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Development of Exhaust Sound Quality on Aston Martin V8 Vantage

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ABSTRACT

The Aston Martin V8 Vantage represents a new chapter in the company's development. In line with brand image the new product was required to exhibit a powerful and sporty yet sophisticated sound which would become a leader against competitors.

The exhaust orifice sound was tuned via a combination of CAE simulations and iterative modifications coupled with subjective assessments.

The final product exhibits a strong, linear, firing-order dominated sound which is unique to the vehicle and unlike many other traditional V8 soundtracks. The exhaust sound quality can be seen as a vehicle feature affirmed by the positive feedback from customers and press.

INTRODUCTION

As the demand for vehicles to become more and more refined increases, sound quality is becoming a greater concern to manufacturers. Increasingly it is not only the sound level that is considered in noise control, but also sound quality. Pang et al [1] have shown that sound quality is an important attribute that relates strongly to customer satisfaction. Furthermore, sound quality can be used to enhance the brand image of a manufacturer [2], being used as a competitive advantage over other brands.

Powertrain NVH is an extensive subject covering both error states and sound quality tuning of the whole engine, driveline and associated systems. Exhaust and intake sound are two of the major contributing elements to vehicle noise that a driver responds to. Consequently, the sound quality of the exhaust note is an important factor for the vehicle's customer appeal [3].

This paper gives an account of the target setting, design process and iterative tuning steps employed within the development of the exhaust sound quality.

BRAND DNA

Traditionally there are two main vehicle sound classifications: the limousine/cruiser with a quiet and discrete sound, whereas for sports cars a more rough and powerful sound is requested. The company's brand image is of a luxury sports car, and as such, it crosses the boundary between the above two classical groupings. It is desired that the product displays a powerful, sporty image, and therefore sound, but at the same time, the vehicle should be capable of cruising comfortably and luxuriously.

This contradiction was achieved successfully on other company products by utilising the exhaust bypass valves. A similar system was to be used for this new sports car, but it was key to incorporate brand images;

Exhaust sound quality should be:

- Sophisticated sound
- Lightweight, free revving character
- Leader amongst competitors

It should not be:

- Large, lazy, rumbling
- Highly stressed, racing engine
- A silent, super refined luxury engine

TARGET

As part of the target setting process each attribute is split into individual sub-system and component level targets. Figure 1 details a high level generic breakdown of the overall vehicle sound quality through to exhaust sound quality.

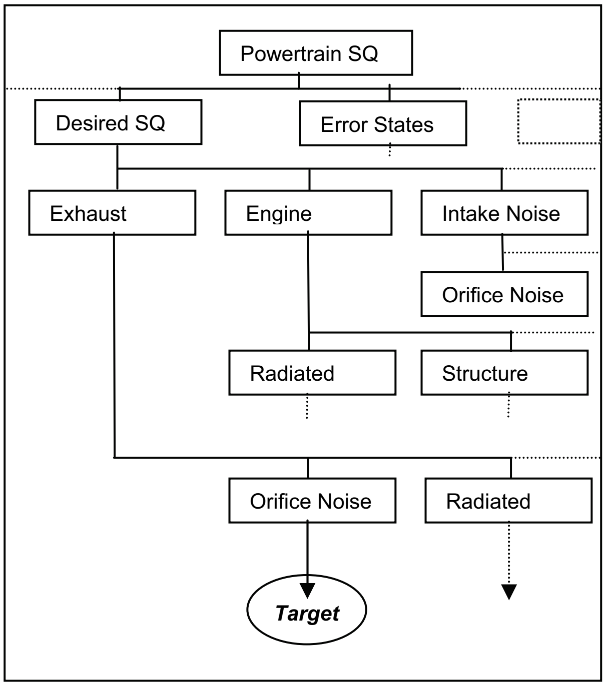

Figure 1: Example of high level breakdown of sub-systems and component targets.

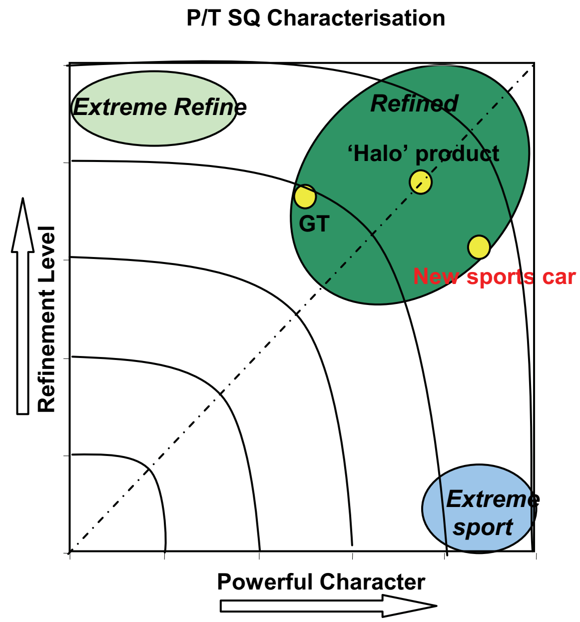

Figure 2: New sports car product position within company portfolio.

