

Understanding the Fundamentals of Boxer Engine Behavior on Sound Quality

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ABSTRACT

An engine configuration has a significant influence on the sound quality from the powertrain. Whilst the fundamental order content can be readily apparent from the firing order over the engine, or bank of a V engine, some characteristics and how the engine design can influence them requires some more specific investigation. Understanding, on a fundamental level, the aspects of the engine design which influence these characteristics is critical to allow more detailed analysis and development work to be focused appropriately.

The configuration of a Boxer engine gives a distinctive sound characteristic producing a unique sound compared to an In-Line configuration. Depending on the application it may be desirable to enhance or subdue some of these characteristics. The fundamental differences affecting the sound characteristics of a 4 cylinder Boxer engine in comparison to an In-Line engine are investigated by consideration of component loading and structural deformations across different excitation orders. Specifically fundamental comparisons are made on engine structural deformation, cranktrain-block interaction, piston loading and valvetrain loading.

The process described in this paper can be applied to determine which critical aspects of the engine design should be a focus for helping to develop the desired sound characteristic. Finally it is discussed how this process can be applied to other configurations for the same purpose.

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INTRODUCTION

Advanced NVH analysis techniques such as those detailed in [5] and [6] can be utilized to help determine the specific contributions of structural modes and component vibration on the radiated noise or mount vibration from the engine. Whilst this level of analysis can be used to guide the detailed design and structural optimization of engine components the fundamentals behind the sound characteristics of the engine may not be readily apparent. These fundamentals however are important in understanding which design changes are likely to provide the desired changes to the sound and why they are effective.

As with engine balance calculations the fundamental loading of the powertrain for a specific engine configuration can be calculated quickly at the pre-concept phase. This allows an early insight into the powertrain behavior and provides a focus for more detailed NVH analysis work during definitive design.

FUNDAMENTAL LOADING

From the kinematic motion of the engine components, functions describing the cyclic (time domain) variation of kinematic loads can be calculated. Each load can be represented in the frequency domain by application of a FFT as complex amplitudes. By consideration of the relative phasing and direction of these loads from each cylinder bay some fundamental behaviors of the engine can be assessed based on a number of methods outlined below.

- Engine torque recoil and balance
- Pseudo-static load interactions between powertrain and engine components
- Pseudo-static powertrain deformation shapes

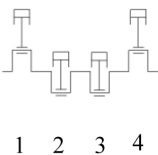
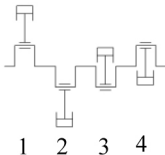
Details of the calculations of the frequency domain loading summations and phase diagrams are shown in [Appendix 1](#). General NVH attributes of the engine can then be inferred and compared by consideration of how this behavior differs across different engines orders, dependent on the engine configuration and firing order.

The fundamental firing frequency $N/2$ (for an N cylinder 4 stroke engine) and higher harmonics tend to govern the dominant order content of the engine and the resulting NVH. The resulting loading and behavior from the various assessments above results in either contributions to these dominant harmonics or to other orders. Contributions to the firing frequency harmonics leads to a purer engine sound whilst contributions to other orders will result in the firing frequency harmonics becoming less dominant, altering the sound quality. For a 4 cylinder engine the dominant firing frequency harmonics are the even orders (2,4,6...). Behavior which contributes to half (0.5,1.5,2.5,...) and odd (1,3,5,...) orders tends to lead to a ‘rumble’ or ‘growl’ sound quality. The desirability of this sound depends on the frequency range, engine speed, and in more general terms the engine application.

The correlation of ‘rumble’ sound quality with the presence of half and odd orders is discussed in [6] for a 4 cylinder in-line engine. In [6] subjective assessments of ‘rumble’ were carried out for various levels of filtering of the half and odd orders, with the results indicating that in general a 12dB reduction in half orders and a 6dB reduction in odd orders was required to achieve the necessary improvements in ‘rumble’ quality.

The following sections detail each assessment method, focusing specifically on comparing a 4 cylinder engine In-Line and Boxer configuration with the firing orders and crank arrangements shown in Table 1.

Table 1. Engine configurations and firing order.

Configuration	In-Line	Boxer
	 1 2 3 4	 1 2 3 4
Firing Order	1-3-4-2	1-3-2-4

The methodology behind the comparison is however generalized and can be applied to any engine configuration.

Engine Torque Recoil and Balance

For any components exhibiting cyclic accelerations (inertial loads) there must be an equal and opposite load acting on the powertrain structure. This loading will excite the powertrain flexural (non-zero frequency) modes but also will excite the rigid body motion of the powertrain.

