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Monte Carlo Simulations for Evaluating Engine NVH Robustness

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Abstract

This paper describes the use of a design-oriented engine cycle simulation model in Modelica for evaluating robustness of engine NVH (Noise, Vibration, and Harshness) to noise factors. This paper highlights the novel use of the cycle simulation model for analytic robustness studies using Monte Carlo simulations. The Monte Carlo simulations allow the robustness of a statistically significant engine population to be examined upfront in the product development process. The paper also discusses a flexible, extensible tool that was developed in conjunction with the Modelica models to streamline the description, execution, and results post-processing from the simulations.

Keywords: engine cycle simulation; NVH; Monte Carlo simulations; Fourier analysis

1 Introduction

Engine NVH is typically one of the vehicle attributes that contributes strongly to customer satisfaction and perceived quality [1]. The customer experiences the NVH characteristics of the vehicle via multi-sensory feedback. Radiated noise, steering wheel vibration, and seat track vibration are just a few of the common audible and tactile feedback mechanisms.

The vehicle NVH characteristics related to the engine result from the coupling of the dynamic engine torque with the transfer characteristics of the vehicle. The vehicle transfer function is affected by many different system-level design attributes, such as the design of the engine mounts and engine block, the vehicle frame design, and the vehicle stiffness, just to name a few. The design of the individual components and the overall system design are crucial for the development of a system that meets the functional requirements while maintaining acceptable NVH characteristics.

NVH evaluation is often performed on hardware components, primarily early prototypes. Due to the cost and limited availability of prototypes early in the design process, the evaluations are necessarily restricted in scope and usually at the nominal design. While more extensive evaluations can be performed on hardware later in the design process, the impact of the evaluations on the design is often limited due to the additional cost and potential program timing impact of design changes further downstream in the product development process. Furthermore, evaluating the impact of the manufacturing process and capability on the vehicle NVH is extremely difficult with prototype hardware due to the lack of a statistically significant population.

A robust product design requires the evaluation of the nominal design performance and sensitivity with respect to noise factors. This paper presents an analytic approach for evaluating engine NVH robustness to noise factors. The advantages of analytic NVH evaluation are many. Analytic evaluations are a cost-effective way of assessing NVH attributes upfront in the design process where changes are most easily accommodated. In addition to being costly, "cut and try" hardware experimentation can be extremely resource-intensive and time-consuming. Analytic evaluations can provide data in a more timely manner and allow for streamlining the NVH audits via batch simulations, parallel computing, and automated data collection and post-processing. Because even the noise factors can be set and accurately measured in the analytic models, the resulting data can clearly show the impact and interactions between the various factors. In addition, an analytic robustness evaluation can easily include the impact of manufacturing capability on the resulting NVH, thereby providing the opportunity for an optimal design including the effects of the manufacturing process for a statistically significant population representative of that in the hands of the customers. Furthermore, a detailed knowledge of the nominal design and its sensitivity to noise factors can lead to the feeding forward of additional requirements or control actions for the manufacturing process by the product development team to ensure robust product delivery to the customer.

2 Engine NVH Analysis

Engine NVH can be quantified in many different ways. One typical way of assessing engine NVH due to combustion torque is via calculation of the standard deviation of Indicated Mean Effective Pressure (SDIMEP) in the engine, essentially a measure the variation in the combustion event amongst the various cylinders. An engine with good NVH characteristics would typically have uniform combustion and thus similar power output from the various cylinders. However, past work has shown that SDIMEP does not often correlate well with engine NVH metrics observed by the customer [1]. A new technique for evaluating combustion variation called Combustion Torque Uniformity [1]-[2] is applied in this work. This approach examines the frequency content of the engine torque to analyze combustion non-uniformity. This section describes the models and techniques used to analytically calculate Combustion Torque Uniformity metrics for a V6 engine subject to noise factors.

2.1 Cycle Simulation

At the heart of the analytic engine NVH methodology is the cycle simulation model. This model describes the detailed thermodynamics of the breathing, compression, combustion, and expansion of the gas mixture. Figure 1 shows the Modelica representation of the GESIM predictive cycle simulation model [3]-[4].

