Target setting and source contribution for sound quality of a motorcycle

Ming-Hung LU[1]; Ming Une JEN[2]

[1,2]Industrial Technology Research Institute, Taiwan

ABSTRACT

Sound quality is an essential competitive attribute for motorcycles’ marketing. In this study, the sound perception of a motorcycle, powered by a 400 cc single-cylinder engine, didn’t achieve its “sporty” statement and the associated sound quality refinement engineering was initiated. The first phase of refinement included benchmark, noise source contribution and target setting. This paper focuses on the methods in setting sound target through source contribution and sound synthesization. Noise data were measured in a hemi-anechoic chamber with a rolling road facility. Loudness, sharpness and order spectra were used to provide objective quantification metrics. From the results of subjective and objective evaluation, it was concluded that the motorcycle studied should increase its sound pressure level, loudness and sharpness; it also should magnify the lower integer-order components of the perceived sound and suppress the single-cylinder engine characteristic half-order components. The noise source contribution results validated the exhaust and intake systems should be improved first to fulfill a favorable sound quality. Combining the objective, subjective and source contribution results, this study successfully synthesized a promising and feasible vehicle level sound target. It was then cascaded to get the synthesized intake and exhaust noise targets for next CAE design modification.

Keywords: Sound quality, Motorcycle, Powertrain I-INCE Classification of Subjects Number(s): 13.2.2

1. INTRODUCTION

Besides attractive style and high performance requirements, sound perception is regarded as a valuable attribute for enhancing the competitiveness and satisfaction of motorcycles’ marketing. Especially, emitted sound pressure level from powertrain and the related distribution of order components give an overall impression of the quality of a motorcycle. It is expected to meet the relevant legislation noise limit and refine the sound quality of motorcycle as well. After reducing the noise level for regulation approval, however, a motorcycle may be too quiet to be exciting from customers' viewpoints. To make a particular brand statement and favorable sound characteristics, sound target setting and design are essential. Nevertheless, the engineering of desired sound quality based on customers’ viewpoints is a complex and challenging task (1, 2). To enhance the sound quality of a motorcycle studied and to provide the needs of sound design, the authors built a brand specific sound target with sound quality development framework.

Several kinds of noise affect the rider’s sound perception of a motorcycle, such as engine and transmission noise, intake and exhaust noise, tire induced noise, wind noise as well as the vibration quality a rider experienced (3). Although several studies have investigated on improving interior sound perception of passenger vehicles over the past few decades (4–9), few researches have investigated the sound quality of motorcycles (2, 3, 10). Compared with passenger vehicles, motorcycles have less controllability for their noise emission because of their exposed powertrain and constrained space. To tailor a brand specific sound for a motorcycle, it is crucial to initialize a comprehensive sound design during product design and development stages. Depending on the proposed target, concerned operating conditions and engineering feasibility, the sound refinement is never going to be easy. In this work, psychoacoustic parameters and order spectra were used to provide objective quantification metrics on differences of sound characteristics between the studied

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[1] minghung-lu@itri.org.tw
[2] mujen@itri.org.tw

motorcycle and the benchmark one. To aid the target setting and examine the level of refinement, we designed a subjecting rating form associated with conventional semantic differential method (4, 6) and conducted a subjective evaluation using paired comparison method (11). These subjective assessment results were then correlated with the objective measures of the two motorcycles. Furthermore, virtual sound synthesization was developed for defining a preliminary target sound.

This paper focuses on the methods in setting sound target through source contribution and sound synthesization for applications of motorcycles. In addition to tailor the firing order components, virtual sound synthesization technique was proposed as an effective method of favorable sound design for both of subjective and objective goals. The analyses and tests were based on a motorcycle equipped with a 400 cc single-cylinder engine and a continuously variable transmission (CVT). This motorcycle didn’t achieve its “sporty” statement and the associated sound quality refinement engineering was initiated. This paper first addresses the development framework of sound quality. Then the methods for objective and subjective evaluation were highlighted. With benchmark, acoustic gaps associated with psychoacoustic parameters, order spectra and subjective rating between the two motorcycles were analyzed in detail. The noise source contribution results validated the exhaust and intake systems were the major subsystems that can be further engineered to fulfill a favorable sound quality. By synthesizing and assessing each feasible sound design, this study virtually enhanced the sound quality and derived a preliminary “sporty” sound profile for the motorcycle studied.