Crankshaft Torque Recoil

Figure 1 shows the inertial loads acting on a slider crank mechanism which, as detailed above, can be represented as complex amplitudes in the frequency domain.

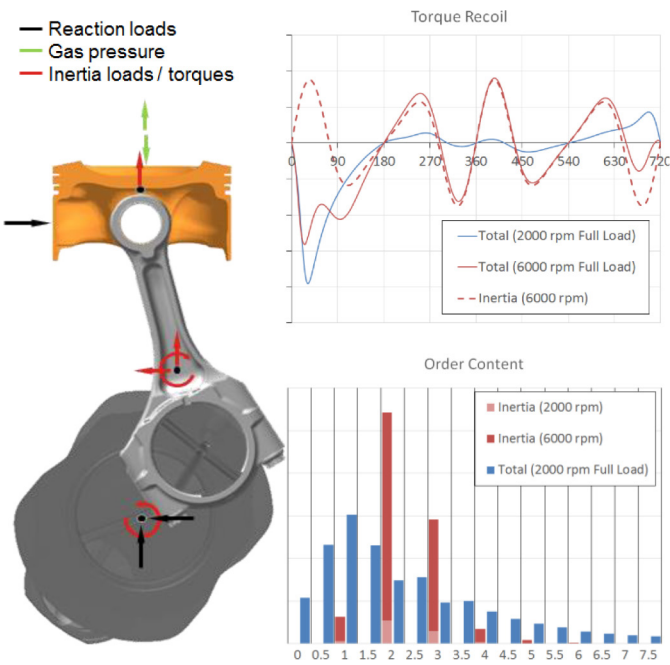


Figure 1. Kinematic loads on slider crank and resulting torque recoil for 4 cylinder engine.

Taking moments of the inertia loads and torques about the crank center gives the torque recoil reaction on the cylinder block, applied to the block through the piston skirt, gas face and main bearings. The torque recoil has contributions from both cylinder pressure loading on the piston and inertial loads from the piston and rod, these are plotted in Figure 1. Torque re-coil due to the inertia loads increase proportionally to the square of engine speed, the torque recoil due to cylinder pressure will increase with engine load. Torque recoil due to inertia loads is significant only for orders 1, 2, 3 and 4.

Summation of the torque recoil amplitudes across each cylinder gives the total torque recoil on the engine about the crank axis. This is compared in Table 2 below for unit torque amplitude at each cylinder. This can be considered as a normalized torque recoil summation.

The engine normalized torque recoil is dependent only on the number of cylinders and the firing intervals and is independent of engine configuration and firing order. As such there is no difference between the In-Line and Boxer configurations regarding the torque recoil magnitude. The crankshaft torsional rigid body motion and, therefore also the engine torque recoil, has a magnitude of N (considering unit amplitude at each cylinder) at all harmonics of the firing frequency and is zero for all other orders.

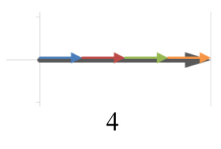
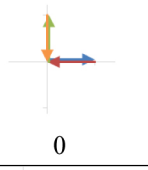
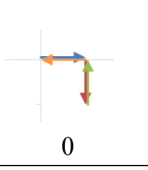
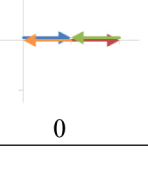
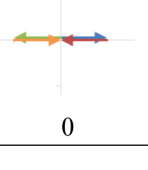
Engine torque recoil is a significant contributor to the rigid body motion of the engine and mount vibration and therefore the NVH of the dominant harmonics (even orders for 4 cylinder engine).

Cranktrain Balance

The inertial loads acting on the piston and rod are reacted through the cylinder block as shown in Figure 1. The configuration of the engine and firing order alters the relative phasing between cylinders and direction vectors of the loads, resulting in differing total un-balanced

forces and moments on the engine. Details of engine balance due to the cranktrain inertia loading for a large number of configurations is well documented by Heisler [1] and Wilson [2].