The details of the cycle simulation submodels influence the types of noise factors that can be considered in the NVH analysis. The cycle simulation model used in this study includes the following submodels:

- Multi-zone, predictive combustion based on thermodynamics and bulk fluid motion
- Pseudo-species formulation with detailed mixture property calculations for the thermodynamic media
- Gas exchange across the valves with the valve lift kinematically determined from the cam position and the valve lash
- Detailed thermal response models for the block, head, and piston
- Intake reservoir boundary conditions including the pressure, temperature, and composition

GESIM has previously been used to simulate cycle-to-cycle variability based on factors related to the physics of early flame development [5].

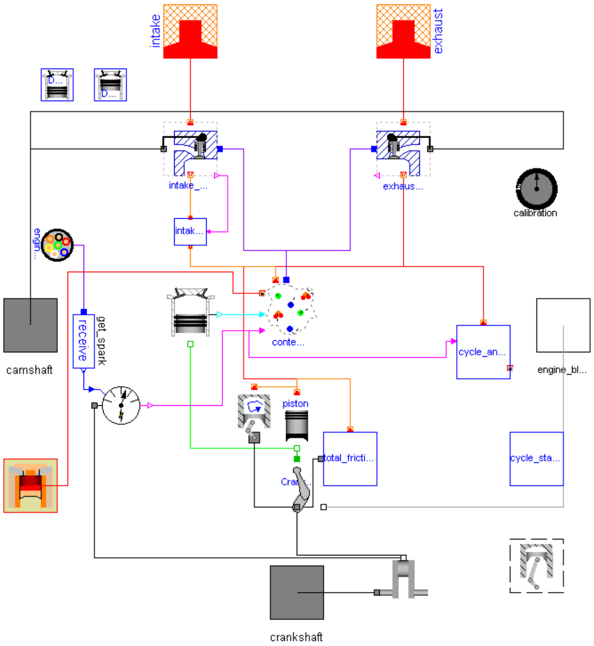

Figure 1. GESIM cycle simulation cylinder

The cycle simulation model shown in Figure 1 can be inserted into predefined engine templates to simulate multi-cylinder engines [4], [6]. The multi-cylinder engine templates use a `replaceable` cylinder model that is instantiated locally. The specific engine to be simulated is created by extending the appropriate engine template (*i.e.* single cylinder, I4, V6, *etc.*) and redeclaring the cylinder model. Figure 2 shows the dual-plenum V6 engine configuration with each cylinder as the GESIM cycle simulation model shown in Figure 1.

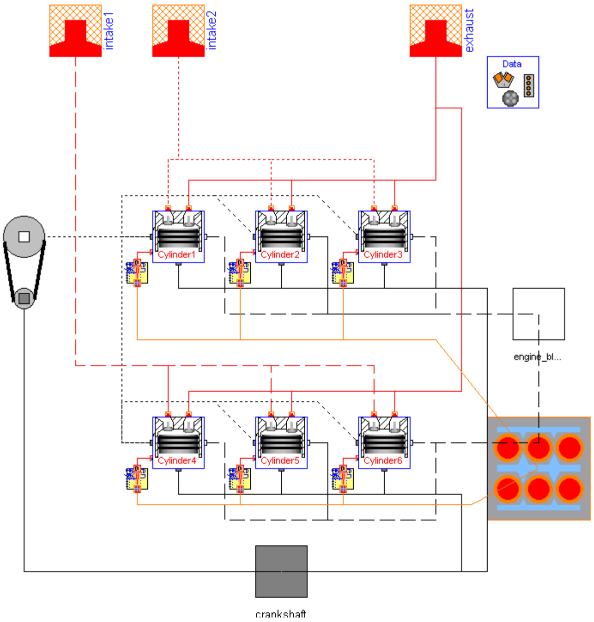

Figure 2. V6 (dual plenum) engine configuration

The test case for the engine NVH simulations is shown in Figure 3. This model is an extension of our existing flexible dyno template [4] and has previously been used for detailed powertrain NVH simulations [7]. Figure 4 shows the code required to modify the dyno template to simulate a V6 engine with GESIM cylinders. The engine geometry data is specified by the `redeclare` of the EngineData package. The user defines the test conditions to be simulated by specifying the engine speed, spark timing, and intake conditions via the engine controller. An additional block was added to the top-level model to perform the Fourier analysis of the resulting engine torque and will be discussed in greater detail in the next section.