2. SOUND QUALITY DEVELOPMENT FRAMEWORK

To determine the favorable sound profile for the motorcycle studied, this study benchmarked competitors’ motorcycles, irrespective of their different cubic capacities and number of cylinders. For convenience, the motorcycle equipped with a 400 cc single-cylinder engine of this study is referred to as motorcycle “**A**”. A same category competitive motorcycle “**B**” configured with a two-cylinder engine was selected as benchmark object. Since the fundamental difference in the type of engine in these two motorcycles, it will unlikely to change the sound quality of a single-cylinder engine to be similar to that of a two-cylinder engine. With brand specific in mind, however, it is feasible to modify the motorcycle sound characteristics to improve the subjective perception of the single-cylinder engine.

To enable the development of hardware to deliver the sound quality target, it is essential to have an objective characterization of the key noise sources and representative subjective ratings. Figure 1 shows the vehicle sound quality development flow diagram. Objective evaluation and subjective assessment were performed for both motorcycles, and the differences of the acoustic characteristics between those two motorcycles were identified. On the other hand, noise source contribution test was conducted to identify the dominant subsystems to be improved and to assist defining the feasible synthesized sound target. Through an in-house sound synthesization and assessment system, a synthesized sound was set to be the target sound of motorcycle **A**. Sound source strength test (12) and analysis will be done to define the source level sound target. Following that, countermeasure designs, validation tests and hardware tuning will be necessary to fine tune the performance of the supplied parts to meet sound quality targets.

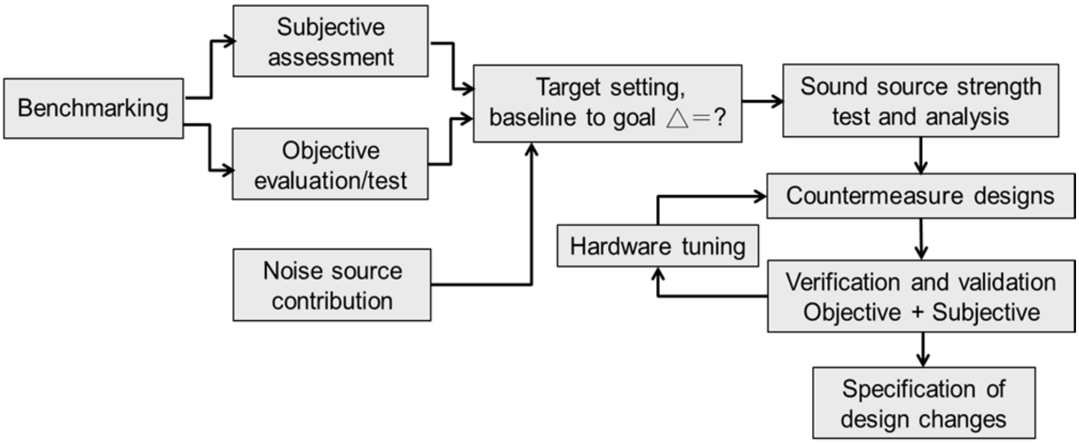


Figure 1 – Vehicle sound quality development flow diagram

3. METHODS FOR OBJECTIVE AND SUBJECTIVE EVALUATION

3.1 Objective Evaluation Method

The noise emitted from the powertrain of interest was measured by several microphones. Since structure-borne noise caused by the powertrain was unnoticed for the motorcycle **A**, effort focused on ways to evaluate air-borne noise. Noise data were measured for both motorcycles **A** and **B** in a hemi-anechoic chamber with a rolling road facility for idle, throttle snaps, run-up and constant speed conditions. Cruising speeds of 3500 and 6000 rpm, indicators for riding at low- and high-speed, were used to explore their noise characteristics. The noise perception at rider was acquired by a binaural headset measurement system and a microphone. At the same time, two microphones at a distance of 50 cm from the left-hand side and right-hand side of the engine were used to measure the engine radiated noise; one microphone measured the intake orifice noise; one microphone at a distance of 50 cm and 45 degree from the exhaust tailpipe was used to measure the exhaust orifice noise.

Sound quality of a motorcycle is multi-dimensional. Nevertheless, good correlation is recognized between loudness and the impression of “powerful” factor; it is also known that good correlation exists between sharpness and the impression of “shrill” factor. Accordingly, loudness, sharpness and sound pressure level were focused on for describing various psychoacoustic phenomena as well as benchmarking studies.

3.2 Subjective Assessment Method

The method of subjective rating scales, one to ten, associated with self-paced paired comparison and semantic differential method were used to evaluate what sound profile is suitable for the intended purpose. Table 1 shows the subjective assessment form for this study. For analyzing the different features of the sound, each binaural recording sound was conditioned into three sound samples as the original, 250 Hz high-pass filtered and 250 Hz low-pass filtered. The sound samples each auditor heard then were presented over headphones.