Table 2. Total engine torque recoil from summation of unit torque amplitude of each cylinder

Order	In-Line	Boxer	Other
	4 Cyl	4 Cyl	
Multiple of firing frequency ($n \cdot N/2$ for integer n)	 4	 4	N
Even orders (2,4,6,...) for even firing 4 cylinder			
Odd orders (1,3,5,...) for even firing 4 cylinder	 0	 0	0 (for non firing frequency harmonics)
Half orders (0.5,1.5,3.5,...) for even firing 4 cylinder	 0	 0	

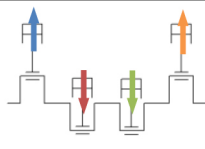
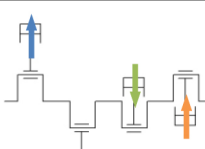
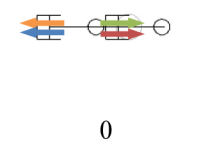
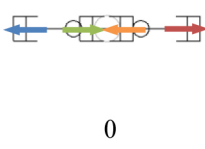
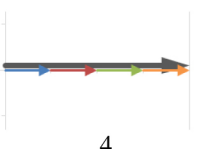
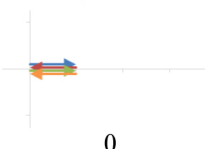
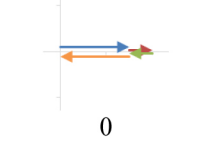
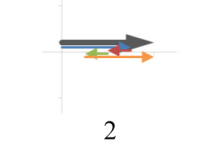
The inertial load along the cylinder axis is dominated by 1st order (primary) and 2nd order (secondary). The lateral inertia load on the rod is purely primary. The resulting cranktrain engine balance is shown by the illustrations and vector diagrams in Table 3 for the In-Line and Boxer configurations.

All primary loads and moments are balanced for both the In-Line and Boxer configurations. For the In-Line engine there is a secondary out-of-balance force, which is often balanced by balancer shafts when targeting good NVH. For the Boxer engine the secondary force is balanced but there is a resultant out of balance secondary moment. In both cases this will result in additional vibration at the fundamental firing frequency and reduce the 'rumble' sound quality.

Valvetrain Balance

Just as with the piston and connecting rod inertia loads described in the previous section the inertia loading due to the acceleration of the valvetrain components is also reacted through the cylinder head (Figure 2). The firing order and engine arrangement again affect the summation of these loads across each engine cylinder resulting in differing total un-balanced forces and moments on the engine. Consideration of valvetrain balance forces was conducted by Eichorn [3] primarily for a 6 cylinder In-Line engine, with data also documented for 3, 4, and 5 cylinder In-Line engines and 8 and 12 cylinder V engines.

Table 3. Total engine balance from cranktrain primary and secondary inertia loads for unit load magnitude (Vector diagrams are omitted for the zero primary loading)

Order	Force / Moment	In-Line	Boxer
1 (Prim.)	Vertical Force	 0	 0
	In Plane Moment	0	0
	Lateral Force	 0	 0
	Out of Plane Moment	0	0
2 (Sec.)	Force	 4	 0
	In Plane Moment	 0	 2

Conversely to the loading that affects the cranktrain balance the valvetrain inertia loading is present at all 0.5th order multiples, proportional to the square of engine speed, with magnitude dependent on the harmonic content of the valve lift profiles.

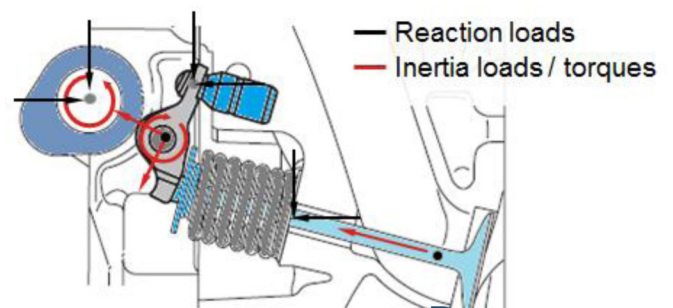


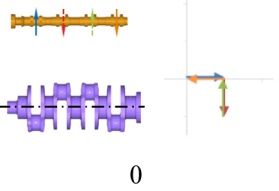
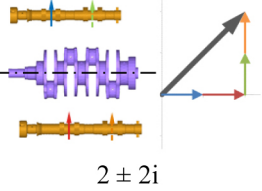
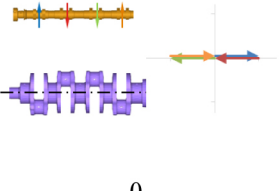
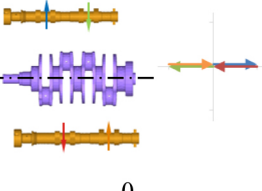
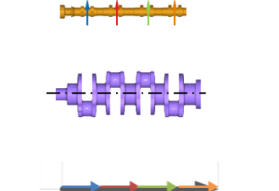
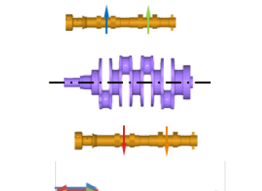
Figure 2. Kinematic inertia loads on valvetrain mechanism

Summation of the net loading on the engine causing rigid body motion along and about each axis can be conducted in exactly the same way as with the cranktrain but with consideration of the appropriate direction vectors of the loads ([Appendix 1](#)). Typically (as with the valvetrain arrangement shown in [Figure 2](#)) the resulting inertia loads from the valvetrain components will be most significant along the cylinder axis. [Table 4](#) therefore shows a comparison of the total unbalanced valvetrain force along the cylinder axis of the engine for an In-Line and Boxer configuration. As detailed in [Appendix 1](#) the vector diagrams illustrate amplitude and phase of the loads.