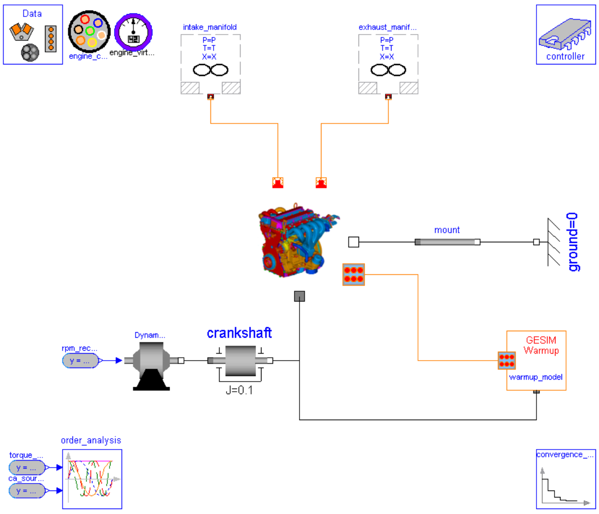

Figure 3. Engine NVH test case

```
model EngineNVH
  extends DynoSetup(
  redeclare package EngineData = MyEngine,
  redeclare model CylinderModel = GESIM,
  redeclare model Configuration =
    V6DualPlenum(redeclare model
                   CylinderModel= CylinderModel));
…
end EngineNVH;
```

Figure 4. Code excerpt from engine NVH test case

2.2 Fourier Analysis

The Combustion Torque Uniformity technique [1]-[2] analyzes the harmonics of the engine torque waveform. The torque order content above the 0th order and less than the firing frequency is computed via Fourier decomposition. The 0th order torque content represents the work done on the crankshaft while the magnitude of the other harmonics are non-zero as a result of non-uniform combustion events. The magnitude (A_n) and phase (ϕ_n) of the nth order harmonic [1] is given by the following Fourier representation:

$$A_n \cos(n\theta_i + \phi_n) \qquad (1)$$

where θ_i is the crank angle. The code excerpt in Figure 5 illustrates the Modelica implementation of the discrete Fourier transform calculations.

```
model OrderAnalysis
…
  for m in 1:num_order loop
    s_sum := 0;
    c_sum := 0;
    for i in 1:no_pts loop
      s_sum := s_sum + waveform_sample[i]*
        sin(4*pi*order[m]*(i - 1)/no_pts)*2/no_pts;
      c_sum := c_sum + waveform_sample[i]*
        cos(4*pi*order[m]*(i - 1)/no_pts)*2/no_pts;
    end for;
    s_sum_temp[m]  := s_sum;
    c_sum_temp[m]  := c_sum;
    mag[m]  := if (order[m] == 0 or order[m] == no_pts)
       then 0.5*((s_sum)^2 + (c_sum)^2)^0.5 else
       ((s_sum)^2 + (c_sum)^2)^0.5;
    phase[m]  := if atan2(-s_sum, c_sum)*rad2deg < 0
       then 360 + atan2(-s_sum, c_sum)*rad2deg else
       atan2(-s_sum, c_sum)*rad2deg;
  end for;
…
end OrderAnalysis;
```

Figure 5. Code excerpt from order analysis model

The analysis can be performed either on the torque from a multi-cylinder engine model or via the superposition of the calculations from individual cylinders. The following equation can be used to calculate the contribution to the engine harmonic from an individual cylinder based on the cylinder phasing and firing order:

$$A_n \cos(\phi_n - \psi_i n) \qquad (2)$$

where A_n is the magnitude of the nth order harmonic for the ith cylinder, ϕ_n is the phase of nth order harmonic for the ith cylinder, and ψ_i is the firing angle for the ith cylinder.

As an example of a typical engine torque signature, Figure 6 shows the simulated engine torque from one firing cycle of a uniform V6 engine along with the torque from cylinder 3. The engine torque shows the 6 distinct firings and superposition of the resulting torque pulses from the individual cylinders. Note that the torque pulse from each cylinder is identical as there was no noise introduced in the geometry or operating conditions for the individual cylinders. Figure 7 shows the simulated engine torque for the same V6 engine as in Figure 6 but with the introduction of noise into the operation conditions such that cylinders 1-3 are still operating at a stoichiometric air-fuel (AF) ratio of 14.6 while cylinders 4-6 are now operating lean at AF=16. In comparing both the engine and cylinder torques from Figure 6 and Figure 7, it is clear that the resulting torque signatures are different and could lead to the excitation of different vehicle NVH modes when coupled with the transfer function of the vehicle. Table 1 shows the torque harmonics for Cylinders 3 (AF=14.6) and 4 (AF=16) from the engine in Figure 7. Note that the lean cylinder has lower torque magnitudes as expected.