Subjective assessments were conducted by employees of motorcycle maker. The selected employees came from different departments including NVH, powertrain design and development, strategic planning and marketing. The adjective scales used for semantic differential study included loud vs. soft, weak vs. powerful, and the like. The auditors ranked the sound quality descriptors according to which adjective best described their experience. It is clear that “sporty” sound perception should have strong link to the adjectives like exciting, powerful, deep, etc.

Table 1 – Subjective assessment form for sound quality

ID	Test condition	Sound samples	Motorcycle **A**		Motorcycle **B**	
			Rating (1–10)	Adjective scale	Rating (1–10)	Adjective scale
1	A	Original				
		250 Hz high-pass filtered				
		250 Hz low-pass filtered				
2	B	Original				
		250 Hz high-pass filtered				
		250 Hz low-pass filtered				
3	C	Original				
		250 Hz high-pass filtered				
		250 Hz low-pass filtered				
4	D	Original				
		250 Hz high-pass filtered				
		250 Hz low-pass filtered				

Unacceptable				Action Needed		Acceptable			
1	2	3	4	5	6	7	8	9	10
Very Bad	Bad	Very Inadequate	Inadequate	Barely Adequate	Fair	Good	Very Good	Excellent	Perfect

Adjective scales	
loud	soft
deep	shrill
pleasant	unpleasant
hard	soft
calm	exciting
weak	powerful
busy	tranquil
slow	fast
distinct	vague
tense	relaxed
noisy	quiet
rough	smooth

4. ACOUSTIC CHARACTERIZATION OF THE TWO MOTORCYCLES

4.1 Psychoacoustic Analysis

Figures 2 and 3 show the comparisons of loudness and sharpness at rider's ear location of the two motorcycles for part load run-up, idle and constant speeds conditions. For run-up condition, the loudness of motorcycle **A** was only around two-thirds the one of motorcycle **B**; the sharpness of motorcycle **A** was also lower than **B** around 0.3–1 acum above 4000 rpm. Similar qualitative trends were also observed for constant speeds condition, except that the sharpness of motorcycle **A** was 0.25 acum more than **B** under idle condition.

For throttle snaps transient test, the loudness of motorcycle **A** was less than **B** around 8–9 sone; on the contrary, the sharpness of motorcycle **A** was higher than **B** around 0.3 acum. This deviation in sharpness was caused by their engines running at different speeds even with similar throttling for these two motorcycles. In general, the loudness and sharpness of the motorcycle **A** were significantly lower than those of benchmark motorcycle **B**.

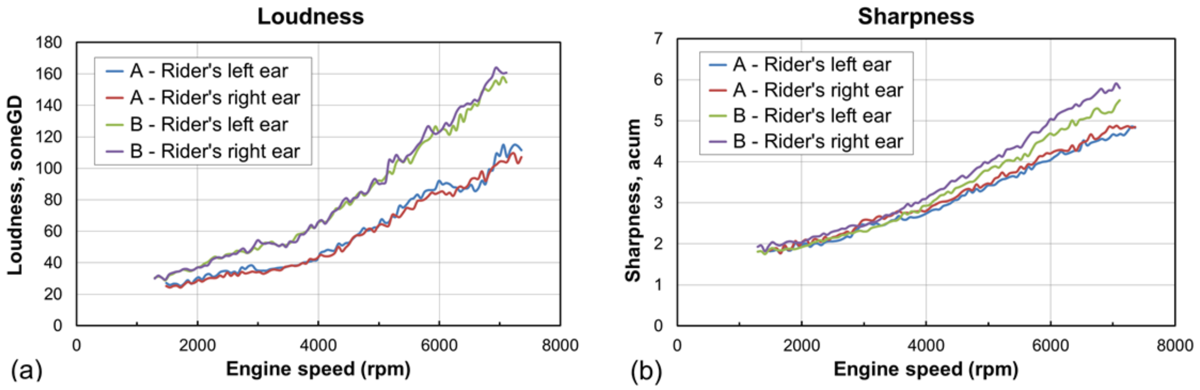


Figure 2 – Psychoacoustic parameters analysis result at rider's ear location under part load run-up condition: (a) loudness; (b) sharpness