Within the company brand image, much emphasis is placed on the exhaust orifice noise contribution above other attributes to create the overall sound quality. This is partly as a result of a strong brand image in this field, but also due to the difficulty of allowing only desired noises from the engine bay into the cabin without added devices.

In order to achieve a desirable exhaust orifice noise, the target sound needs to be carefully planned. Firstly it is important to establish and understand the type of vehicle, its image and product placement within the company and also market place. Figure 2 demonstrates where the sports car will sit within the company's model range.

It is clear from the graphic below that there should be an aggressive and sporty sound quality in line with the vehicle. Evoking this quality involved the tuning of many systems within the vehicle (as highlighted in figure 1), but it is the tuning of the exhaust orifice noise that is the subject of the following.

	Sports car	GT	'Halo' product
Concept Styling	Benchmark sports cars	Sportiest GT	Prestigious Flagship
P/T Performance	380bhp	450bhp	520bhp
Engine	V8	V12	V12
P/T Sound Quality	Sporty, Powerful Unique	Powerful Comfortable Smooth	Powerful Strong Exciting

Table 1: Sports car positioning within the brand.

Defining the target sound for a sporty vehicle is key. Many studies have been performed on what makes a sporty exhaust sound. Generally it is accepted that the firing order of the engine should be dominant [1]. However it is often stated that in addition to this, it must also contain multiples of the fundamental firing order, as well as a degree of sub-harmonics, or half orders [3].

The first basic method for giving a performance or sporty impression to the customer is volume. Surveys have shown that loudness has a distinct effect in the performance impression, with louder sounds giving a higher performance impression. [4]

However, simply increasing the volume alone is not enough to generate a sporty quality sound. Naylor et al [3] have demonstrated that for a sound to be perceived as sporty it should in addition to the firing order have a sub-harmonic sound content. For a V8 engine they demonstrated that three components were found to correspond to an improved 'sporty' sound. These were: rumble (half orders); deepening of sound (amplified 4th & 6th orders); hollow sound (amplified 8th, 10th & 12th orders)

The amplification of sub and half orders provides a roughness to the sound which is usually perceived as sporty. This is as a result of increasing the periodicity of the combustion waveform which creates a modulation – perceived as roughness. The amount of roughness is dictated by the levels of the sub and half orders [4 & 5]. If the modulation is too much, the sound can be unpleasant, therefore the level of half orders need to be very well balanced otherwise the sound will become unpleasant.

With this said, the desire was to exhibit a sporty, powerful, and unique sound, identifiable with the brand. However, key to the product is its everyday usability, and in line with this, the sound should also be comfortable for daily use, and not too extreme. In line with the findings above and benchmark data from current products and competitors, the target sound was specified as shown in figure 3:

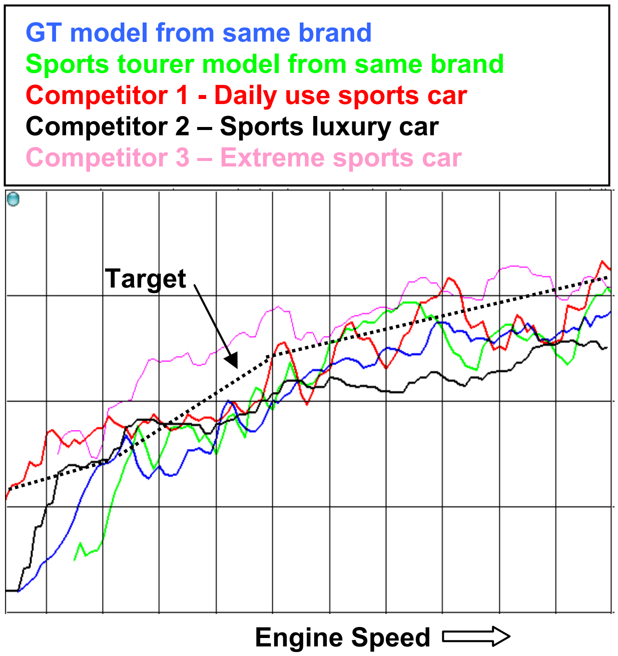

Figure 3: Overall cabin noise during 3rd gear WOT run up for several European competitors.

Target Sound:

- 3dB higher than current GT product overall SPL.
- Firing order dominated (4th EO)
- Minimum half and odd order contents (10dB lower than 4th EO), but enough to contribute to a sporty sound.
- Linear transition under acceleration.
- Comfortable sound to cruise with and for everyday use at low engine speeds.
- Exciting sound at high engine speeds.

