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Sound Quality Enhancement with Exhaust Manifold and Hot-End Structure Optimization on H8 Engine Systems

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Abstract

Idle sound quality for motorcycles is very important to the customers [1,2]. People would like to have a strong individualized sound in idle, linear and smooth sound in the driving condition. Since the idle fluctuation noise is based on the engine firing sequence, the exhaust manifold structure and the idle frequency eight or six cylinders engine are really hard to get a real good fluctuated tailpipe sound in the idle condition compared to the two or three cylinders engines. However, some surrogate methodology can be applied to these engines. Based on the noise cancellation process in amplitude and phase in the exhaust manifold system, engineers can manipulate the noise with several lower peaks, and the other higher peaks can be perceived by the masking effect in the time domain. In this scenario, people only feel the big noise fluctuation peaks, even the smaller peaks are still there in the background. In addition, waves can be further improved by the Hot-End structure. The structure could provide more opportunities to separate and cancel the waves in the duct system by phase. In this paper, a special case is presented by these methodologies and techniques. An eight-cylinder horizontal engine with an uneven firing sequence makes very irregular tailpipe noise in the idle condition originally. By optimizing the exhaust manifold structures in shapes and lengths by the DOE method, and also applying the new H Type Hot-End structure with the active-controlled valve in the middle of the connecting pipe, the tailpipe noise is finally optimized successfully. Good idle impulsiveness and less half-orders tone in running up can be achieved simultaneously with these techniques.

Introduction

Impulsiveness is a kind of sound quality that describes the noise pulsation characteristics in the time domain. A good impulsive sound should have clear peaks, such as "Kong-Kong-Kong…. or Dong-Dong-Dong……" while you hear it. Compared to the two or three cylinders engines, eight-cylinders engines are even hard to achieve a good impulsiveness performance. The reason is that the tailpipe noise comes from the wave's summation in the exhaust duct system and the peak occurrence timings are controlled by the combustion frequency. For an eight-cylinder engine, its combustion frequency is four times faster than the two cylinders engine in idle condition. That means the pressure peaks occur 4 times more than the two cylinders engine in the same time period. That DNA drives the complexity to engineers to manage a good impulsiveness performance to the eight-cylinders engine for the idle sound quality. The other issue that affects impulsiveness performance is the firing sequence. That affects the timing of each wave that reaches the sum point in the duct system. A good firing sequence can effectively offset the pressure wave in the duct systems [3] by offsetting the amplitude and phase in different ducts that noise can be amplified or attenuated by the phase shift. The exhaust manifold optimization in geometry could improve the wave summation by manipulating the wave's amplitude and phase while it gets to the joining points [4]. It is discussed that exhaust manifold optimizations on a V6 engine that pursue enhanced impulsiveness by their subjective evaluation matrix [5, 6]. These improvements are based on the wave amplitude and phase summation principle that depends on the duct shapes variation and the length difference. The other way of noise improvement on noise frequency components is to mix the wave pressures between left and right banks while it gets into the exhaust Hot-End structure. The waves from the left and right banks can be canceled by the noise from the other side by the phase. In this paper, due to the H8 engine's odd firing sequence, the original pressure peaks are very chaotic in the duct system that is hard to give you a clear impulsiveness feeling in the idle condition and also hard to provide a clear tone in the running-up condition. Thus, the goal of this paper is to build a smooth vehicle with a special impulsive idle quality and fewer half-orders sound in the running.

Engine Firing Sequence

Engine firing sequence affects the pressure occurrence timing in the exhaust manifold. The sequence is driven by the engine crankshaft type you use. The horizontal eight-cylinders engine (H8 engine) has two banks of cylinders symmetrical. The cylinder layout and numbers can be seen in Figure 1. This kind of engine has two different crankshaft types, which are Cross-Crankshaft and the Full-balanced Crankshaft. They have different balancing performances that can be summarized in Table.1. The Cross-Crankshaft has the unbalanced rotational inertia moment and the first-order reciprocating inertia moment. In contrast, the Full- balanced Crankshaft shows all balanced in force and moment inertia. The first-order reciprocating inertia force is completely balanced. Based on the design requirement from the crankshaft engineering, it has to follow three general rules for this kind of engine:

1. The left and the right bank should ignite alternately;
2. There must be an adjacent ignition on the same bank;
3. Two cylinders on the same bank are ignited separately;

