HUMAN PERCEPTION AND FAN NOISES

Said NAJI [1], Anne SANON [2]

[1] VALEO Thermal Systems, 8 rue Louis Lormand – La Verrière, 78321 Le Mesnil Saint-Denis - France

[2]VALEO Visibility Wiper Systems, 8 rue Louis Lormand – La Verrière, 78321 Le Mesnil Saint-Denis - France

SUMMARY

Human interactions with external environment need to be very efficient in a survival mode and there is a very good match between sound perception and external stimuli such as speech, which is a key communication skill. But global perception is related to all senses.

New technologies products are created to enhance human comfort. They produce sounds and can be evaluated in a human perception point of view. Different perceptive quotation scales are discussed. An overview of Psychoacoustics tools applied to fan noises is presented.

Comfort enhancement strategy for Automotive Heating Ventilation and Air Conditioning systems consists in a first step in a classification into different noises characteristics and presence conditions. In a second step, optimisation of the main perceptive characters of each pre-classified noise is proposed, generally involving other comfort parameters.

Concerning Automotive Cooling Fan systems, Loudness criterion is the main characteristic of the acoustic annoyance.

INTRODUCTION

Rotating machines with fans produce air flow. Whenever in a first approach the modal behaviour of the machine is not taken into account, the higher the rotation speed is, the stronger the air flow is, and the higher the radiated sound pressure is. Thus, acoustic level increases with the performance of the fan. Spectral characteristics of sound produced by rotating machines, speech or music are very similar: numerous harmonics of rotation speed are prominent in the spectral shape. Decreasing annoyance or improving comfort is not just only a matter of global acoustic level decrease. A quick overview of human perception is presented, followed by a focus on sounds perception and acoustic evaluation in automotive industry. Heating Ventilation and Air Conditioning system acoustic comfort improvement strategies are detailed, and cooling fan system psychoacoustic criteria are discussed.

HUMAN COMMUNICATION AND BRAIN PERCEPTION

Acoustics and vibrations at the heart of the communication

Hearing sense is dedicated to communication: we are able to share valuable information using our complex speech skills. Hearing is a clue sense linked to the human basic needs listed by biologists: food, reproduction, protection and locomotion (Figure 1). These communication skills also help us to adapt to new environments and configurations. Psychoacoustics definitely stands at the crossroads between humanities and biology.

In any human language, independently of the size and the age of the speaker, there are clue informative sounds in the frequency range between 1000 Hz and 3000 Hz (Figure 2). In this frequency range, human's ear is the most efficient: the sound pressure coming from the outside is very efficiently transformed into an electrical stimulus. In the rest of the audible spectrum of the ear – from 20 to 1000 and over 3000 up to 20000 Hz –, the sound is filtered. Speech emission is adapted to ear perception to make the communication very efficient. The ear perception is also very much adapted to the sounds carrying information about basic needs listed above. In human's natural environment, birds can be considered as preys and big cats as predators. Bird songs and branches creaks are informative signals for eating and protection, and these sounds are in the audible range. To conclude, sound perception ensures optimised communication with human environment.

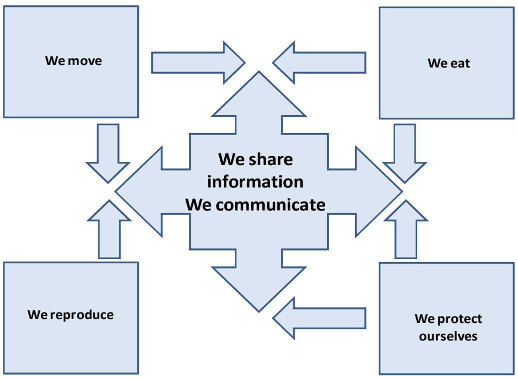


Figure 1: Basic human needs[1]

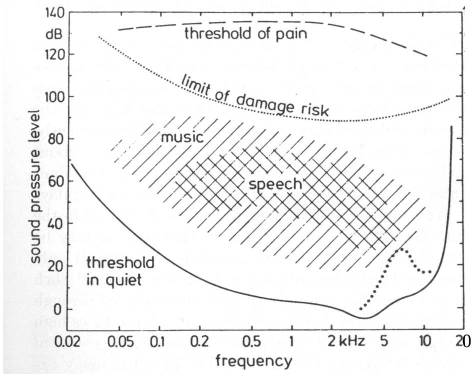


Figure 2: Hearing area [2]

Perception and brain

Our ears are sensors that transform the sound pressure into a vibration, and then into an electrical signal. The signals coming from the two ears are then post-processed synchronously inside the brain, including sound spatialisation. Different brain zones are dedicated to each sense. If each part of our body was to be represented relatively to the brain volumes related to each sense, the ears would be much bigger than they really are (Figure 3).

