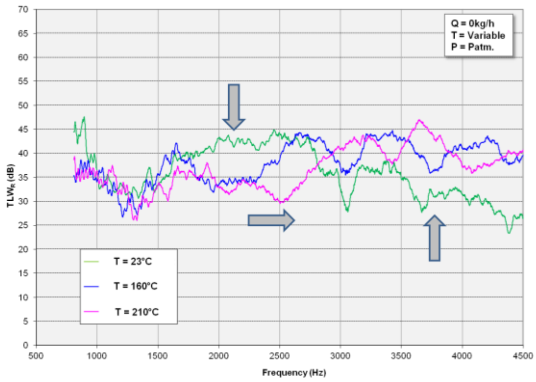

Figure 22: Intensimetry method, TLw_R depending on T

At 160°C, contribution on TLw_R of areas previously defined led to the results presented on figure 23 :

- [0.8-1.8kHz], rubber part is driving alone
- [1.8-2.8kHz], rubber & att. drive together
- [2.8-3.8kHz], attenuator is driving alone
- [3.8-4.5kHz], rubber & att. drive together

As TLw_T tuning needs to take into account celerity relation with temperature ($c = 20\sqrt{T}$) [5], TLw_R has also to considerer temperature influence on material parameters.

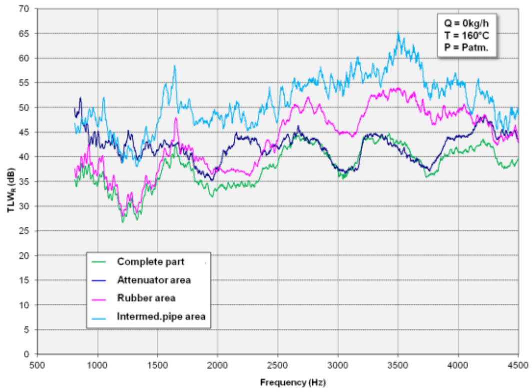

Figure 23: Intensimetry method, TLw_R of complete part & subsystem areas at T = 160°C

5. Comparisons between methodologies

The first comparison can be done between two experimental methodologies. The second one will be numerical and experimental results.

Reverberating room / Intensimetry method

Common part definition and tested setup is the following :

- Complete turbocharger outlet part
- Temperature = 23°C
- Pressure = Patm.
- Air flow = 0 kg/h

The main difference is the fact that for reverberating room method intermediate duct is closed at the end. For intensimetry method, intermediate duct is linked to downstream pipe with anechoic termination.

The next figure shows the comparison between those two experimental methods.

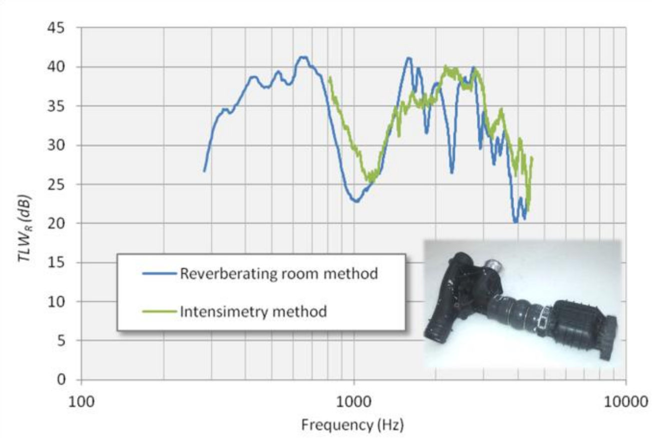

Figure 24: Reverberating room method & Intensimetry method, TLw_R of complete part

For a global overview, let see that both curves get the same shape and the same amplitude range. Weakness points are located in the same frequency range.

Deeper in details, note that reverberating room method (blue curve) presents oscillations around Intensimetry method (green curve), and several anti-resonances. That point can be due to:

  - Different boundary conditions at the end of outlet pipe
- Too large scanning with intensity probe [4], even if that point has been already studiedTo get a better understanding of that behavior, other investigations needs to be done by testing again both methods.

After analysing results, pros and cons of these methods can also be compared.