As a production vehicle, it also required to pass all legislative noise control tests such as the drive-by cycle test.

DESIGN PROCESS

For sound quality development a prototype vehicle was assigned for use with development mufflers. Traditionally the exhaust orifice sound was tuned via iterative steps in modification to prototype hardware and on vehicle subjective assessment of each design.

Throughout development of this product a sound quality CAE tool was fully used for the first time within the company to assist with the development. Ricardo WAVE allowed many design iterations to be quickly assessed which previously would have not been considered. The CAE capability was not intended to replace subjective assessment but to aid the direction of development. As this was the first programme within the company to use acoustic CAE, much of the early work was concentrated on correlation and building up confidence in the techniques and results with the intention of its use on future programmes.

CAE MODELLING

Ricardo WAVE is a 1D CAE code used to analyse the dynamics of pressure waves, mass flows and energy losses in ducts. It can be used to model engine systems including intake and exhaust manifolds, pipes and mufflers. It provides a fully integrated treatment of time-dependant fluid dynamics and thermodynamics. [6]

Using the 3D builder add-on package, an air-to-air (induction-engine-exhaust) CAE model was built up for the entire engine system from clean air ducts through to muffler exit orifice. A post processing element was then used to simulate the sound from the modelled system. This allows changes to be made quickly and efficiently to the model and the effect on the sound analysed.

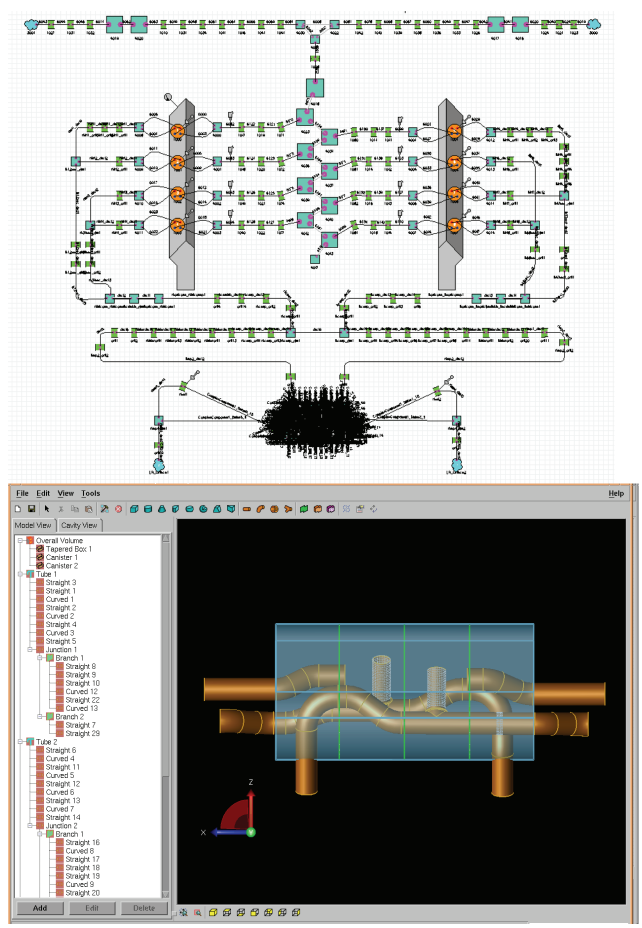

Figure 4: Screen grabs of the model used and the 3D build element within WAVE.

Whilst CAE can produce a WAV file export of the simulated sound, the direct playback of the noise file generated does not sound realistic enough to be used for a general, non-specialised audience as noted by Hetherington et al. Instead, it is often more useful to export the sound file to an external, more specialist sound analysis package for post processing.

Once the model was built up using known physical properties of the system, for example, duct dimensions, geometry and temperatures, it was necessary to ensure that the model correlated well with the available test bed data for the engine. Once this was complete, the model could be used for simulation of exhaust orifice noise and sound quality tuning investigations.

MEASUREMENT & EVALUATION

Whilst CAE was used to run through many iterations of exhaust design, concurrently the best design variations were built as prototypes for assessment. Subjective evaluation of the sound quality is critical to achieve the best condition and to provide further direction; ultimately this is the customer's viewpoint/contact with the vehicle.

Typically the prototype parts were fitted to the vehicle and subjectively assessed both on track under repeatable conditions, but also on local roads under more realistic customer driving conditions and patterns.

Several full and part throttle accelerations were measured for each condition, together with constant speed, idle and coast down conditions. Further to this, drive-by testing was conducted to ensure that the legislation would be satisfied.

With the objective data gathered, and subjective feedback from the drive assessment, the direction for further improvement was fed back to the CAE model where quick alterations could be made.