With such a perception body shape representation, the word comfort is clearly related to all senses and cannot only be applied to acoustic comfort. For a product such as an automotive HVAC (Heating Ventilation and Air Conditioning), driver and passengers global comfort is clearly a mix between Acoustics, Thermics on the face and the hands, air flow on the face, and vibrations on the hands via the steering wheel.

Recent advances in neurosciences show that particular zones in the brain are dedicated to each sense, and for each sense particular zones in the brain are dedicated to specific related signal post-processing. They also show that related volumes to these zones are variable through time, life, individuals, depending on the environment stimuli. These researches point out the extreme "plasticity" of the brain, and the extensive individual's ability to learn. For example, extreme concentration on a specific stimulus is possible, and specific acoustic evaluation of an HVAC is possible can be requested to an individual, independently of global comfort evaluation. Plasticity of the brain is a clue factor for adaptability to modern life environment in which there is a huge diversity of acoustic stimuli associated with new technologies.

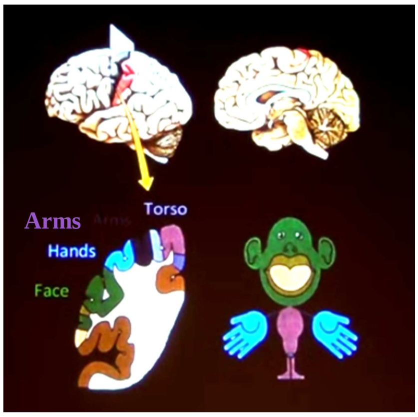


Figure 3: Functional architecture of perception activity in the cortex [3]

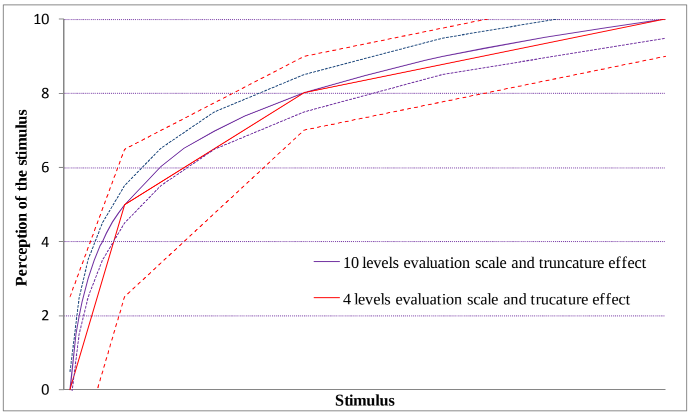


Figure 4: Evaluation scale: mark accuracy resulting from truncature effect

Weber-Fechner law:

Weber stated experimentally during the 19th century that the amount of change needed for sensory detection to occur increases with the initial intensity of stimulus; in other terms, the change ΔS in a stimulus S that will just be noticeable is a constant ratio of the original stimulus and is proportional to it (1):

$$\frac{\Delta S}{S} = \text{constant} \qquad (1)$$

$$P = \text{k} \times \log S \qquad (2)$$

The left hand of the equation can be considered as the differentiation of a logarithm and Fechner writes a few years after Weber that the perception P of a stimulus is related to the stimulus by a logarithmic law (2). The reductionist character of this law to evaluate the ability of our brain to interact with its environment has been widely criticized, but this law is a very good first approach for any perception: light brightness, vibration level, pain perception, educational evaluation, or even mental representation of numbers [4]. It is applied to acoustics with the logarithmic unit for sound pressure level scale deciBel, to octave and third octave band analysis for the frequency scale, but interaction between frequency and level is not purely logarithmic (threshold limit is not a straight line in Figure 2 for example), leading to Equal-loudness curves and Loudness and Bark notions.

CLASSIFICATIONS

Human constantly sorts and classifies information related to basic human needs and communication. Evaluation is part of this classification process: perceptive evaluation can be performed by jurors who qualify many sounds in a very short time. Jurors and sounds shall be chosen in order to be statistically representative of a population; it is mandatory to be able to listen to the sounds with a realistic audio system replay and to switch from one sound to another in less than five seconds, which is the time memory for sounds.

Classification of acoustic stimuli

The acoustic stimulus of the human ear is the sound pressure quantity. Musicians classify sounds into four properties: level, pitch (frequency), timbre and duration. Time specificities can also be classified: stationary versus transitory, level and frequency modulation through time.