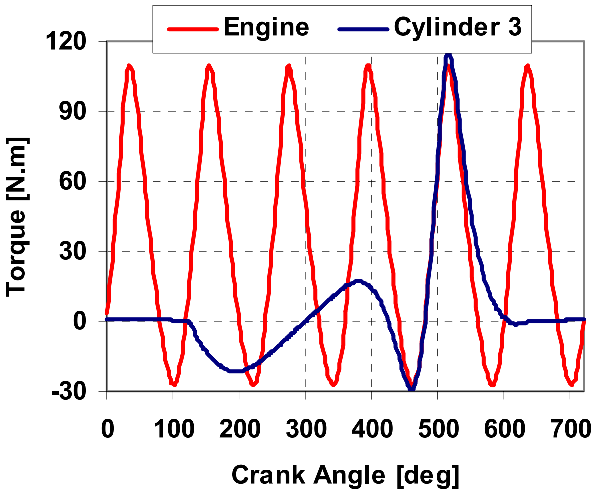

Figure 6. Torques from a uniform V6 engine

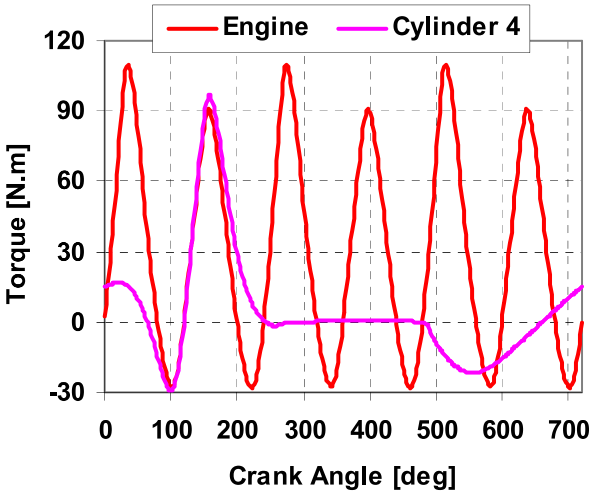

Figure 7. Torques from a V6 engine with cylinders 1-3 operating at AF=14.6 and cylinders 4-6 at AF=16

Table 1. Cylinder torque harmonics calculations

Torque Harmonics		Cyl. 3 AF=14.63	Cyl. 4 AF=16
0	Mag [N.m]	5.64	4.72
	Phase [deg]	0	0
0.5	Mag [N.m]	20.61	18.81
	Phase [deg]	336.3	335.8
1	Mag [N.m]	7.79	6.10
	Phase [deg]	332.7	335.1
1.5	Mag [N.m]	17.15	15.98
	Phase [deg]	265.9	262.1
2	Mag [N.m]	14.91	13.57
	Phase [deg]	266.7	264.0
2.5	Mag [N.m]	14.57	13.36
	Phase [deg]	247.9	245.0
3	Mag [N.m]	10.82	9.55
	Phase [deg]	245.6	243.4

2.3 Methodology

A key advantage to analytical engine NVH analysis is the ability to evaluate a statistically significant engine population. Rather than simulate a large number of V6 engines with a multi-cylinder engine model subject to various noise factors in the individual cylinders, it is far more computationally efficient to simulate a large number of single cylinder engines using the Monte Carlo method [8] to choose the value of the noise factor(s) for each run and then "virtually" assemble the single cylinders into a V6 engine. The following methodology was used to perform the analytic engine NVH analysis (see Figure 8):

1. For the given engine, build and calibrate the single cylinder cycle simulation model.
2. For the operating condition of interest, configure the Monte Carlo simulations by determining the noise factors and their distributions (*i.e.* from manufacturing process capability, *etc.*).
3. Perform the Monte Carlo simulations with the single cylinder model to generate a library of single cylinder results.
4. Assemble multi-cylinder engines from library of single cylinder results.
5. Analyze engine population and calculate statistics of interest.