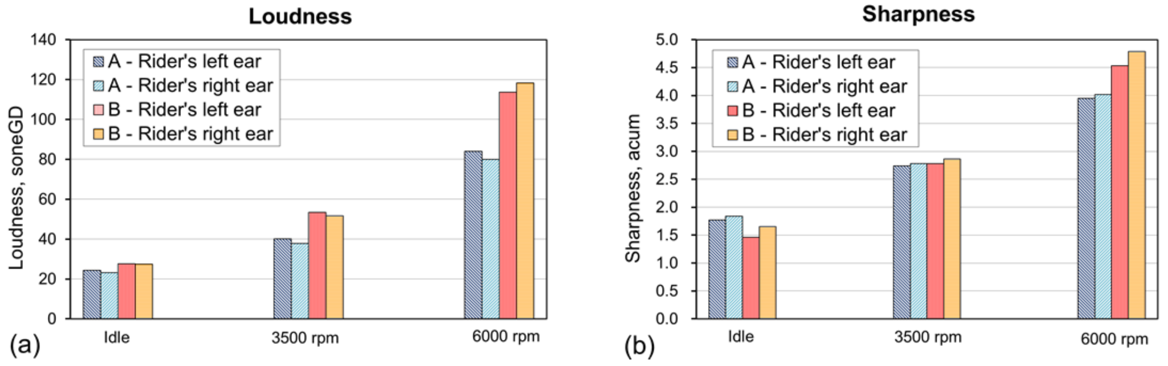


Figure 3 – Psychoacoustic parameters analysis result at rider's ear location under constant speeds condition: (a) loudness; (b) sharpness

4.2 Order Analysis

The feature of sound order determines the sound quality since engine sound is linked with the firing orders (6, 9). To examine how the discrepancy in the order spectrum affects the "sporty" sound perception, benchmark data was used for assessment. Figure 4 shows the comparisons of the order spectra measured at rider's right ear location of these two motorcycles for part load run-up and throttle snaps conditions. For part load run-up condition, the major orders for motorcycle **A** were the harmonics of half-order components such as 0.5th, 1st, 1.5th and 2nd orders with 0.5th order throughout the speed range and the others at higher engine speeds; the major orders for motorcycle **B** were the harmonics of integer-order components such as 1st, 2nd and 3rd orders with 1st and 2nd orders throughout the speed range. For throttle snaps condition, the dominant order for the motorcycle **A** was 0.5th while those were 1st and 2nd for the motorcycle **B**. The results reflect the fundamental differences of engine configuration and acoustic characteristics between these two motorcycles. Compared with the benchmark motorcycle **B**, sound pressure level of the motorcycle **A** was too low at the lower integer engine orders and too high at the half-order components. Thus the distinct integer-orders, 1st and 2nd orders, were significant contributors for “sporty” sound.

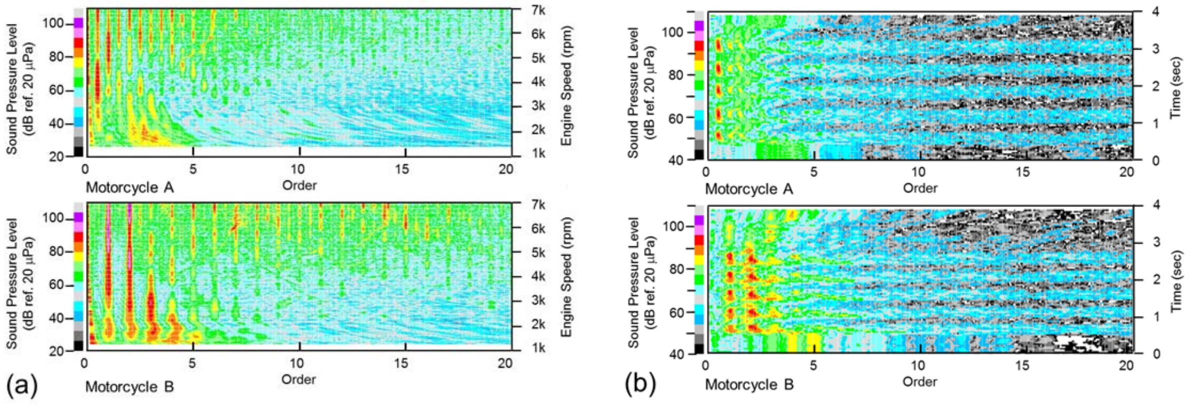
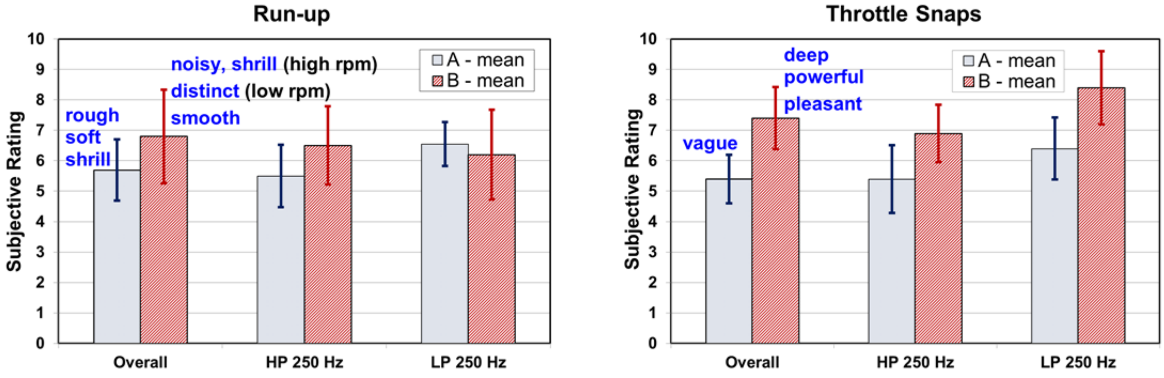