INITIAL SYSTEM DESIGN

The starting point for development was a dual system with a 4-2-1 unequal length exhaust manifold design. Catalysts were positioned underfloor immediately after the manifolds prior to a long centre section (split bank-to-bank) leading to the muffler. The first prototype muffler allowed gas mixing. The muffler also incorporated bypass valves to allow switching of the gas between two routes.

The bypass system was fitted so that the backpressure could be minimised at high engine speeds in order to protect the engine. It was known from previous product development that the route required through the muffler in order ensure enough attenuation to pass legal requirements resulted in high backpressure at high engine speeds, which could damage the engine.

Some sources believe that it is vital to tune sound quality at the hot end of the system (i.e. runners, down-pipes and manifolds), and that very little can be accomplished at the muffler [5]. However, others consider the internal design of muffler, with a given volume, can create quite different tailpipe sounds. [2].

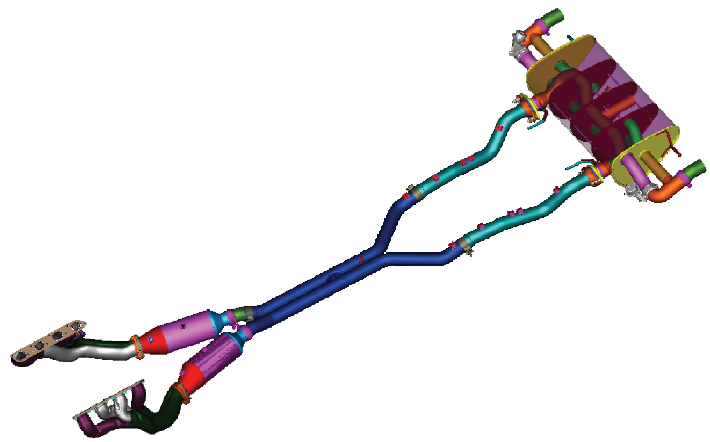

Figure 5: V8 Vantage exhaust system.

Whilst it is certainly true that it is necessary to ensure that the manifolds are not emitting unwanted orders, often due to constraints within the programme, it is not possible to make changes here, and modifications need to be made at the cold end (muffler). Experience within the company has shown that much can be achieved in terms of sound quality tuning with modifications to the muffler only.

With this latest sports car programme due to packaging and engine performance targets, the manifold, catalysts and centre pipes were largely frozen, and therefore not available for tuning the sound quality. Thus the muffler was therefore the main option for tuning the sound.

CAE analysis of the exit noise content of the manifold showed that the order content and balance was acceptable. There was sufficient firing order (4^{th} EO) present, and any unwanted orders were not dominant.

Although the outer package volume was fixed, along with the entry and exit orifice positions, there was still plenty of flexibility over the internal design. The key design parameters of the muffler internals were;

- Route of pipes
- Diameter of pipes
- Position and number of perforations
- Chamber volumes
- Absorption material
- Bypass routing

The exhaust bypass system fitted (figure 6) allows two different gas routings to be effected at different engine speeds. The purpose of this is to force the gas through the muffler and provide good attenuation whilst the vehicle was at low engine speeds to conform to legislation, but also protect the engine from high backpressure at high engine speeds.

The second advantage of this system is that it allows a refined level of muffler noise with the valve closed, which can be used for cruising or urban driving. Whilst with the valve open, at higher engine speeds, the gas can flow through a less restricted path in the muffler and provide the less attenuated, powerful and sporty sound that was required.

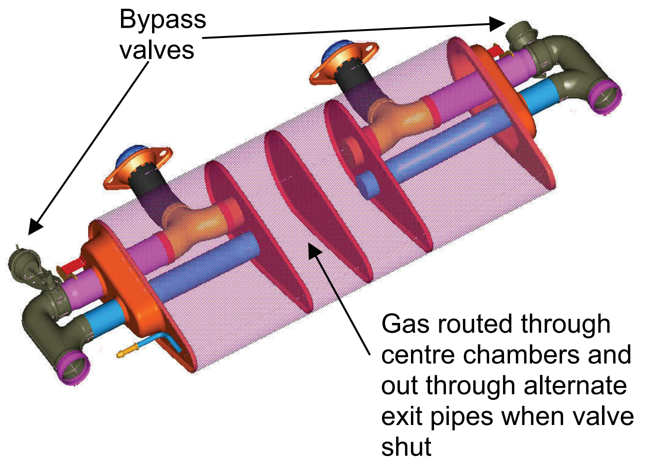

Figure 6: Original prototype muffler design.

MUFFLER DESIGN ITERATIONS

Tuning the muffler required several further iterations from the base prototype muffler, these were designed from a combination of subjective feedback and CAE results.

Initial feedback from the original prototype system (see figure 6) was that it was too loud under both valve open and shut conditions. Consequently a significant redesign was undertaken to provide a better route for the valve shut condition in order to give more attenuation. This involved repositioning the internal baffles and packing the outer chambers with E-glass to provide more high frequency absorption. Also the routing forced the gas to exit through a perforated section rather than the open end of a pipe.