In the «Information theory» field, an informative acoustic stimulus is qualified as a “signal”, while a non informative acoustic stimulus is qualified as a “noise”. In everyday language, the term of noise applied to acoustics is a bit different: it is an "annoying informative signal". "Annoyance" or "discomfort" is related to an evaluation.

Speech perception mechanisms classification is very informative to understand acoustic perception: the same classification process is used to evaluate the manufactured products. Speech perception highly depends on two vocal chords characteristics which determine the frequency modulation of the speech signal [5]: the Glottal Pulse Rate, which is a characteristic of the signal variation through time, and the Vocal tract length characterized by its spectral envelope. The mechanisms that help to separate different voices emitting sounds in the same period of time are also highly dependent on related levels and on their variation through time:

- whenever there is substantial zone of spectral overlap between two simultaneous emitted sounds, the loudest sound (depending on related frequencies and levels) can mask the other one: it is related to frequency masking effect,
- if two signals appear sequentially, the loudest sound (related levels and time durations) can mask the other one: it is related to temporal masking effect,
- restoration capacity is linked to the auditory nerve capacity to decompose a speech sound into a series of harmonics, even if not all the information is present; auditory enhancement enables to focus neuronal activity to a particular characteristic of a signal that is considered as "informative" or "useful.

Such complex characteristics are used in every communication scenario of everyday life. Extensive acoustic perception characteristics have been classified by Zwicker and Fastl [2].

Natural and non-natural acoustic signals

Acoustic signals can also be classified as *natural* or *non-natural*. A *natural* acoustic sound is a non disturbing, acceptable, and sometimes needed – even if the level is high – sound. Several definitions can be given:

- signal that appears, increases or changes after an action done by the user,
- signal that gives a feedback and helps to take a decision,
- signal indicating a usual operation of the machine,
- signal indicating robustness,
- signal related to the environment.

A *non-natural* acoustic signal, or "noise" is a disturbing and unacceptable – even if its level is low – acoustic signal. It sometimes can be considered as a failure. Several definitions can be given:

- signal that appears, increases or changes suddenly without user action,
- signal that gives not required information or that could give wrong information,
- signal not related to the environment.

The objective for manufacturers is to design their products in order to avoid non-natural acoustic signals: in automotive industry, the comfort is a key buying factor.

Jury evaluation

Numerous evaluation scales for perception exist and are used. Borg scale for pain strength is widely used in hospitals with a quotation of 0 to 10 [6] (Figure 5). This scale is a logarithmic scale for which the term of "strong" appears at a rate of 5. Such scales are also used during acoustic jury evaluation tests: the highest mark would be qualified as "dislike", disturb", or "annoy".

In automotive industry, there is a quotation scale for Acoustic comfort evaluation of a product (Figure 6), with "acceptance" criterion for levels equal or over 6. It is very important to point out that for both car manufacturer and product supplier, a quotation strictly above 8 is considered as "over-quality", and a quotation lower or equal to 5 for a product will result in not being sold.

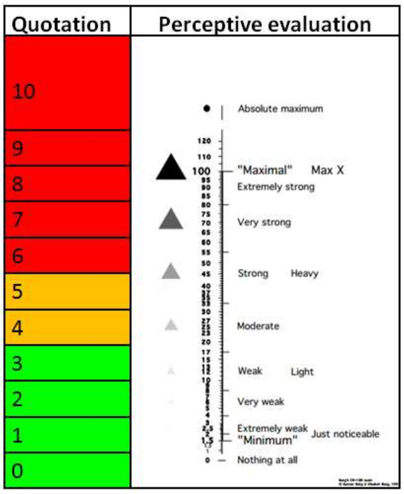


Figure 5: Borg's scale for exertion and pain [6]

Quotation	Acoustic comfort evaluation
1	**Very bad** : Non operational
2	**Bad** : Limited operation
3	**Very poor** : Complained as bad failure by all customers
4	**Poor** : Rated as failure by all customers
5	**Unsatisfactory** : Rated disturbing by all customers
6	**Acceptable** : Rated disturbing by some customers
7	**Satisfactory** : Noticeable by all customers
8	**Good** : Noticeable only by critical customers
9	**Very good** : Noticeable only by trained evaluators
10	**Excellent** : Not noticeable even by trained evaluators

Figure 6: Typical automotive industry acoustic comfort evaluation

Sometimes, quotations for quality evaluation are requested to be performed with a 4 values scale: from very bad to excellent through unsatisfactory and satisfactory. In a scale of 1 to 10, a truncation effect of 0.5 in the mark is inherent. In a scale from 1 to 4, the two extreme values are not very informative because they represent too low or too high quality. Not only mark 2 and 3 are not very representative of the logarithmic scale itself, but the truncation effect in this zone is huge (graphically illustrated in Figure 4). In real life, such 4 steps evaluation scales quotations are not informative enough and can very easily lead to misunderstandings about the product itself.