Figure 4 – Order spectra at rider’s right ear location: (a) part load run-up condition; (b) throttle snaps condition

4.3 Subjective Rating

Figure 5 shows the subjective assessment results of the binaural recording sounds of the two motorcycles for part load run-up and throttle snaps conditions. In the figure, the listed adjective scales were the highest counts for each condition. The results show clearly that the auditors preferred the sound quality of benchmark motorcycle **B** to that of **A**, especially for the throttle snaps case. As both motorcycles are made as “sporty” image, the “powerful” and “deep” sound adjectives are essential for riding, especially for throttle snaps case. Pair comparisons revealed the motorcycle **B** achieved the “powerful” and “deep” sound image. For all riding conditions, a “smooth” sound is expected for riders. However, the motorcycle **A** got a “rough” rating at run-up condition. As described in these ratings and adjective scales, the subjective assessment results reflected the sound quality of motorcycle **A** should be improved to achieve its “sporty” statement.



(a) (b)

Figure 5 – Subjective rating results (± 1 SD): (a) part load run-up condition; (b) throttle snaps condition

5. NOISE SOURCE CONTRIBUTION TEST AND ANALYSIS

According to the previous psychoacoustic and order analysis results, the motorcycle **A** needs to magnify its sound pressure level, loudness and sharpness to achieve similar sound image as the benchmark motorcycle **B**. Therefore, for a brand specific sound design of the motorcycle **A**, magnifying the lower integer-order components and suppressing the half-order components can offer riders with an exciting and powerful sound perception. To enable the development of hardware to deliver a sound with desired engine orders, it is necessary to identify the key noise sources. Moreover, integrating the results among objective evaluation, subjective assessment and noise source contribution test was crucial to set a proper and feasible sound target.

The noise source contribution tests were conducted on the motorcycle **A** under constant speed cruising and run-up conditions. The potential sources for vehicle level noise are exhaust orifice noise, intake orifice noise, exhaust muffler radiated noise, intake airbox radiated noise, engine radiated noise, CVT radiated noise and tire noise. The classical method of masking the sources sequentially and calculating their individual contribution to the total was used. This study adopted various methods to mask the sources. Intake gas noise and exhaust gas noise were attenuated by using additional silencers and were ducted away; the exhaust muffler and intake airbox were encapsulated with fibrous material and acoustic insulation. The CVT was encapsulated with absorption and insulation materials. Furthermore, the CVT was disconnected from the engine and the tire was driven alone by chassis dynamometer to count for the contribution of tire noise.

The medium speed range, around 60–80 km/h, is significant for setting sound target since wind noise is dominated at higher vehicle speeds. Thus operating engine speed at 5000 rpm during run-up condition, around 73 km/h, was selected as a focused operating condition for analyzing noise source contribution. At 5000 rpm, the overall noise of the motorcycle **A** was 6 dB less than that of the motorcycle **B**. Although such a substantial acoustic gap directly linked to the absence of "powerful" sound quality, the motorcycle **A** can be refined to have a better sound quality by changing the noise contributions among key sources. Figure 6 shows the overall noise and 250 Hz low-pass filtered noise source ranking results at the rider's ear location under 5000 rpm condition; Table 2 summarizes individual noise source's predominant contribution results over 1/3 octave frequency bands. The evidence shows that the exhaust orifice was the second largest source for the noise components at lower frequency range, i.e. below 250 Hz. The major contribution of intake system was at lower frequency ranges till 125 Hz. Note that exhaust and intake systems inherently were the major contributors for the harmonics of 1/2 crank order, namely, 0.5th, 1st, 1.5th, 2nd orders, etc. The engine radiated noise was the main source for the frequency range above 125 Hz. Although the tire noise had specific contributions at frequency bands of 400 and 800 Hz when running at 73 km/h, it did not relate with the desired engine orders.