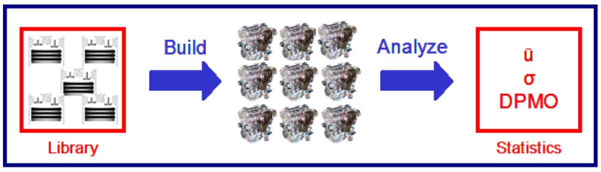

Figure 8. Engine assembly methodology

3 NestedAnalysis Toolkit

While considerable effort is made in these kinds of analyses to capture the appropriate level of detail in the models, it is important not to lose sight of the bigger picture. Ultimately, the simulation of the underlying model is simply a means of generating data. Such data can then be used in a variety of ways. For example, frequently models are used as the basis of a design optimization process whereby the simulation evaluates perspective designs according to a set of objectives or constraints.

For this reason, an analysis tool, called the NestedAnalysis Toolkit, has been developed internally that can be used to construct models of the complete analysis. The term “nested” refers to the fact that complete analysis is composed of a hierarchy of other analyses. For example, in quality and robustness analyses it is quite common to try and minimize the variation of a products performance with respect to uncontrollable noise factors.

Figure 9 shows how such an analysis could be represented graphically. At the bottom of the hierarchy are individual simulations. Each simulation represents slightly different conditions. The conditions are generated automatically based on statistical information about the noise factors being considered and their impact on the inputs to the simulation. After these simulations are completed, the results are compiled and analyzed to produce statistical information. This statistical information can then be used in subsequent analyses (*i.e.* an optimization process in this case) to minimize the variation.

The construction of these analyses was originally described in Python [9]. The descriptions were essentially declarative in nature, and the analysis engine would use the declarative descriptions of the analysis to coordinate the complete analysis. In order to make the toolkit more useful to end users, a graphical user interface was developed. Using the new interface, users constructed the analyses graphically in a hierarchical manner. The goal of the user interface was to show users a representation that was intuitive, like the overview shown in Figure 9. Figure 10 provides screenshots from a sample Monte Carlo analysis of a Dymola[1] [10] transient model, in this case the `TwoMasses` example from the Modelica Standard Thermal library.

While support for running simulations generated from Dymola was a key feature of the toolkit, the toolkit architecture was developed to accommodate a range of different types of analyses. For example, support for using Excel spreadsheets within the framework was easily added. Furthermore, each plug-in added to the framework was developed specifically to support each analysis type. So, for example, the support for Dymola simulations was able to automatically construct lists of input parameters and results and display them for the user to choose as either inputs or outputs in the nested analysis. In addition, the toolkit has an extensible architecture for adding node analyses. Currently the architecture supports Monte Carlo analysis, full factorial Design of Experiments (DOE), and some optimization functionality. The vision is to be able to develop new analysis plug-ins as needed. Some examples of possible additional analysis plug-ins are sensitivity analysis, Latin hypercube sampling, and fractional factorial DOEs.

There is a fundamental philosophical principle in our toolkit that bears some explanation. We do not rely on the simulation tools themselves to provide these capabilities. There are two reasons for this approach. First, we want our analysis capabilities (Monte Carlo analyses, optimization, *etc.*) to work with multiple tools, not just Dymola. Furthermore, we do not want to distract simulation tool developers with functionality that we consider to be “above” the simulator. That being said, we recognize that there are also great advantages to having these capabilities integrated into a simulation tool as well.