PSYCHOACOUSTICS CRITERIA

In this section, a focus on Sound pressure level evaluation is presented, followed by other indicators characteristics of our ear/brain perception [7].

dB(A) and Loudness

In the late 1930's, a frequency weighting A is defined in the acoustic international standard for sound level meters. It is issued from the 40 dB equal-loudness contour and was manufactured adding internal RLC electronics circuits inside the sound level meter. At the same time, the dB(B) is also defined, from the 60 dB equal-loudness contour, but has not been as widely used as the dB(A). Since 1970, digital era allows to implement the whole iso-sonic contours, and to implement the "Loudness" psychoacoustic indicator. Loudness unit is expressed in Sones, or in Phones (3):

$$P = 40 + 10 * \log_2 S \qquad (3)$$

with P Loudness level in Phones, S Loudness level in Sones

24 critical frequency bands named Bark 1 to Bark 24 are defined in the audible frequency range and 24 "Specific Loudness" values are calculated. Global Loudness is calculated over the whole audible frequency range. In terms of order of scale, Phones are much like dB: 100% of people can hear a 3 Phones gap between 2 sound recordings, 10 Phones is the gap between the loudest and the weakest product among the different brands and ranges of a same type of product, 1.5 Phones is a typical measurement uncertainty.

Today, Loudness calculation includes time and frequency masking effects, and the last ISO 532 norm, *Method for calculating loudness level*, includes determination of time varying Loudness. Despite 40 years of possible use, it shall be pointed out that Loudness is still not THE Sound Pressure Level evaluator in automotive world.

Other criteria

In the automotive industry, psychoacoustics is used for:

- binaural recording and replay: massively used for acoustic comfort evaluation inside the car,
- pitch perception: tone to noise ratio (TNR), Prominence ratio, or Tonality criteria appear in some automotive specifications, mainly for fans and electrical motors,
- pleasantness: Sharpness versus time for quasi periodic signals and Roughness for electrical motors and fans are the most used.

HVAC SYSTEM DESCRIPTION AND OPERATING

The Heating Ventilation and Air Conditioning system is a major contributor to thermal comfort of driver and passengers inside the car. The function of the HVAC is based on the circulation of cold or hot air (Figure 7). Outside air is picked up at the base of the windshield and then blown inside the vehicle. The air is successively filtered, cooled or heated, mixed, and then distributed into the cabin. Another function is to use the recirculation inlet, which takes the air from inside the cabin. In order to cool down or heat up the car cabin faster. It is also used in case of detection of pollution outside the vehicle. To warm up and cool down the air, inside the car cabin, two closed loops are today necessary. The cold loop is based on circulation of the refrigerant. The hot loop is based on circulation of engine coolant.

1. Recirculation Air Inlet – 2. Air Inlet Flap – 3. Outside Fresh Air - 4. Blower – 5. Air Filter – 6. Evaporator – 7. Refrigerant A/C Loop – 8. HVAC Structure – 9. Condensate Outlet – 10. Mixing Air Flap– 11. Heater Core –12. Heater Water Loop – 13, 15, 16, 17, 19, 20. Air Outlet – 14. Air Distribution Flap – 18. Defogging-demisting Flap.

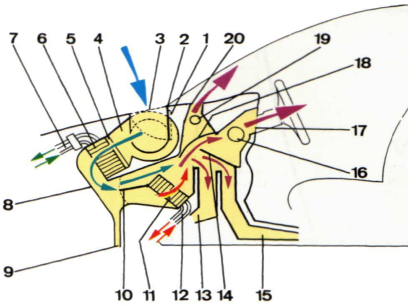


Figure 7: Automotive Air Conditioning System

The air conditioning system shall satisfy the end user comfort in terms of cooling capability, heating capability, advanced comfort (individualisation, soft diffusion, pre-conditioning), air quality (filtration and odorisation), acoustics (low overall noise level, good sound quality, no transient noises). On the other hand, the supplier of the air conditioning system must satisfy the car manufacturer needs in terms of packaging, mass, power consumption, and acoustics (overall noise level, sound quality). All criteria can be satisfied but a compromise must be found between acoustics and others criteria.

