Target Setting Procedures for Vehicle Powerplant Noise Reduction

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Powerplant sound pressure level (SPL) target setting is the first critical step to develop an efficient NVH strategy that guides computer aided analysis and hardware research to achieve a desired goal in the early stage of a program. Traditionally, specifications have been set by comparison of a baseline powerplant SPL average of several measurement locations with its target, but it does not cascade SPL to individual component contributions. NVH engineers usually do whatever they can to reduce SPL of individual components but without a target. This guesswork can lead to NVH targets that are not met after all hardware has been developed and tested. An effective method is proposed that can be used to break down a powerplant SPL target to individual component levels at desired frequencies quantitatively. This new method is based on the inverse square law that the reduction of sound power level equals the reduction of sound pressure level at a fixed point in a free field. The calculations presented in this article work for both powerplant upgrades and new designs. The SPL target could be test data or theoretical calculations.

NVH is a very important factor in customer satisfaction and has become a significant issue in automobile design. Both the physiological and psychological effects of NVH on human beings have been carefully studied and investigated by various scientists. Findings show that NVH not only causes annoyance and fatigue, but also adversely affects the efficiency and health of people.[1] On the other hand, a high quality sound is required so people can enjoy music and conversations. Therefore, better sound quality is desirable in vehicles. In order to have competitive NVH goals at the vehicle level we must produce powerplants that have best-in-class NVH characteristics. Cascading powerplant NVH targets to component levels is the first step to achieving this goal.

For many years, engineers have been trying to find a simple and economic method to cascade NVH targets to the component level quantitatively. This has been difficult since no single measurement method can achieve this goal.[2] Several test methods, such as sound pressure level,[3] sound intensity,[4] surface velocity, laser vibration, spatial transformation of sound fields (STSF), near field acoustic measurements and cladding tests have been developed. Most of these methods are used for NVH improvements and have their advantages and disadvantages. Only a sound pressure level average of all microphones at a desired RPM range has been used in target setting processes.

This traditional method can no longer meet current NVH development demands. First, it does not cascade SPLs to component levels. Without an explicit NVH target for individual components, it has been difficult to deploy an adequate strategy for NVH design or improvement. Usually engineers make their predictions on the NVH roadmap based on their experience. These estimations are unreliable since they lack exact calculations. Second, it requires physical test data from both baseline and target powerplants. Therefore, this traditional method does not work for a new powerplant design. It becomes apparent that the traditional method is not sufficient as a basis for a completely satisfactory target setting process.

By combining sound pressure level and sound source ranking test data of a baseline powerplant, one can cascade a target to its component level at desired frequencies quantitatively. This ensures that resources will be spent on the right components that affect SPL the most. The cascading can be done by comparing individual SPL measurements and frequency content of a baseline powerplant with its target, then reducing the component power level in a manner that the highest power component gets the most reduction at the desired frequency range. For a completely new design, the baseline powerplant can be used as a reference to calculate the differences between the target and new design. The SPL of a new design can be predicted by comparison of two differences.

This new method can be used to set priorities of components for NVH improvement, to identify those components that may not need any NVH improvement and to analytically verify if a new design meets its target.

Powerplant Sound Target Setting

Powerplant sound target setting consists of three parts: sound pressure level, sound quality and tonal noise. Sound pressure level can be set by matching a target powerplant or by back calculations from an interior noise target through transfer functions. Sound quality focuses on the order contents of the engine speeds. The sound quality target is usually cascaded on the powerplant, induction system and exhaust system. Tonal noise results from some components like power steering, air conditioning, water pump, transmission gear and pump, alternator and valve train. These components have their own rotating or moving parts and generate noise at particular orders. The target for tonal noise is based on the ratio of the tonal noise level and its corresponding critical band background noise level. As a rule of thumb, any tonal noise level should be 6 dB lower than its corresponding critical band background noise.

Traditionally, the powerplant SPL target was set by comparison of a baseline powerplant SPL average of all measurement locations with its target. This can be done by measuring SPL at different locations, then averaging the SPL of corresponding locations. A typical target specification is given in Figure 1. This target specification is often used in roadmap development. NVH and component engineers identify some components for NVH improvement and estimate SPL reductions. These estimates are based on individual experience and could be different from one engineer to another. It is not easy to verify the estimates until all hardware has been developed and tested. Such guesswork lacks scientific prediction and at the end of a program the NVH target may not be met. Although this method is simple, it has been difficult to implement since it does not address the following two areas. First, SPL reduction does not directly relate to individual components quantitatively. Second, SPL reduction does not address frequency content of individual components. Without this information, engineers may have trouble making a full NVH assessment of individual components at the beginning of a program.