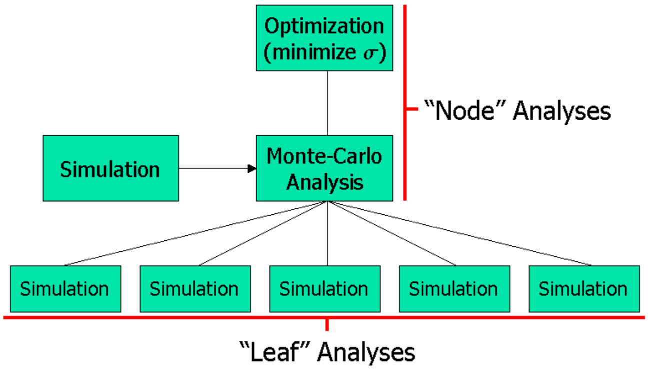

Figure 9. Building blocks for hierarchical analyses

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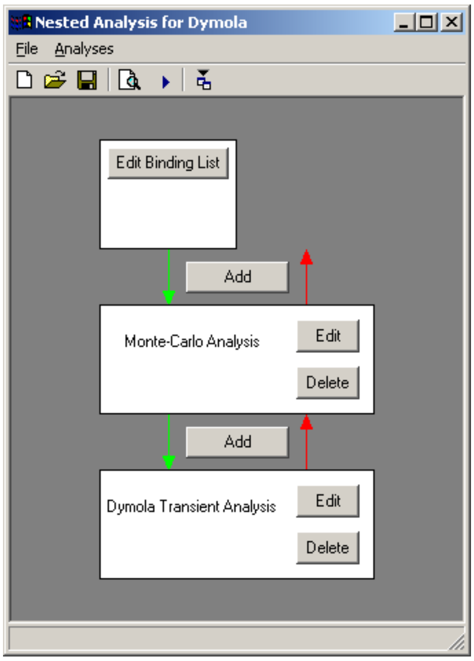
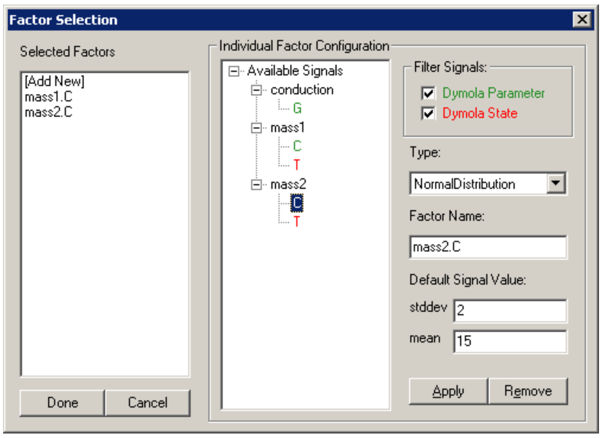
[1] Dymola is a trademark of Dynasim AB



(a) Analysis construction



☑ Dymola Parameter
☑ Dymola State

Type: NormalDistribution

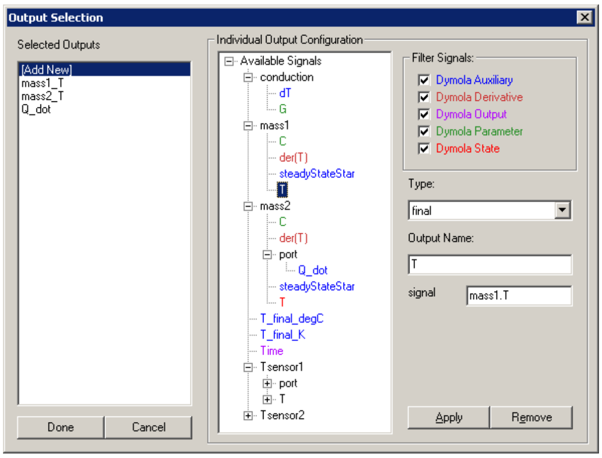
Factor Name: mass2.C

Default Signal Value:

stddev 2

mean 15

(b) Monte Carlo factor selection



☑ Dymola Auxiliary
☑ Dymola Derivative
☑ Dymola Output
☑ Dymola Parameter
☑ Dymola State

Type: final

Output Name: T

signal mass1.T

(c) Output variable selection

Figure 10. NestedAnalysis Toolkit GUI screenshots for a Monte Carlo analysis of a Dymola transient model

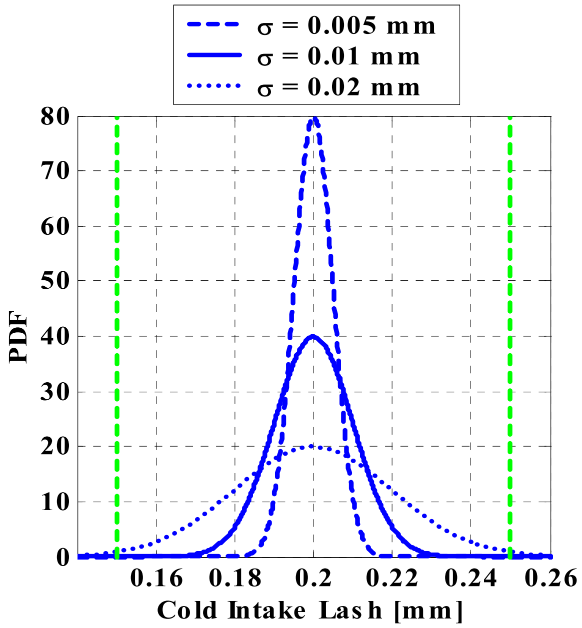
4 Results

The methodology described in Section 2.3 was used to simulate the effects of valve lash variation in a sample V6 engine at a fixed operating condition. Valve lash is an important design variable as it affects the timing and duration of the valve events, the maximum valve lift, and the overlap between valves. Thus, it directly impacts breathing, mixture preparation, and combustion. Since there is some variation in the lash of each cylinder in the assembled engine due to the manufacturing process, it is highly desirable to understand the NVH effects of this variability in the engine population.