APPLICATION TO AIR CONDITIONNING SYSTEM NOISES

As mentioned, thanks to the blower, the air passes through different exchangers and ducts and is blown inside the car cabin and extracted from the vehicle. Thanks to flaps, actuators and steppers, the airflow distribution at needed temperature is ensured. All those components are not known or not visible (under the dash board) for the end users. The only visible thing used by end users is the HMI (Human Machine Interface). The only thing expected by the end user is the thermal comfort. The car makers and the suppliers translate this expectation into an air flow quantity, a temperature level and a distribution type.

However, both active and passive components in the HVAC can be sources of noise. Each source is identified as magnetic, aero-acoustic or mechanic source. Each type of noise can be classified as natural or unnatural. Valeo has created a data base where each noise is identified by detection conditions, the frequency band and its sound.

Non-natural ticking and U-Tone noises: description and root causes

Very irritating noises can appear at low blower speed, because the air flow noise is very low (Figure 8). The root cause of the ticking is the roughness of the surface of the motor collector. Numerous rotation speed harmonics are present in the noise spectrum: the main root cause is the magnetic field fluctuation that creates vibration modulo the number of slots on the rotor. In those two cases, vibrations are transmitted to the motor. Any contact between the motor and plastic parts like motor cover creates the noise.

Due to lower background noise in electrical vehicles, hybrid and electrical cars users may be more sensitive this kind of annoying noises. For example, acceptable ticking and / or U-ton noise in thermal power train vehicles could be very annoying in electric power train vehicle (Figure 8 and Figure 9).

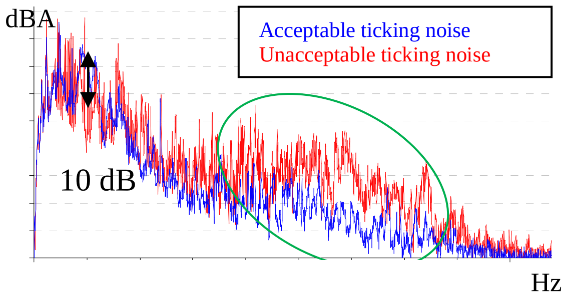


Figure 8: Ticking noise spectrum

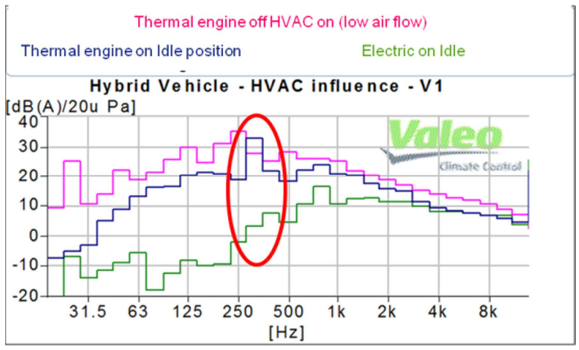


Figure 9: High harmonicity in the spectrum

Non-natural ticking and U-Tone noises: recommendations

Two solutions can be implemented to eliminate this kind of noise. The first one is to select only very good motors. In this case, an end of line control is mandatory for 100 % of production. The second one is to implement efficient decoupling system between the motor and the motor cover. The second solution is most efficient than the first one because the decoupling system reduces the motor dispersion. In order to reach the car maker specifications and to offer good quality and comfort to the end user, new decoupling system has been developed recently by VALEO (Figure 10 and Figure 11). This system is very efficient for thermal power train vehicles and still efficient for hybrid and electric power train vehicles.

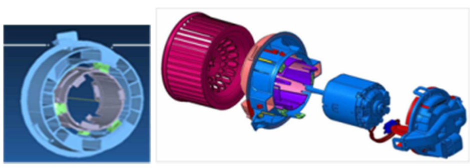


Figure 10: Efficient decoupling

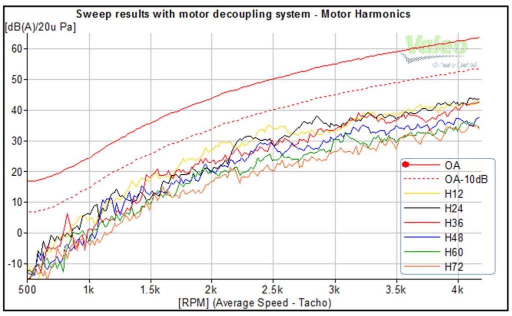


Figure 11: Significant gap (12 dB) between the harmonics levels and overall level

Non-natural recycling noise: description and root causes

The recycling function is used to warm up and cool down the air in the cabin very quickly. This function is also used in case of air pollution. In some HVACs, the recycling air is permanently used to upgrade the thermal performances. To realise this function, the air is picked up from the cabin via an inlet under the dashboard. Due to this opening and because of pressure loss difference in this configuration, the noise inside the cabin can be sometimes totally different compared to fresh air, in terms of spectra, and level. This noise difference will be more annoying in case of electrical power train vehicles. This will be not acceptable for the end user, especially in case of automatic HVAC - in this case, the end user does not manage the recycling air inlet-.