FIGURE 1 H8 Engine Cylinder Layout

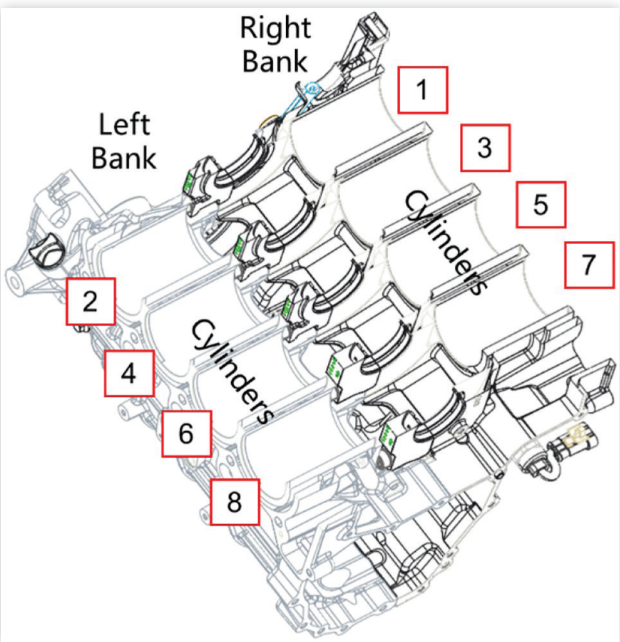


TABLE 1 Crankshaft Balance Capabilities

Crankshaft Type	Cross	Balanced
Rotational Inertial Force	0	0
Reciprocal Inertial Force in 1_{st} Order	0	0
Reciprocal Inertial Force in 2_{nd} Order	0	0
Rotational Moment of Inertia	$\sqrt{10}\ P_r L$	0
Reciprocal Moment of Inertia in 1_{st} Order	$3P_j L \cos\alpha + P_j L \sin\alpha$	0
Reciprocal Inertia Moment in 2_{nd} Order	0	0

TABLE 2 Firing Sequence for Crankshaft Types

Type	Firing Order	Crankshaft Type
A	1-6-7-4-2-3-8-5	Cross Crankshaft
B	1-6-2-5-8-3-7-4	Cross Crankshaft
C	1-4-7-6-2-3-8-5	Balanced Crankshaft
D	1-4-8-5-2-3-7-6	Balanced Crankshaft

Based on these rules, these two crankshaft types have different firing orders to be matched which are listed in Table.2. Firing sequences A and B are used for the cross crankshaft, C and D are matched to the balanced crankshaft. From NVH standpoints, the noise performances are compared between these firing sequences in Figure 2. Data shows the order distribution of these types is very chaotic in the running up condition. They all appear a lot of half-order components. To be specific, type A is same as the type D which are shown fewer half-orders components than type B and type C.

In our case, considering the layout and balancing issues on the crankshaft, from engineering standpoints, Type C is finally decided to be the baseline firing sequence that applied to the H8 system. Since these comparisons are based on the FFT average which can't describe the noise flotation in the idle, the time signal impulsiveness is also compared in Figure 3. It shows the H8 engine with a type C firing sequence could not achieve a good impulsiveness performance compare to the competitor.

From the NVH perspective, types ABCD cannot effectively avoid the half-orders and provide good impulsiveness performance. To deep investigate the reason for that, the wave summation process is analyzed in the time domain that is shown in Figure 4 for firing sequence type C. From that picture, it can be seen the pressure waves from each side are not equally separated to reach the exhaust manifold outlet in the same time period. The peak occurrence timing is not even in the manifold. These generate the odd half-orders and less fluctuation performance in the idle condition.

To figure out the relationship between ignition sequence and half-orders generations, and also illustrate the process of wave summation in the time domain, with ignoring the crankshaft layout and balancing attributes in purpose, the firing sequences E, F, and I are also proposed in Table 3. GT-simulated results are shown in Figure 5. The noise from types E, F, and I