Further to this, the valve open condition was attenuated by making the route longer. This involved the gas crossing the length of the muffler and exiting on the opposite side. The advantage of this setup was not only that the valve open route was now significantly longer, but by running through both inner and outer chambers, there was more opportunity for tuning. Figure 7 shows the revised layout for the second prototype design muffler.

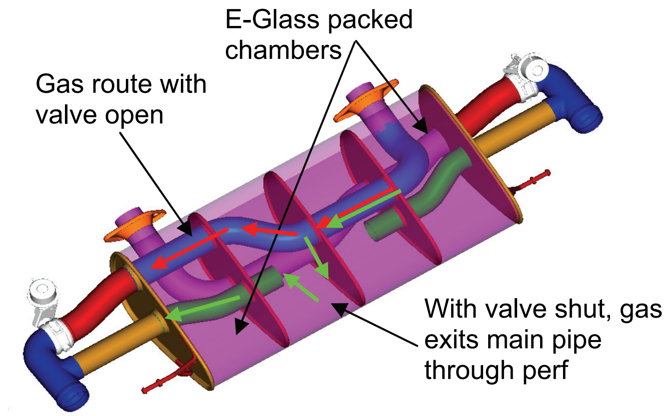

Figure 7: Revised muffler layout.

From CAE analysis and early testing of the second prototype design, it was confirmed that the valve shut condition which diverted the gasses into the chambers and provided much better attenuation, gave sufficient performance to pass the drive-by legislation. For this reason, the volume of the chambers, the baffles and amount of E-glass was fixed, and the main areas of change were the perforated sections in both the inner and outer chambers in order to satisfy the valve open sound quality requirements.

Table 2 details the various different muffler iterations that were assessed. Many of these were small incremental changes to the amount of perforated section on one or both of the pipes.

Outer volume perf	Inner volume perf	Tuning Tube (Perf)	Perf End Caps	Centre mixing pipe
20mm	35mm	NO	N/A	NO
0mm	35mm	NO	N/A	NO
10mm	35mm	NO	N/A	NO
10mm	15mm	NO	N/A	NO
0mm	25mm	NO	N/A	NO
0mm	0mm	YES (0mm)	NO	NO
20mm	0mm	YES (0mm)	NO	NO
40mm	0mm	YES (0mm)	YES	NO
30mm	0mm	YES (0mm)	YES	NO
20mm	0mm	YES (0mm)	YES	NO
10mm	0mm	YES (0mm)	YES	NO
0mm	0mm	YES (75mm)	YES	YES
10mm	0mm	YES (100mm)	YES	YES
10mm	0mm	YES (110mm)	YES	YES
10mm	0mm	YES (110mm)	NO	YES
14mm	0mm	YES (110mm)	NO	YES
20mm	0mm	YES (110mm)	NO	YES

Table 2: Prototype iterations tested on vehicle

After several iterations a T-piece was added into the centre chamber (see figure 8). This pipe allowed the gas to travel into the centre chamber when the valve was closed, but did not dramatically attenuate the gas as it travelled past it (valve open), unlike the perforated section that was previously employed.

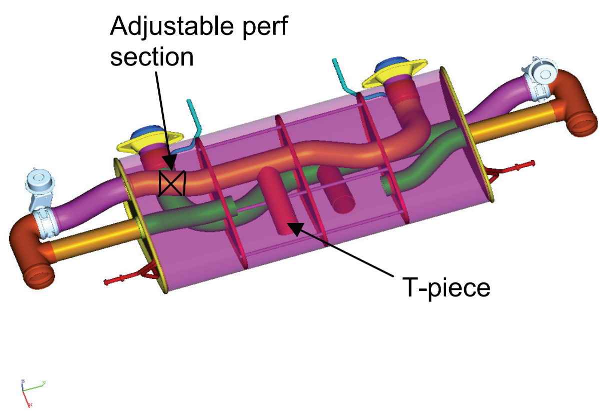

Figure 8: Revised design with T-piece added.

The effect of the T-piece was not only to allow a louder valve open condition, but because it behaved as an open ended resonator, it also gave an element of tone control to the sound. By increasing the length of the T-piece that was perforated, the sound became deeper. This was something that had not been apparent on the CAE predictions, and required subjective assessment to judge the correct level.

The perforated caps that were initially placed on end of the T-piece were also deleted because the valve shut condition was sufficiently attenuated to pass drive-by legislation and the caps were not needed. Also a reduction in backpressure was seen, again beneficial to engine performance.

Once the T-piece was fixed in design, the main focus of development was to achieve the correct overall level to suit the product. This was an iterative process because the prototype vehicles were becoming more mature, and as such had better sealing, trim and NVH acoustic packs. Consequently, the overall level needed to be changed several times to achieve the desired effect.