Non-natural Recycling noise: recommendations

Use of VALEO recommendations lead to reduce the noise gap between fresh and recycling air. These recommendations are based on two principles: 1- In fresh mode and in recycling mode, air flow and pressure drop of both circuits must be the same. 2 - Direct noise shall not radiate directly through the recycling air inlet. In this way, a PSA/VALEO patent (Figure 12 and Figure 13) consists in placing the Fresh and Recycling inlets in the car plenum [9]. In this case, the same pressure losses between the two modes are obtained and the direct emission of the blower in recycling mode is avoided. With this design, the same perception of recycling and fresh air is obtained.

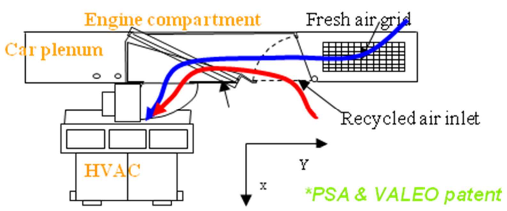


Figure 12: Concept of new recycling air inlet

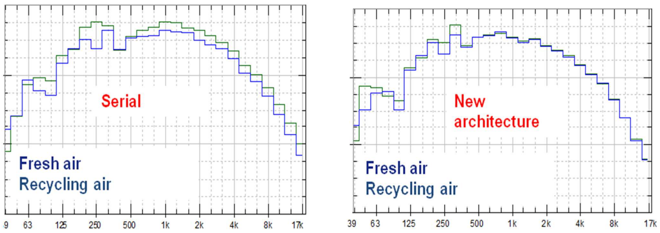


Figure 13: Comparison between recycling and fresh air

Natural Air Flow noise: description and root causes

For the thermal needs in vehicle (warm up and cool down) the HVAC unit can produce an air flow rate up to 600 kg/h, which causes a high noise level. This natural noise: it is needed by the end-user as a feed back for the ventilation system well functioning. Moreover, it must have good noise quality, with “pure” air noise (no cavity modes, “fallen leaves” noise…), and an acceptable level in high frequencies. This natural noise can be perceived as not acceptable in case of electrified vehicle because of low background noise in electric modes (**Erreur ! Source du renvoi introuvable.** and **Erreur ! Source du renvoi introuvable.**).

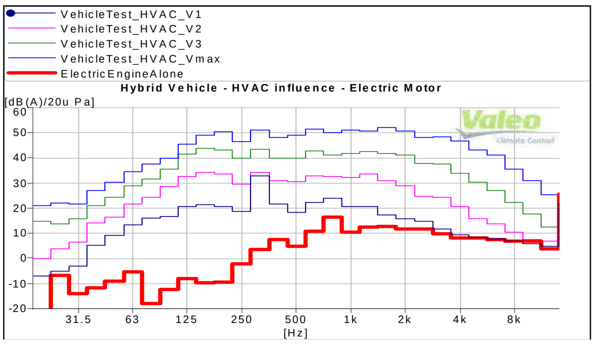


Figure 14: HVAC air flow noise Thermal power train noise

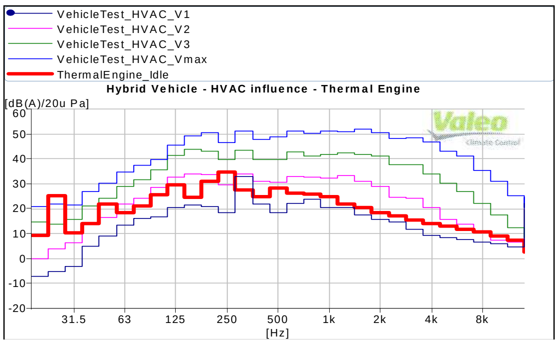


Figure 15: HVAC air flow noise Electric power train noise

The worst case is changing the power train mode from thermal engine mode to electrified mode. In that case, the background noise drops from a level that can cover completely or partially the HVAC noise to a level that cannot cover the HVAC noise. The recommendations done, in case of thermal engine power train, still apply to the electrified vehicles but other recommendations shall be implemented to manage the air flow sound quality.