For a completely new powerplant design, NVH analysis is very critical. The traditional method does not work since it requires test data from both base line and target powerplants.

A New NVH Component Cascade Method

A new method is urgently needed to meet current NVH development demands. First, it should cascade a NVH target to component level quantitatively. NVH engineers can deploy different strategies for different components by applying various technologies. CAE engineers can study the possibility that a component can be modified to meet its target or not at the beginning of a program.[5] This will increase communication efficiency between engineers and management. Second, this method could be used for new powerplant designs. Based on these requirements, an effective method is proposed that can cascade a SPL target to the component level of a baseline

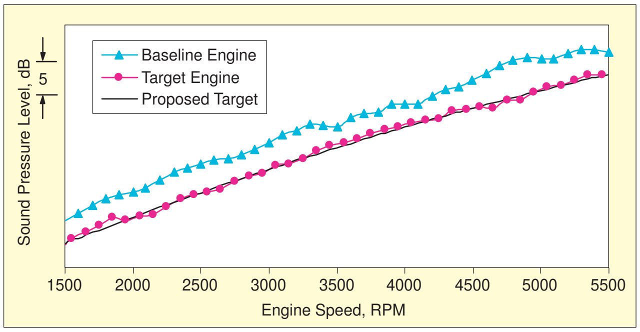

Figure 1. A typical engine target setting – engine radiated noise, WOT, 4 microphone average.

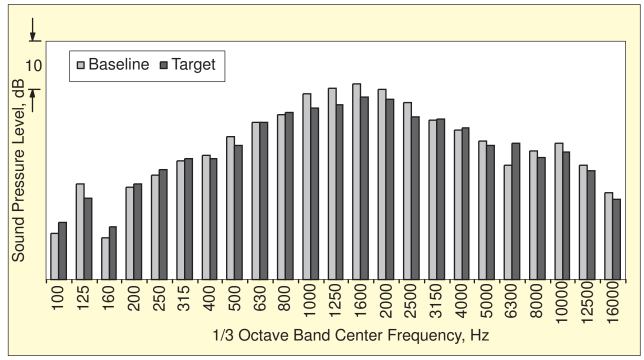

Figure 2. Comparison of 1/3 octave data – baseline vs. target engines, front microphone location.

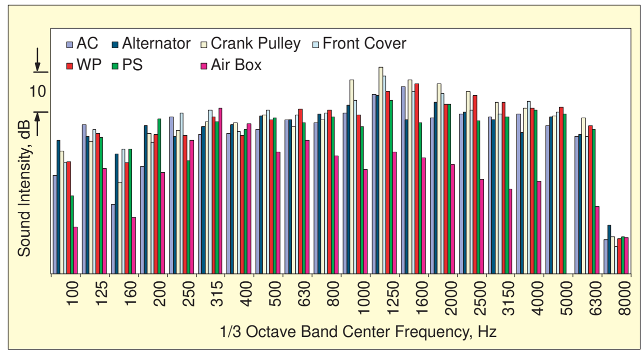

Figure 3. Sound intensity measurement of the engine front side components.

powerplant and match the frequency content.

Baseline Powerplant SPL Data. This new method requires baseline powerplant SPL and sound source ranking data. SPL data can be collected in a hemi-anechoic room per industry standards and then used to calculate the differences between a target value and individual measurement locations. The frequency range of interest – the range in which the most significant SPL differences occur between the baseline powerplant and target – can be identified. This is also the range on which NVH improvement should focus. Figure 2 is a comparison of 1/3 octave SPL data from the front microphone, showing the 1000 to 2500 Hz frequency range of interest.