It was found very quickly that there was an ideal window with respect to the length of perforated section in the outer chambers. This region of tuning tended to act as a crude volume controller. If it was too short (<12mm,), then both the interior and exterior noise level was too loud and harsh. If the perforated section was too long (>30mm), the sporty sound began to disappear, and idle and low speed quality was lost. Ultimately it was a balancing act between maintaining the idle quality and low speed refinement, but also retaining a sufficiently loud and sporty sound at high engine speeds.

Further challenges included the ignition timing and general engine calibration. As this became more mature, the ignition advance was increased. Fortunately this had a positive effect of reducing some harshness that was being experienced at 5000rpm.

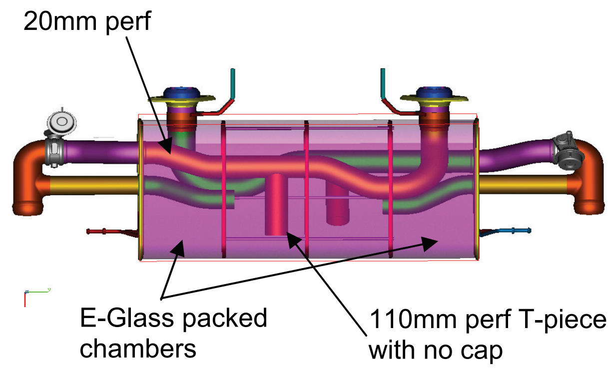

Figure 9: Final production muffler design

CENTRE PIPE – GAS MIXING

Due to the non-alternate firing cycle of the V8 engine, the gas pulsation from each bank cannot be treated as if it were two 4cylinder in line engines. There are irregular firing intervals between cylinders on the same bank: 180°; 90°; 180°; 270°. Figure 10 details the firing order of each cylinder of the V8.

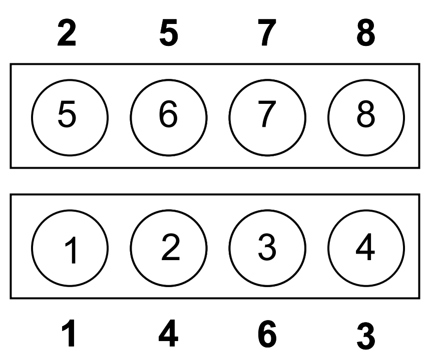

Figure 10: Firing order of V8 – order shown in bold.

Due to the irregular firing order at each bank, the order contents of the noise contain many half orders. Theoretical analysis shows that half order contents will be cancelled for equal length Y-pipes [1], however this is not an option with the irregular firing. Instead in order to try and cancel/reduce the odd orders (1.5EO, 2.5EO), and enhance the firing order (4EO) there was a necessity to mix the gas from bank to bank. This need was further enhanced by the presence of non equal runner lengths on the manifolds. The options were to mix the gas in the muffler or in the down-pipes prior to the muffler.

Hosomi [8] demonstrated that mixing banks from an irregular firing V8 at the muffler, or any other large volume, does not result in a satisfactory cancellation of half orders, or indeed promote the firing order sufficiently. Instead, the delay from the pulsation propagating through the volume leads to a first order fluctuation.

Whereas if the gasses are mixed in a pipe prior to any volume, the characteristics of the pulsation wave inside the pipe are changed, and the two pipes dissipate the pulsation of each other resulting in a cleaner firing order at the volume (muffler) [8].

For this reason it was decided to try and mix bank to bank gases in the centre pipe prior to the muffler. Simulation demonstrated that if the centre pipe was mixed completely, it would indeed increase the firing order and reduce the sub and half orders. However, the level of attenuation of sub orders meant that the firing order now stood too strong above other orders. This resulted in a tonal sound which had little modulation and was not sporty. Together with other programme influences, the decision was made to go with a centre pipe that allowed mixing, but still maintained a majority gas split.

Figure 11 shows the final modified centre section with the mixing pipe fitted. CAE analysis was used to determine the best size and location for the pipe. The effect of this was reduce, but not delete, some of the unwanted half orders, particularly 4.5EO and 2.5EO and allow the firing order to stand out. This effect was particularly evident at idle and lower engine speeds where the gas flow was low. This was ideal because is allowed a stronger idle, with greater 4th EO presence without increasing the overall level over the entire engine speed range.

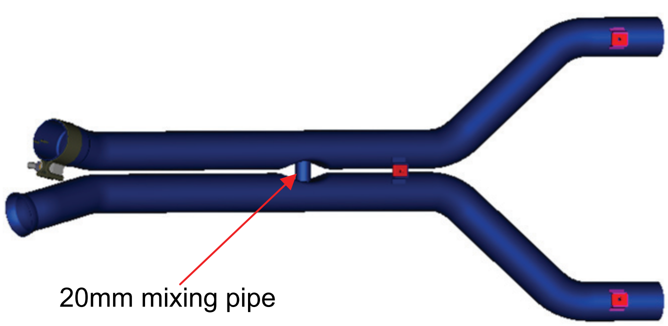

Figure 11: Exhaust centre section pipe.