Natural Air Flow noise: recommendations

The noise level of HVAC (overall and 1/3 octave) is linked to the air flow, pressure drop and the efficiency of the blower [10]. Therefore, it illustrates well the impact and great potential of improvement for the acoustic results by decreasing as much as possible the air flow rate and pressure resistance (Figure 16 and Figure 17). It is possible to predict the air flow noise (overall level and spectra) using a blower pre dimensioning tool developed by Valeo. Two levers can be used to reduce the air flow noise: pressure drop and air flow optimization.

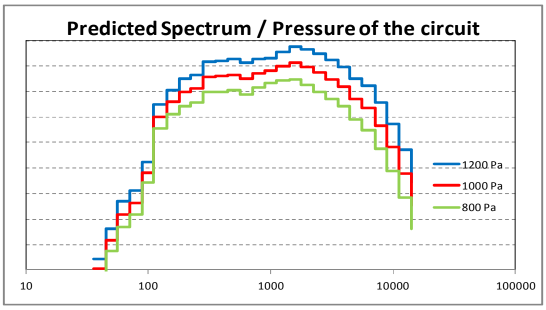


Figure 16: Influence of the circuit pressure

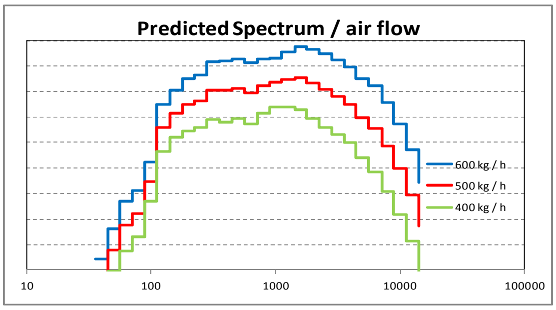


Figure 17: Influence of the air flow

Natural noises: Pressure drop optimisation

The total pressure drop of the complete circuit is the sum of vehicle pressure drop and HVAC pressure drop. The HVAC pressure drop is due to air inlet, diffuser, filter, exchangers and distribution circuit. The vehicle pressure drop is due to the water separator, the ducts and the extractor (Figure 18). The blower adapts its rotation speed to overcome this total pressure drop. The higher the pressure is, the higher the blower speed is, and the louder the noise is.

To reduce the air flow noise, the HVAC and vehicle pressure has to be optimized. The pressure drop of each part of the circuit is minimized using car manufacturer and VALEO know how. Several CFD simulations can be necessary to optimize the circuit pressure drop (Figure 19).

The required blower pressure head is reduced (Figure 19); it is also the case of the blower rotation speed and power consumption. In some cases, the dimensions of the blower can be changed to be altered to the new operating point. In some cases there is a physical limit for pressure optimisation. In this case the specification or the packaging has to be reviewed.

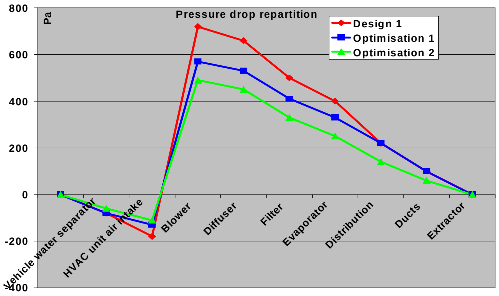


Figure 18: Example of Pressure drop distribution

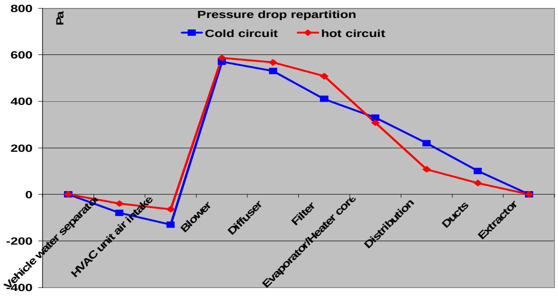


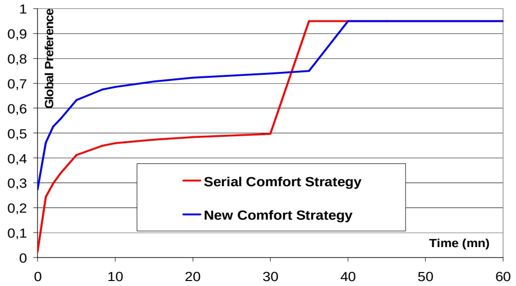
Figure 19: example of pressure drop optimization

Natural noises: Air flow optimization

There are two approaches to reduce the air flow. The first one is based on new management of the end user thermal comfort. New air flow distribution result in air flow reduction while the comfort is the same. The thermal validation of this approach shows very interesting results. To implement this approach in serial production, collaboration between VALEO and the car makers is mandatory.