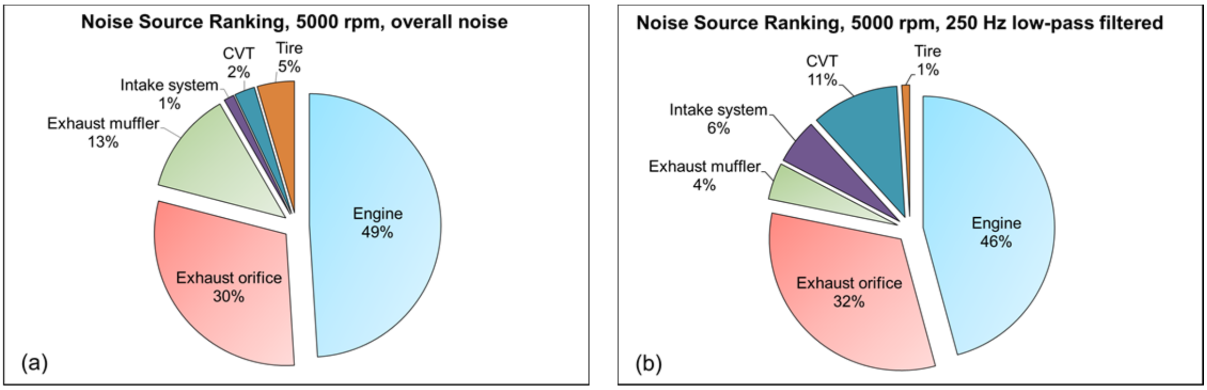
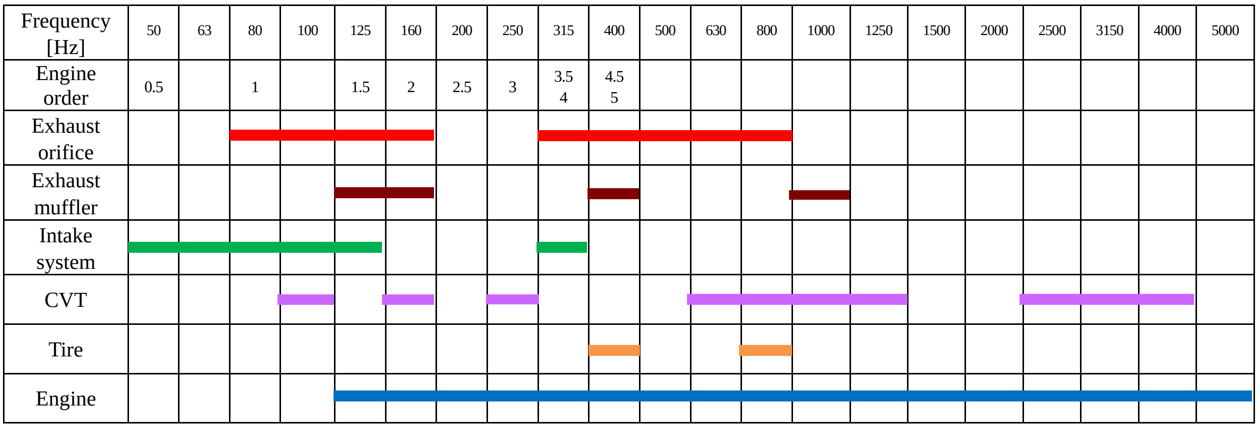


Figure 6 – Noise source ranking results at 5000 rpm: (a) overall noise; (b) 250 Hz low-pass filtered

Table 2 – Frequency contribution results for each noise source under 5000 rpm condition



Frequency [Hz]	50	63	80	100	125	160	200	250	315	400	500	630	800	1000	1250	1500	2000	2500	3150	4000	5000
Engine order	0.5		1		1.5	2	2.5	3	3.5 4	4.5 5											
Exhaust orifice			🟥	🟥	🟥	🟥			🟥	🟥	🟥	🟥	🟥								
Exhaust muffler					🟫	🟫				🟫				🟫							
Intake system	🟩	🟩	🟩	🟩	🟩				🟩												
CVT				🟪		🟪		🟪				🟪	🟪	🟪	🟪			🟪	🟪	🟪	
Tire										🟧			🟧								
Engine					🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦

6. ACOUSTIC TARGET SETTING

6.1 Sound Synthesization and Verification

Sound simulation model can serve as a valuable tool for setting sound targets and assessing alternative design scenarios. Based on auditors' responses, engineers can adjust various parameters of the model to ensure the results sticking to customers' expectations. To build up a synthesized sound, noise measurement data, noise source contribution, powertrain specifications as well as the relationship between engine speeds and vehicle speeds are required. With an in-house sound synthesization and assessment system shown in Fig. 7, operating noise of the motorcycle **A** was summed up with individual noise contribution from intake, exhaust, engine, CVT and the residual. Specifically, sound components of order, broadband and pitch bend loop were combined and tuned to synthesize intake noise and exhaust noise. Similar approach was used to establish engine and CVT sound profiles.