FIGURE 2 Order Distribution by Firing Sequence ABCD

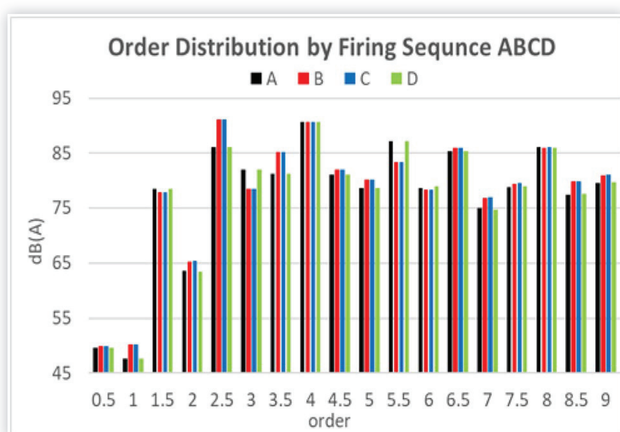


FIGURE 3 Baseline (Type C) vs. Competitor

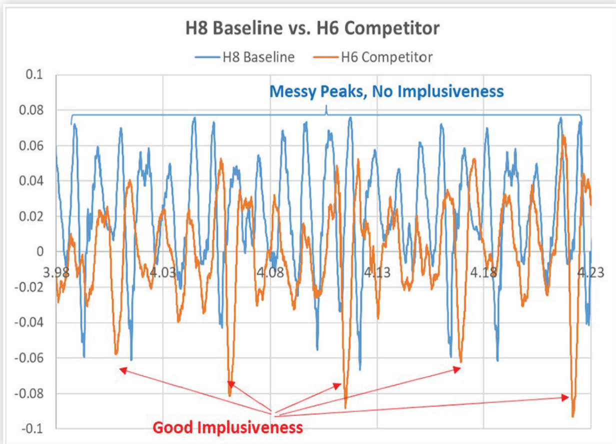


FIGURE 4 Type C Pressure Wave Distribution in the Exhaust Manifold

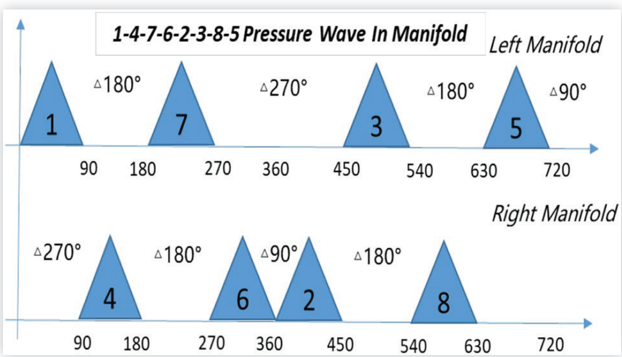


TABLE 3 NVH Firing Sequence Recommendations

Type	Firing Order
E	1-7-8-2-3-5-6-4
F	1-7-6-4-3-5-8-2
I	1-5-2-6-3-7-4-8

FIGURE 5 Order Distribution by Firing Sequence E, F, and I

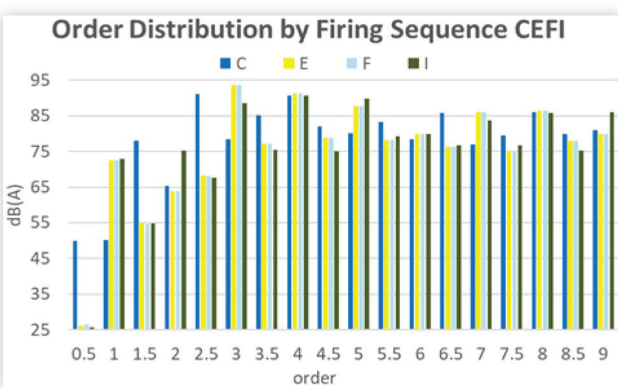


FIGURE 6 Baseline Type C vs. Type I

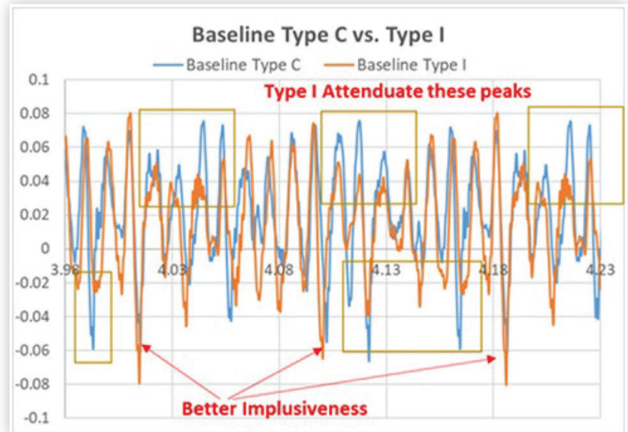
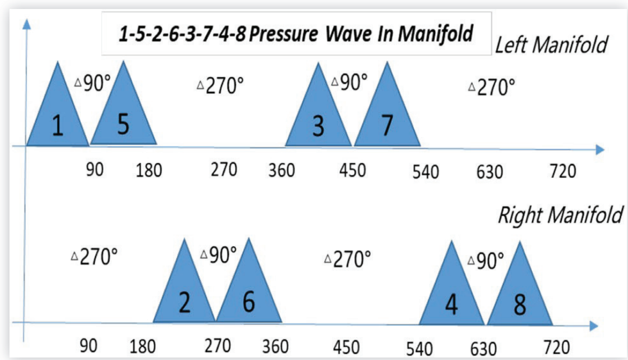