The second approach consists in establishing a strategy for end user global comfort. A model mixing thermal air flow and acoustic preference shall be found. Collaboration between VALEO and the academic world [8] was organised, in order to evaluate the end user comfort needs. This study of the psycho-acoustic perception of several HVAC systems provides a classification of several configurations ranked from acceptable to the most disturbing. Correlation between subjective and objective measurements provides a preference model obtained from 2 complementary methods (preference and dissimilarity). Two parameters have been identified in this model: Loudness and Speech Interference Level. These parameters have different influences depending on the frequency. By modifying the acoustic level in a precise frequency band, it is possible to improve the acoustic perception of the end user without changing the overall noise level.

A mixture between the acoustic preference model, thermal needs and air flow rate allows finding a new method of A/C system control to offer a global comfort to the end user. The example in Figure 20 shows a new temperature control strategy for cabin cool down, a better comfort curve compared to current production cool down: a slight thermal comfort and air flow performance decrease can result in a drastic noise reduction. The end user prefers the new strategy because the noise level is lower than the production strategy even if the time duration of the cool down is longer.



Objective: cool down the air inside the vehicle from 70 °C to 20 °C	**Current production strategy**	**New control method**
Time duration to achieve 20°C	30 minutes	35 minutes
Air flow rate	500 kg/h	400 kg/h
Overall noise level	65 dB(A)	60 dB(A)
End user head temperature	T=Fct (Time)	T=Fct (Time)+1°C

Figure 20: New Cool Down new strategy to offer global comfort

APPLICATION TO AUTOMOTIVE COOLING FAN SYSTEM: AXIAL FAN

An axial fan system is positioned in the air flow through the heat exchangers full of fluids. This fan system (fan mounted on an electrical motor) operates whenever the temperature of the cooling liquid reaches a value considered as dangerous for the engine operation and duration. While operating, vibrations on the steering wheel can be perceived by the driver, due to fan unbalance transmitted through the car body, mainly when the engine is at idle or OFF. Inside the car, the airborne noise created by the fan system is hardly audible. As airborne noise level is speed dependent, electronic speed driving enables to avoid long durations at high rotation speeds. However, when the fan is operating, global level is always above 55 dB(A) for a person at distance of 1 meter from the fan system.

Psychoacoustic studies on cooling fan have been performed through the last 15 years [11]. Different techniques to establish a correlation between jury evaluations and various models have been studied. The most significant characteristic of the "fan system noise" is the specific loudness. It is clearly more adapted than the dB(A), which is not suitable for levels much higher than 40 dB: global Loudness results correlate much better than the dB(A) with Jury evaluations. Jury evaluation using a scale of annoyance (replacing pain by annoyance in the Borg scale) show that any fan system has the characteristic to be at least "strongly annoying".

It is also possible to calculate a peak level strength related to neighbour broadband frequencies, a tonality, or a prominence ratio which takes into account several harmonics. It is also possible to calculate a Roughness indicator. But none of these various indicators correlate better than 85%. Tests at iso-sonic level can be performed, but as they are performed at realistic levels, the global "strongly annoying" characteristic seems to be prominent in the global perception.
In other domains such as wiper systems annoyance [12], Loudness has been successfully used in the last decade and is deployed in many specifications, because correlation with jury evaluation is over 90% and loudness levels are not so high.

The high loudness levels of cooling fan systems seem to not let clear trends for other criteria to evaluate their sound quality. This could be an explanation for the very exceptional use of such criteria to cooling fan systems perceptive evaluation in the last decade.

CONCLUSIONS

Sound perception ensures optimised communication with human environment. New technologies products are created to enhance human comfort. They produce sounds and can be evaluated in a human perception point of view. Different perceptive quotation scales are discussed showing that 10 levels scales are adapted to perception in general.

An overview of Psychoacoustics tools applied to fan noises is presented. Numerous models are able to characterise the spectral characteristics of sound produced by rotating machines -numerous harmonics of rotation speed are prominent in the spectral shape-.

Comfort enhancement strategy for Automotive Heating Ventilation and Air Conditioning systems consists in a first step in a classification into different noises characteristics and presence conditions. In a second step, optimisation of the main perceptive characters of each pre-classified noise is proposed, generally involving other comfort parameters.

Concerning Automotive Cooling Fan systems, Loudness criterion is the main characteristic of the acoustic annoyance and other criteria are not commonly used because Loudness levels are really high.

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