Figure 8 shows a comparison of the measured sound and the synthesized sound at rider's ear location under wide open throttle run-up condition for motorcycle **A**. The comparison between the measured and synthesized sound of benchmark motorcycle **B** was also done. With promising similarities in time signature, spectrum diagram and subjective appraisal, we confirmed the accuracy of sound synthesization model and process.

Figure 7 – In-house sound synthesization and assessment system

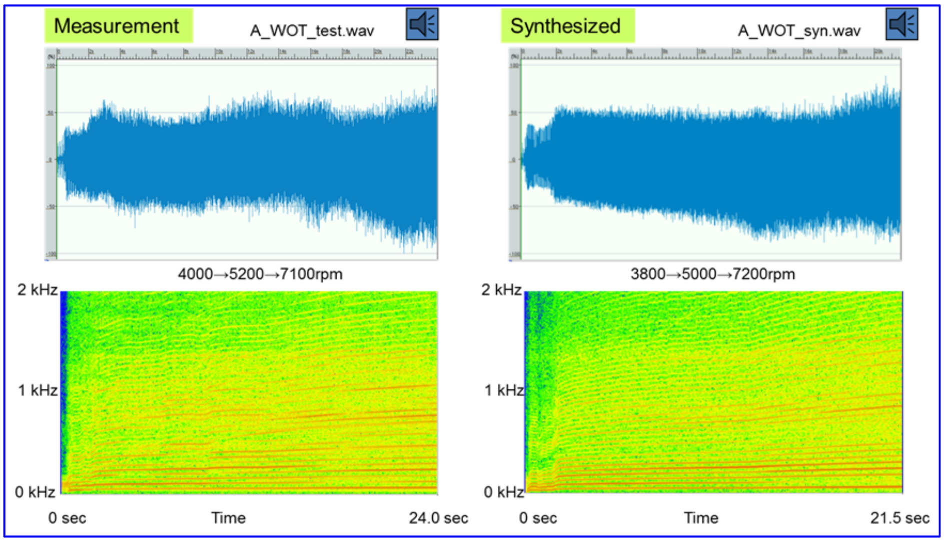


Figure 8 – Comparison of measured sound vs. synthesized sound at rider's ear location under wide open throttle run-up condition

6.2 Sound Target Design

To synthesize a sound target for the motorcycle **A**, this study virtually altered the noise source contributions among the subsystems of the powertrain and sound attributes such as order distribution, frequency distribution and related amplitudes. Recalling that the motorcycle **A** should increase its sound pressure level, loudness and sharpness as well as magnify its lower integer-order components, we tailored a synthesized sound target candidate, target 1, for further subjective assessment and final sound target setting. Figure 9 shows a comparison of the synthesized sound target 1 of motorcycle **A** with the synthesized sound of benchmark motorcycle **B** at rider's ear location under wide open throttle run-up condition. This synthesized sound target 1 mimicked the benchmark sufficiently well in time signature, spectrum diagram and subjective appraisal with the residual effects of half-order components.

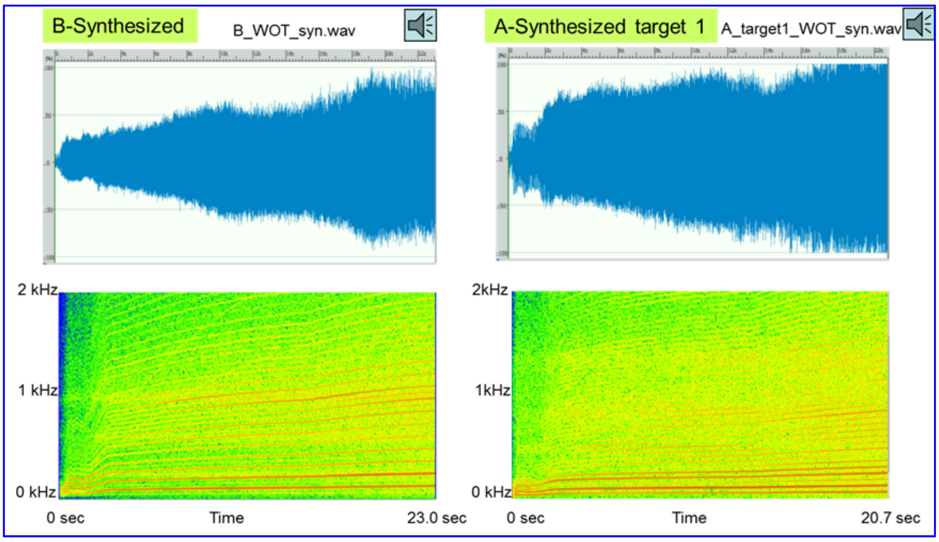


Figure 9 – Synthesized sound target 1 vs. benchmarking sound at rider's ear location under wide open throttle run-up condition

To further account for the suppression of half-order components of the motorcycle **A**, the authors also tailored a synthesized sound target, target 2. However, we thought target 1 is more promising and feasible than target 2 from the viewpoint of engine architecture and engineering efforts.