Baseline Powerplant Sound Source Ranking Data. There are several ways to measure individual component sound power. Among them are sound intensity (SI), surface velocity, STSF, laser vibrometry, near field acoustic measurements, cladding, etc. Each has its advantages and disadvantages. In this article, sound intensity and near field measurements were adopted. Sound intensity measurements are relatively easy and provide a reasonable frequency bandwidth. This technique can measure contoured surfaces, hot surfaces and acoustically induced noise. But, this method requires an operator inside the test cell while the engine is running. Due to safety issues at high engine speeds, near field measurements are also required to calculate SI by scaling low speed SI values to higher speeds. The sound power levels (PWLs) of baseline components can be calculated from SI measurements and their corresponding dominant PWL frequency ranges can be identified. The calculation of component PWLs are very critical in this new method since the reduction of SPL at a given location can be calculated from the reduction of individual component PWLs according to the inverse square law.[6]

The dominant component frequency range is another important parameter. This is the frequency range in which most of the sound power energy is located. Any improvements outside this range will not have a significant effect on SPL. If this frequency range does not overlap the frequency range of interest, this component may not need any NVH modifications since it may not reduce the overall SPL very much. Components can be divided into different groups, each group corresponding to a measurement location. Figure 3 shows SI measurements of those components that belong to a measurement location at the front of an engine.

Target Setting Steps (Component Cascade). There are two critical steps in this new method. First, identify component contributions to individual measurement locations – some components may contribute sound power energy to more than one measurement location. Then, find the workable frequency range for each individual component. The workable frequency range is the common dominant frequency range and the frequency range of interest. Any modifications outside this common range may not be effective for NVH improvement. Second, assign PWL reductions to individual components. Usually the component with the highest PWL should get the most reduction and have the highest priority for NVH improvement. Neglect components with PWLs 10 dB below the highest level, or outside the workable frequency range. Next, calculate the overall PWL reduction L_{wOA} for each measurement location based on Eq. 1. Repeat this process until the target is met. The total reduction of PWL should equal the required reduction of SPL. PWL reductions can be relocated from one measurement location to another as long as their effects on the vehicle remain the same,

$$L_{wOA} = 10\log \frac{\sum_{i=0}^{n} j_{(i)} 10^{\left(\frac{L_{w(i)}}{10}\right)}}{\sum_{i=0}^{n} j_{(i)} 10^{\left(\frac{L_{w(i)} - RD_{(i)}}{10}\right)}} \tag{1}$$

where

L_{wOA} = PWL reduction from a group of components that corresponds to a particular measurement location (dB)

n = number of components that belong to the same group

i = the i^{th} component

$L_{w(i)}$ = the i^{th} component PWL (dB)

RD_i = the i^{th} component PWL reduction (dB)

$j_{(i)}$ = weighting factor, $j_{(i)}<1$ for those components that contribute their sound power energy to more than one measurement location. $j_{(i)} = 1$ for those components that contribute their sound power energy to one measurement location.

The contributions of individual components L_{wC} to overall reduction is given by

$$L_{wC} = \frac{j_{(i)}10^{\left(\frac{L_{w(i)}}{10}\right)} - j_{(i)}10^{\left(\frac{L_{w(i)}-RD_{(i)}}{10}\right)}}{\sum_{i=0}^{n}\left(j_{(i)}10^{\left(\frac{L_{w(i)}}{10}\right)} - j_{(i)}10^{\left(\frac{L_{w(i)}-RD_{(i)}}{10}\right)}\right)} \times 10\log \frac{\sum_{i=0}^{n} j_{(i)}10^{\left(\frac{L_{w(i)}}{10}\right)}}{\sum_{i=0}^{n} j_{(i)}10^{\left(\frac{L_{w(i)}-RD_{(i)}}{10}\right)}} \tag{2}$$

Eq. 2 indicates that the contribution of individual components to overall reduction also depends on other component reductions. Note that Eqs. 1 and 2 are independent of their application. In fact, this methodology could be used in any application with more than one noise source, e.g., vehicles, airplanes, machinery, etc.

Target Setting for a New Powerplant Design. The target setting processes just outlined are designed for a powerplant upgrade. For a completely new powerplant design, the baseline powerplant can be used as a reference to calculate the differences between the target and new design. First, cascade a NVH target to the baseline powerplant and assign sound power reduction to an individual component. Then run computer aided analysis (CAE) on the corresponding baseline powerplant and the new design components. PWL changes between corresponding components can be calculated. To meet a SPL target for a new design, the difference between PWL reductions calculated from the baseline powerplant and its target should equal the PWL changes predicted by CAE.

NVH Roadmap for Component Sound Power Level Reductions. After target setting, a NVH roadmap can be developed that leads to hardware action to achieve a desired goal. The required PWL reduction of individual components should equal the reduction predicted by the roadmap. An adequate NVH strategy can be deployed at the early stage of a program. This strategy should include new technology, timing and cost. A reliable NVH prediction at the beginning of a program is very critical in allowing management to make key decisions when the target may be too costly to implement.