Although the absolute magnitude of the out-of-balance loads vary across each order all half, odd and even orders respectively show the same phase diagrams, considering normalized loads. The data in [Table 4](#) shows that the odd orders are balanced for both the In-Line and Boxer configurations but show a fundamental difference for the half and even orders. The In-Line engine gives a resultant force from the even orders, therefore further adding to the dominant firing frequency harmonics and reducing the ‘rumble’ sound quality. The Boxer has balanced even orders but a resultant force from the half orders therefore increasing the ‘rumble’ sound quality.

Moments of valvetrain forces can also be considered in the same way, however as will be shown in subsequent sections the moments are less significant than the forces.

[Table 4](#). Total engine balance force along cylinder axis due to unit valvetrain inertia loads at each cylinder

Orders	In-Line	Boxer
Half	 0	 $2 \pm 2i$
Odd	 0	 0
Even	 4	 0

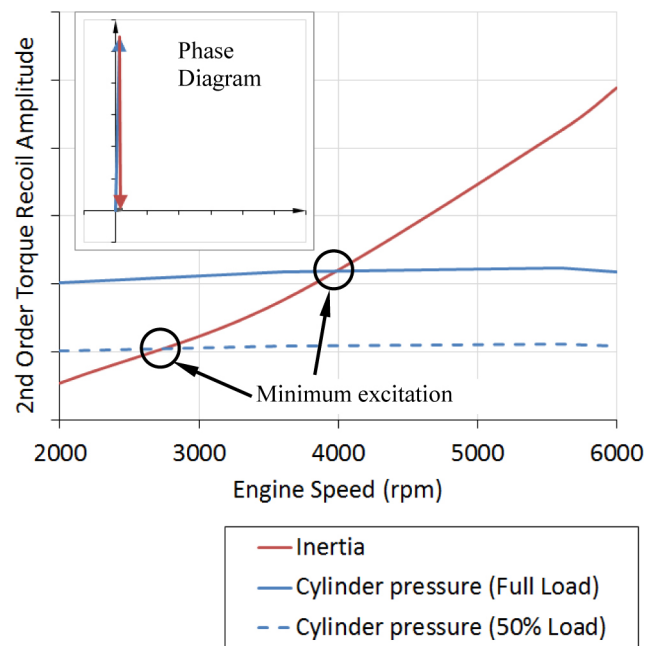
Engine Balance

The above sections have shown the normalized (relative to unit loads) engine out-of-balance loading due to the cranktrain and valvetrain. [Table 5](#) summarises the results from the previous sections from the summation of the normalized loads over the engine.

[Table 5](#). Summary of engine torque recoil and balance

Loading	In-Line	Boxer
Torque recoil	Resultant 2nd order and higher harmonics	
Cranktrain balance	Resultant 2nd order force	Resultant 2nd order moment
Valvetrain balance	Resultant 2nd order force and higher harmonics (2,4,6, ...)	Resultant force for all half orders (0.5, 1.5, 3.5 ...)

The overall effect on the engine rigid body excitation and mount vibration however is dependent on the magnitude of these loads and the engine rigid body response at the mounts.



[Figure 3](#). 2nd order cylinder pressure and inertial torque recoil and minimum excitation

As stated the relative contributions to torque recoil from gas pressure and inertia loading vary with engine speed and load and consequently so can the sound characteristics of the engine. For a 4 cylinder engine both gas pressure and inertial contributions are significant at the fundamental firing frequency (2nd order) as shown in [Figure 1](#). The complex loading amplitudes tend to be almost in complete anti-phase and consequently cancel out at a specific engine speed and engine load ([Figure 3](#)). This minimum torque recoil excitation is discussed in [4] relating to crankshaft rigid body motion. At this minimum excitation the engine will have a tendency to sound more ‘rumbly’ due to the significant reduction in contribution of torque recoil to the 2nd order vibration. At low speed, below this minimum, the gas pressure torques dominate and therefore there will be a tendency to