Firing order was also increased during the valve shut region as well (~2000rpm-4000rpm), due to the increased backpressure resulting in greater mixing. At higher engine speeds, the mixing pipe had very little effect on the engine order balance, mainly due to the speed of flow through the centre section – see figure 12.

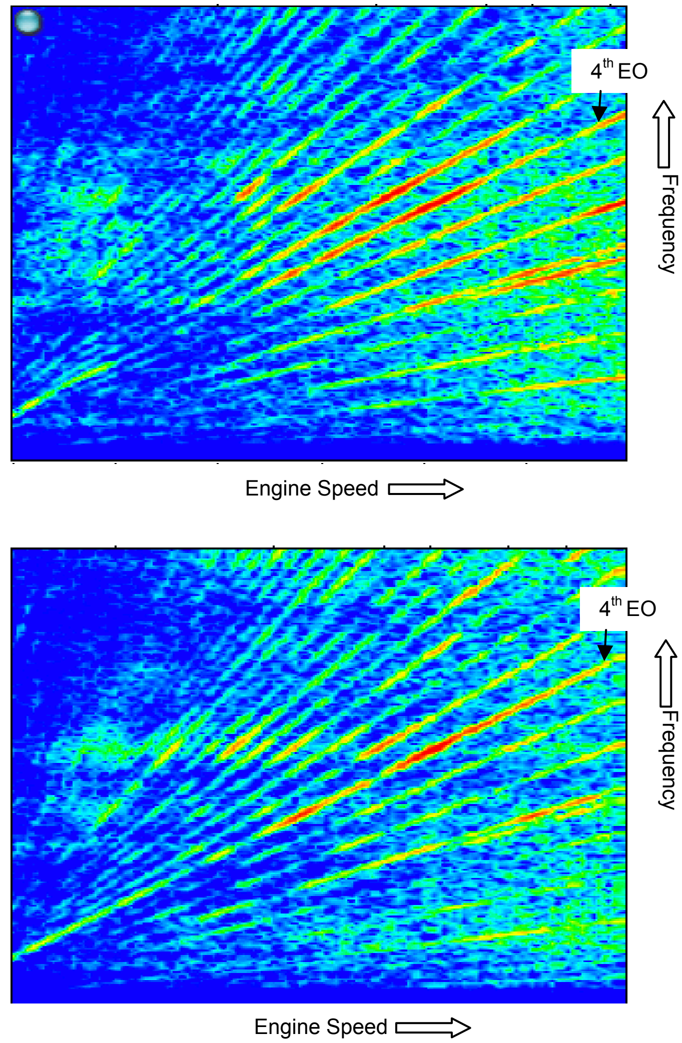

Figure 12: Effect of mixing pipe on tailpipe orifice noise. Top figure shows a 3rd gear WOT run up without the mixing pipe fitted. The lower graph details the effect of adding the mixing pipe.

CABIN ACOUSTIC BALANCE

An important aspect within the tuning process was the perceived balance between the engine, intake and exhaust within the cabin. To achieve this balance it was necessary to tune the vehicle's acoustic pack such that the cabin level was appropriate with the muffler valve in either open or closed states. The desire was to have a comfortable and refined sound during cruising, whilst retaining a sporty sound for the higher engine speeds.

Throughout the evolution of the acoustic pack within the vehicle's development, the transfer function from the exhaust and intake orifice to the driver's ear was constantly changing due to improved prototype vehicle build quality, and greater off tool part content. The development route was to establish a comfortable level of engine and intake noise with the muffler valve shut by tuning the engine bulkhead and engine bay absorption components. This allowed a baseline level of engine originated noise which could be then be balanced with the addition of increased exhaust content.

The transfer function was repeatedly measured between the cabin and engine bay/intake and exhaust orifice with simple speaker tests. This provided direction for where the attenuation needed to be increased or reduced.

Once the desired level of engine noise was achieved it was then possible to tune the acoustic pack towards the rear of the vehicle such as the luggage area, parcel shelf and rear trim. This allowed the adjustment of the transfer path from the muffler to the driver's ear. By bringing in the muffler noise (bypass valve shut), a comfortable cruising level was achieved for mid range engine speeds.

It then followed that when the muffler valve was opened, at higher engine speeds, the cabin level became louder and more aggressive due to the muffler contribution. Equally the engine noise from the front of the vehicle would also rise with the increased engine speed and thus maintain the overall balance.

Particular care was taken during development of the coupe to ensure that when the convertible model was built, there would not need to be significant changes to the exhaust system.

The control system for the muffler valve allowed the valve open and shut points to be adjusted reference to the engine speed and throttle position. Figure 13 below shows the position map for the muffler valves.