Example

In order to illustrate how this method works, an example is presented here. For the purpose of simplicity, the SPLs at all locations are equal except for the front location. The baseline engine is approximately 2 dB higher than that of its target in the 1500-5500 RPM range (see Figure 4). What components should be modified to meet the target (both SPL and frequency content)?

Solution (see Table 1):

1. Compare the overall level of all measurement locations between the baseline and target individually. All locations should match except the front location as shown on Figure 4, which is around 2 dB higher in all RPM ranges.
2. Identify the frequency range of interest by comparison of the front location 1/3 octave data at different speeds. Frequency range of interest is the range in which the most significant SPL differences occur between the baseline powerplant and target. In this example, the 1000-2500 Hz range is shown in Figure 2. Any component modification should be within this frequency range.
3. Identify the dominant frequency range of baseline components as shown in Figure 3. Dominant frequencies are those frequencies that have high sound power energy. For example, the front cover has a dominant frequency range of 1000-2000 Hz, while the air box has a dominant frequency range of 250-400 Hz.
4. Identify all components whose dominant frequency range overlaps the frequency range of interest. Those are the components that may need NVH modification.
5. Select components whose sound power needs to be reduced. The highest sound power component gets the most reduction. In this example (Table 1), the front cover is selected with a reduction of 3 dB at 1000-2000 Hz, an alternator with a reduction of 2 dB at 1000-2000 Hz, and crank pulley with a reduction of 1 dB at 1000-2500 Hz. The overall front location reduction is 2 dB, matching the required reduction.

Table 1. Front microphone component sound power reductions.

Components	Dominant Freq (Hz)	Workable Freq (Hz)	L_W (dB)	L_W Reduction (dB)
Front Cover	1000-2000	1000-2000	74.5	3
Alternator	1000-2000	1000-2000	67.3	2
Crank Pulley	1000-3150	1000-2500	67.1	0
Air Box	250-630	None	66.9	0
Water Pump	1250-3150	1250-25000	64.9	0
Power Steering	1000-2000	1000-2000	62.5	0
A/C	1000-1600	1000-1600	63.0	0

Frequency range of interest: 1000-2500 Hz
Required sound power reduction for each component: 2 dB
Total sound power reduction for each component: 2 dB

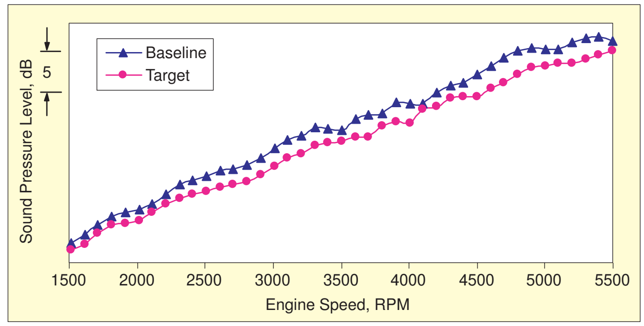

Figure 4. Baseline vs. target engine radiated noise – front microphone location.

In Table 1, the front cover has the highest PWL and therefore is assigned the highest reduction – 3 dB at 1000-2000 Hz. The air box does not need any modification since it does not have a workable frequency range. There are no reductions from the water pump, power steering and air conditioning either since their PWLs are very low. In some situations, the workable frequency range may need to be adjusted in order to meet the sound quality target. The total PWL reduction is 2 dB based on Eq. 1, which matches the required reduction of 2 dB discussed in Step 1. After component PWL reductions and workable frequency ranges are finalized, a NVH roadmap should be developed and the PWL reduction should equal that predicted by the roadmap. SPL reductions could result from structural modifications, redesign, absorption, damping, isolation or decreases in excitation forces.

The same procedure can be used for other measurement locations should the SPL of the baseline be higher than that of the target.

Conclusions

- The proposed method can cascade a SPL target to baseline powerplant component level at desired frequencies quantitatively.
- This method can identify which components need NVH modifications and which do not, ensuring that resources are focused on the components that affect NVH the most.
- PWL reduction can be relocated from one group of components to another as long as their effects on the vehicle stay the same. This gives NVH engineers more options.
- This method can also be used for a completely new powerplant design. The significance for a new design is that the NVH target can be analytically verified before any hardware is available.
- A reliable prediction at the early stage of a program not only helps engineers develop an adequate NVH strategy and robust roadmap, but also assists management in making key decisions.
- This methodology could also be used in any other applications with more than one noise source.

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