⇨ Reverberating room method

- Needs to get input source outside (2nd room)
- Needs to get downstream pipe connected to outside (2nd room), if we use one
- Needs to put a lot of effort to insulate upstream and downstream pipes
- Needs to do masking subsystem or to study subsystem by subsystem (disassembly and adaptations)
- Needs to qualify Tr of room

⇨ Intensimetry method

- Allows to measure in quiet room
- Allows to get subsystem acoustic power without masking or disassembly parts

Numerical / experimental results

Common part definition and compared setup is the following :

- Attenuator
- Temperature = 23°C
- Pressure = Patm.
- Air flow = 0 kg/h

The next figure sum up boundary conditions.

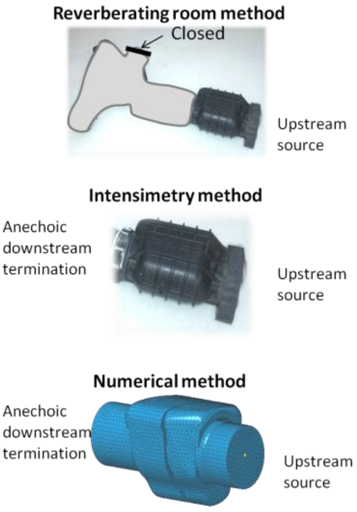

Figure 25: Boundary conditions of 3 methods analyzed

The different TLw_R obtained according to the three methods described in this paper are represented in the following figure.

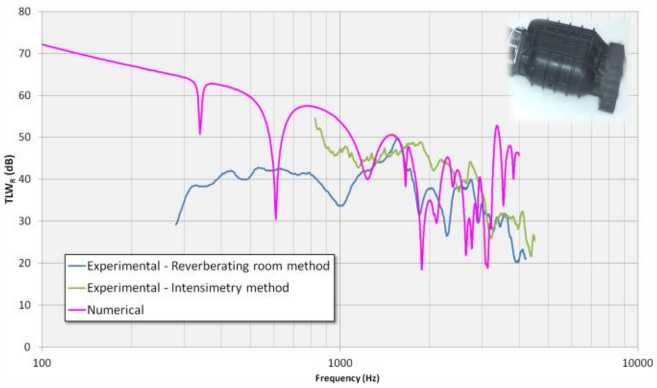

Figure 26: Reverberating room method & Intensimetry method & Numerical method, TLw_R of attenuator area

Results present similar shape between reverberating room (blue curve) and numerical (pink curve) methods between 1.2-3 kHz.

Above 3 kHz both experimental methods get same results and numerical is 10-20 dB higher.

Below 1.2 kHz, intensimetry and numerical methods are close and reverberating room method is 10-15 dB lower.

One point very interesting is about the anti-resonances between [1.5 – 3kHz] that we've already noticed on TLw_R from reverberating room method. Most of them have similar shape with TLw_R from numerical method. It confirms that we should investigate both experimental methods in parallel.6. Conclusion

In this paper, different methods have been investigated to define TLw_R of turbocharger outlet parts and also subsystems.

PSA has tested different methodologies of noise calculations. The physical phenomenon to represent is the fluid-structure couplings. Two different coupled problems have to be taken into account: intern (interaction between air inside the component and the component) & extern (interaction between air outside and the component) problems. According to the impedances involved, both kinds of coupling have been verified (weak or strong).

Mecaplast have validated the facilities for the different acoustic energies to measure: acoustic excitation with sound propagation inside pipes, acoustic radiation in reverberating room. Second step, by using this protocol, the paper shows what the main source of noise contribution is and the frequency range associated.

The intensimetry method, used by CTTM, is an efficient and rapid method to measure the radiated power. The conditions of measurement are not severe : only a quiet field is needed and there is no need to mask the surrounded parts. Furthermore we can easily rank the different parts from the complete part.

On experimental approach, influences of air flow, pressure and temperature have been studied. These results show also that tests under real conditions are needed to reach right conclusions for designing. It can help numerical method to validate the model. At the end, because measuring TLw_R in real engine conditions is very difficult, all that work should help numerical method to improve and develop outlet parts with the representative input data (engine conditions). Many other parameter variations are feasible thanks to numerical way.

This paper can be also used for other parts around turbocharger and engine itself: ducts, air filter box, air intake manifold. Results available during that project are usable to compare different curves, thicknesses, materials…

7. References

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CTTM : Centre de Transfert de Technologie du Mans
SPL : Sound Pressure Level
FE : Finite Elements
BEM : Boundary Element Method
Tr : Room Reverberating Time