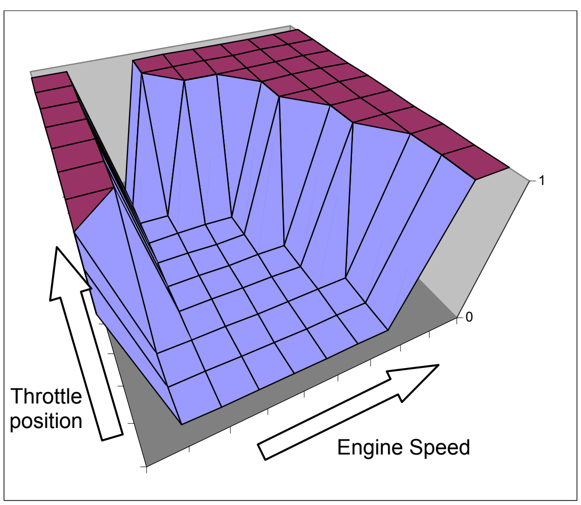

Figure 13: Muffler valve control map.

The map was modified many times after different driving cycles and styles revealed different requirements for the valve position. It was critical that the sound matched the driving style. If the driver was cruising, the valve should be shut and allow a refined drive. Only when the vehicle is being driven aggressively should the valve open, and protect the engine from excessive backpressure, as well as effect the more dynamic and sporty sound from the muffler.

CONCLUSION

With guidance from CAE data and careful iterative modifications, the exhaust orifice sound quality of a new luxury sports car was successfully tuned to produce a sporty sound in line with the product placement and brand image.

Work was successfully completed via modifications only to the cold end of the exhaust system and tuning of the vehicle acoustic pack and associated transfer function.

Whilst traditionally subjective feedback alone was used to tune the exhaust system, this programme was used to trial CAE exhaust tuning for the first time within the company with reasonable success.

The final specification of the exhaust system is shown below together with the 3D colourmap for a third gear Wide Open Throttle (WOT) run up from an early production vehicle.

- Dual exhaust system with 20mm mixing pipe in centre section pipe.
- Fully active bypass valve muffler – allowing quiet cruising, but sporty sound under enthusiastic driving.
- Tuned muffler to the following specification:
  - Two-route bypass system.
  - Perforated section (20mm) in outer chamber main pipe (valve open).
  - Perforated T-piece (150mm) in secondary route (valve shut).
  - Split bank, non mixing system
  - Perforated baffles between chambers.
  - E-Glass packing in outer chambers.

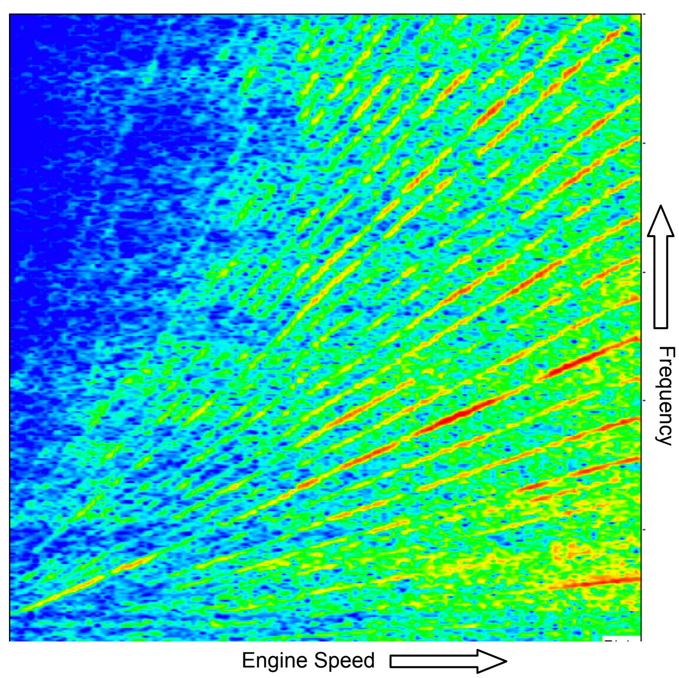

Figure 14: Third gear WOT run up.

Figure 14 shows the clear firing order dominated sound as targeted, but also an even contribution from the sub and half orders. Their presence helps to add to the sporty sound, but without being too dominant because they are sufficiently attenuated. This added spice prevents the sound from being too tonal.

The strong presence of the firing order gives not only the volume, but also provides a good linear base sound, which translates into a positive perception of performance to the customer. The effect is to provide a unique V8 sound which is not deep and rumbling as often associated with American V8s, or indeed high frequency or harsh as some racing engines can be, the sound is distinctive to the brand and the product.

Feedback from customers and press has highlighted the exhaust sound quality as a major feature, giving the vehicle both a strong attribute to the customer as well as a unique identity to the vehicle.

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