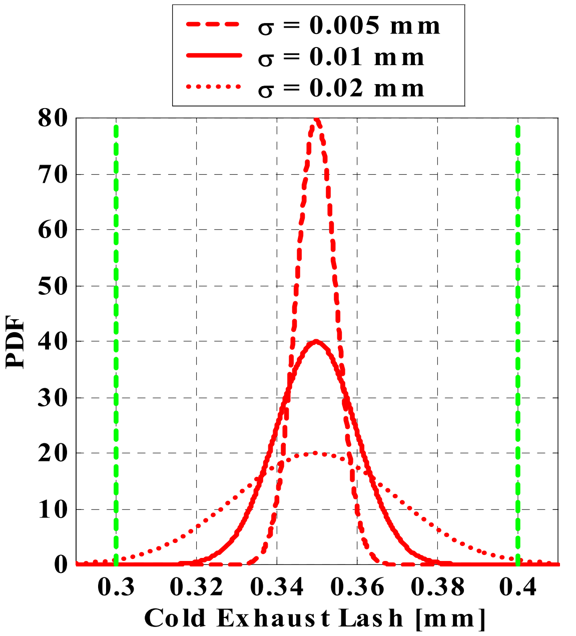
The NestedAnalysis Toolkit described in Section 3 was used to establish and perform the simulations with Dymola [10]. One hundred single cylinder Monte Carlo simulations were performed with a normal distribution for the variation in valve lash. From the library of 100 single cylinder runs, 10,000 V6 engines were assembled and analyzed. Each engine was assembled by randomly choosing 6 cylinders from the library (see Figure 8). To determine an appropriate number of engines to assemble to represent the engine population, the number of assembled engines was increased until the overall engine population statistics converged. To examine the sensitivity of the engine population to the process capability, the Monte Carlo simulations were conducted with four different standard deviations for valve lash. Figure 11 shows three of the simulated valve lash distributions (note that all distributions are normal but with different standard deviations).

Figure 12 shows the results of the engine population analyses for the various valve lash distributions. Figure 12a-b shows the histograms of the 1.5 order torque in the assembled engine populations for $\sigma = 0.02$ mm and 0.01 mm, respectively. Figure 12c shows the engine population statistics for 1.5 order torque. Note that as the standard deviation of the valve lash increases, there is both a larger mean 1.5 order torque and more variability in the engine population as indicated by the error bars showing $\pm 1\sigma$ levels. Understanding the sensitivity of the engine population NVH characteristics to valve lash leads to the ability to optimize the lash centering and manufacturing process capability to optimize engine population robustness. Furthermore, given a specification on the various torque magnitudes, the analysis would also yield information as to the fraction of engines in the population that would meet the specifications.

While the sample simulations shown here considered a single noise factor with a normal distribution, the approach is general and can be used with multiple noise factors and a variety of distributions. Currently the Monte Carlo analysis plug-in supports normal, log normal, uniform, beta, exponential, gamma, and Pareto distributions, and the additions of new, user-defined distributions are trivial. Furthermore, simulations with multiple noise factors can be analyzed with existing statistical techniques to identify main effects and interactions between the factors.