From the results of order analysis, we identified the lower half-order and lower integer-order components were more significant than the higher order components. Furthermore, the exhaust and intake systems were the major contributors of 0.5th, 1st, 1.5th and 2nd orders of perceived sound from the frequency contribution results for each noise source. This study adopted the improvement of intake and exhaust systems as the first priority of sound quality development. Thus the synthesized vehicle level sound target was cascaded down to get the synthesized intake and exhaust noise targets. By subjective assessment, increasing 6 to 10 dB both at the 1st and 2nd orders of intake noise and exhaust noise can enhance the "sporty" sound image dramatically. Figure 10 shows those synthesized targets under wide open throttle run-up condition.

Besides setting the target of sound quality, the regulatory compliance should be addressed in the development stages. For the motorcycle **A**, there are still a 2 dB and a 9 dB allowance to remain within the pass-by and stationary noise regulation, respectively. Moreover, the benchmark motorcycle **B,** louder than **A**, complies with the noise regulation. Consequently, magnifying sound at low frequencies for the motorcycle **A** is expected to meet noise regulation after A-weighed along with minor impact of performance.

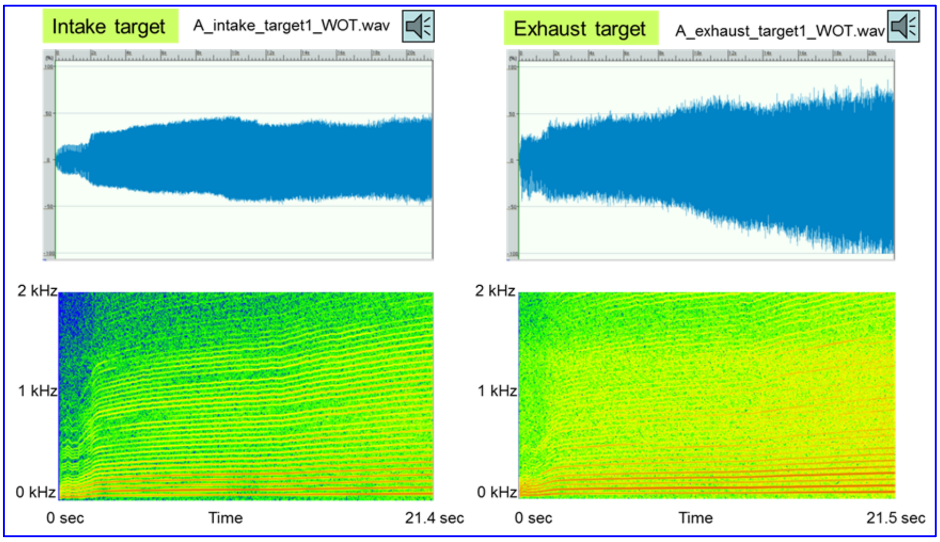


Figure 10 – Synthesized sound targets of intake and exhaust noise under wide open throttle run-up condition

7. CONCLUSIONS

This paper focused on the brand specific target sound setting process and sound synthesization for a motorcycle. Loudness, sharpness and order spectra were used to provide objective quantification metrics on the differences of sound characteristics between the studied motorcycle and the benchmark one. Through subjective assessments employing semantic differential method and paired comparison method, the favorable “sporty’ sound image from the auditors were identified. With objective evaluation, acoustic gaps regarding the psychoacoustic parameters and order distribution between the two motorcycles were highlighted.

Compared with the benchmark motorcycle, sound pressure level of the motorcycle studied was too low at the lower integer engine orders and too high at the half-order components. The loudness and sharpness of the motorcycle studied were also lower than those of benchmark. The noise source contribution results validated the exhaust and intake systems were the major subsystems that can be further engineered to fulfill a favorable sound quality. Combining the objective, subjective and source contribution results, this study successfully synthesized a promising and feasible vehicle level sound target and it was then cascaded to get the synthesized intake and exhaust noise targets. As a result, increasing 6 to 10 dB both at the 1st and 2nd orders of intake noise and exhaust noise can enhance the “sporty” sound image dramatically.

In next phase, this study will conduct a test and analysis to characterize the source strengths of intake and exhaust orifice by matrix inversion process. Following that, alternative component design to deliver the required sound characteristics by CAE modelling and design modifications will be developed.

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