FIGURE 7 Type I Pressure Wave Distribution in the Exhaust Manifold



are dramatically better compared to the baseline firing sequence of type C from half-order standpoints. It appears good performance on the half-orders cancellation. For idle impulsiveness, Type I also shows tremendous improvement compared to the baseline sequence type C in Figure 6. With firing interval switches from 270°-180°-90° (Type C in Figure 4) to the 90°-270° (Type I in Figure 7), the pressure irregularity in the idle is also leveraged. From these comparisons, we can conclude that the idle impulsiveness and running-up half-orders are driven by the engine firing sequence that choosing the firing sequence initially is critical for the NVH sound quality performance.

Engine Exhaust Manifold

The firing sequence-driven pressure wave irregularity in the duct system is already analyzed above. That design makes the pressure peaks are very chaotic in the idle condition. Although we could not change the firing sequence, it is still possible to manipulate the exhaust manifold design to optimize the idle impulsiveness performance. Since the H8 engine has quite high idling frequency that the peaks are 1.333 times to the six-cylinder engine in the condition. Compared to our competitors in Figure 6, our performance shows too much

TABLE 5 DOE Result of Setup #2

DOE Pipe 1357(mm)	Cylinder 1		Cylinder 3		Cylinder 5		Cylinder 7	
	d11	d12	d31	d32	d51	d52	d71	d72
Baseline	29		29		29		29	
DOE-Best	26.9733	32.9773	29.7311	31.2334	28.047	29.3358	32.6847	27.5566
Engineering 29-1	27	33	30	31.5	28	29.5	33	27.5
Engineering 29-2	27	33	30	31.5	28	29.5	32.5	28
DOE Pipe 2468(mm)	Cylinder 2		Cylinder 4		Cylinder 6		Cylinder 8	
	d21	d22	d41	d42	d61	d62	d81	d82
Baseline	29		29		29		29	
DOE-Best	27.1782	32.2884	30.382	26.6233	30.8273	30.5143	32.8886	32.4959
Engineering 29-1	27.5	32.5	30.5	27	31	30.5	33	32.5
Engineering 29-2	27.5	32.5	30.5	27	30.5	30.5	32.5	32.5

FIGURE 21 Baseline vs. Final Optimization Result in the Idle Condition

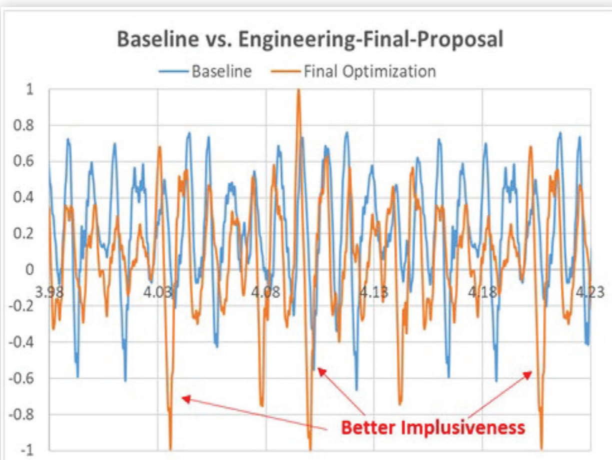
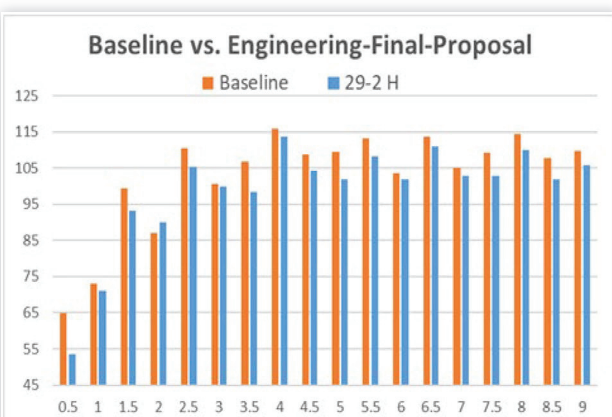


FIGURE 22 Baseline vs. Final Optimization Result in the Running-Up Condition



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There is no hesitation to answer your question. Thank you very much.

Definition and Abbreviation

DOE - Design of Experiment
DRE - Design Release Engineer
H6 - Horizontal Six-Cylinder Engine
H8 - Horizontal Eight-cylinder Engine
P_r - Rotational Inertial Force
P_j - Reciprocal Inertial Force
L - Rod Length
α - Crankshaft Angle
DNA - Deoxyribonucleic Acid
GT - GT Power

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