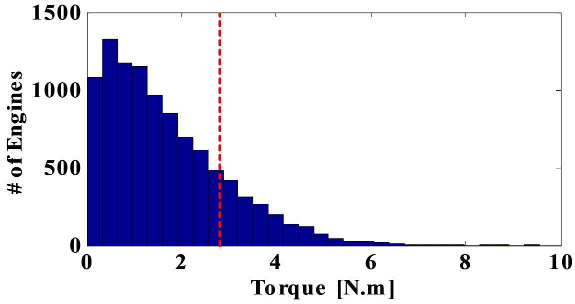


(a) Intake lash

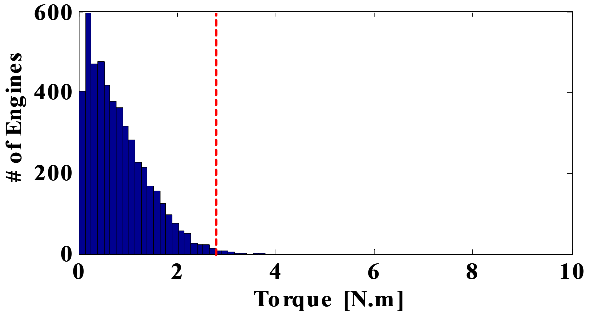


(b) Exhaust lash

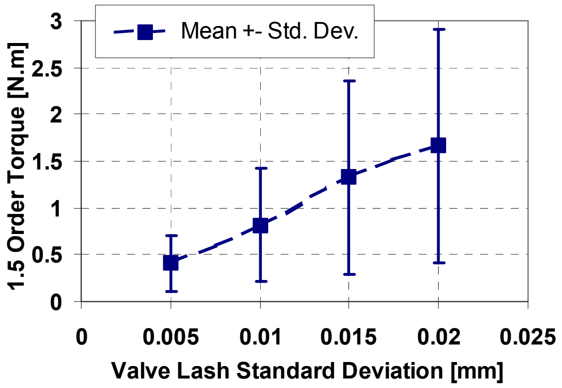
Figure 11. Simulated distributions for valve lash



(a) σ = 0.02 mm



(b) σ = 0.01 mm



(c) Engine population statistics

Figure 12. 1.5 order torque analysis for engine population due to valve lash variation

5 Conclusions

This paper discusses a methodology for analytical NVH simulations using the Combustion Torque Uniformity technique. A novel simulation approach using a design-oriented cycle simulation model and the Monte Carlo method for simulating the effects of noise factors allows the robustness of a statistically significant engine population to be analyzed upfront in the design process. In addition, the approach allows for multiple noise factors to be simulated according to various distributions to examine design sensitivities and interaction effects. The ability to analytically simulate an entire engine population leads to the opportunity for the optimization of the engine design coupled with the manufacturing process capability to deliver the most robust product to the customer. Furthermore, the flexible, descriptive NestedAnalysis Toolkit has been developed to streamline the description, execution, and results post-processing from these sorts of robustness studies.

References

[1] Stout, J.L., Mancini, M., Host, R., and Hancock, K., 2003, "Combustion Uniformity as a Measure for Engine Idle NVH," *SAE-2003-01-1429*, Society of Automotive Engineers.

[2] Stout, J.L., 2001, "Engine Excitation Decomposition Methods and V Engines Results," *SAE-2001-01-1595*, Society of Automotive Engineers.

[3] Newman, C., Batteh, J., and Tiller, M., 2002, "Spark-Ignited-Engine Cycle Simulation in Modelica", 2nd International Modelica Conference Proceedings, pp. 133-142, http://modelica.org/Conference2002/papers/p17_Newman.pdf

[4] Batteh, J., Tiller, M., and Newman, C., 2003, "Simulation of Engine Systems in Modelica", 3rd International Modelica Conference Proceedings, pp. 139-148, http://www.modelica.org/events/Conference2003/papers/h34_Batteh.pdf

[5] Brehob, D.D. and Newman, C.E., 1992, "Monte Carlo Simulation of Cycle by Cycle Variability", *SAE922165*, Society of Automotive Engineers.

[6] Bowles, P. and Batteh, J., 2003, "A Transient, Multi-Cylinder Engine Model Using Modelica", *SAE-2003-01-3127*, Society of Automotive Engineers.

[7] Tiller, M., Tobler, W.E., and Kuang, M., 2002, "Evaluating Engine Contributions to HEV Driveline Vibrations", 2nd International Modelica Conference Proceedings, pp. 19-24, http://modelica.org/Conference2002/papers/p03_Tiller.pdf

[8] Metropolis, N. and Ulam, S., 1949, "The Monte Carlo Method", *Journal of the American Statistical Association*, 44 (247), pp. 335-341.

[9] Lutz, M. and Ascher, D., 1999, *Learning Python*, 1st Ed., Cambridge: O'Reilly and Associates.

[10] Dymola. Dynasim AB, Lund, Sweden, http://www.dynasim.com.