Effects of Charge Composition on SI Engine Cyclic Variations at Idle

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ABSTRACT

To quantify the various factors contributing to idle stability, a novel set of engine parameter perturbation experiments were carried out to study the sensitivity of the engine output parameters to these factors. This work focuses on the effects of the charge composition; i.e., the mass of the air, fuel and residual ingested per cycle. By perturbing these quantities on-line, for example, by injecting a small additional amount of artificial residual gas once every so many cycles, and by synchronously detecting the effects on the gross IMEP, the 0-10%, 10-50%, and 50-90% mass burn durations, the Jacobian matrix of sensitivity of the latter quantities to perturbation parameters could be determined. Then, through this sensitivity matrix, the observed engine output variations at idle are inverted to obtain the charge variations. At idle, the coefficients of variations of air, residual and fuel mass are 5.5, 4.4 and 0.64% respectively. The residual gas fluctuation contributes to ~1/3 (in terms of the square of the coefficient of variations) of the GIMEP variations. The air and fuel fluctuations contribute much less: 7.5 and 4.6% respectively. The remaining ~54% is attributed to the variations in flow field and charge inhomogeneity.

INTRODUCTION

Smooth idle has been identified as one of the most important engine attributes perceived by the customers [1]. Idle roughness is particularly noticeable because the driver is usually not doing any task and any engine noise and vibrations command his/her full attention. Therefore it is important to understand the nature of engine idle cyclic variations for successful design of the engine combustion system.

Spark Ignition (SI) engine operating at idle presents a difficult environment for combustion. Typical modern engines idle at 600-800 rpm, ~0.3 bar intake pressure, ~1.5 bar gross-mean-effective-pressure (GIMEP), and at a spark timing substantially retarded from the Maximum-Brake-Torque (MBT) point. At low speed and intake pressure, the intake Reynolds Number is low and thus the intake process is not effective in creating substantial turbulent motion to facilitate combustion. The low intake manifold pressure results in high residual gas fraction, low compression pressure, and low charge internal energy. All of these factors are detrimental to a robust combustion process and substantial cycle-to-cycle combustion variations (CCV) occur. The retarded timing also renders the torque output of the engine much more susceptible to combustion phasing than MBT timing. Therefore the nature of CCV at idle is substantially different from that of CCV at steady-state operating conditions.

There has been substantial research on SI engine CCV; see Ref.[2] and [3] for literature reviews. The majority of the work, however, were concerned about the variations at normal engine operating conditions (part-load, medium speed, MBT timing), or at lean conditions. This work here specifically addresses the factors affecting the CCV at idle, in particular, the extent of the charge composition variations and their contributions to the CCV.

METHODOLOGY

The origins of the CCV may be categorized as the following [2, 3]:

1. Variations of the charge components; the amount of air, fuel and residual gas in the charge.
2. Variations of fluid motion; the large scale motion which convects the flame modifies the interaction of the flame with the combustion chamber surfaces (including the spark plug electrodes); the small scale turbulence wrinkles the flame and influences the local flame speed through flame stretching.
4. Variations of spark discharge characteristics.

These factors are still applicable at idle; the extent to which they affect idle CCV, however, is not known and is the subject of the present work.

The focus of this work is on item (1), with the charge comprising the charge air mass ($m_a$), fuel mass ($m_f$),
and residual gas mass \( (m_r) \). Items (2)-(3) are lumped together as a ‘field effects’ factor. This focus is motivated by the following.

(i) With modern ignition system, CCV due to item (4) is small [3].

(ii) It is difficult to quantify items (2) and (3) in a practical engine because extensive measurements (both spatially and temporally resolved) are necessary; and even if the velocity, temperature and concentration fields are available, it is difficult to represent them parametrically for assessing their effects on CCV. Thus grouping them together as the ‘field effects’ makes practical sense.

(iii) In a previous work, the charge composition variation was found to contribute significantly to the fluctuation of the GIMEP [4]. At idle condition, the situation is more severe because the charge mass is smaller, hence more susceptible to individual component mass fluctuations.

In the past, one approach to model engine CCV is to use a Monte-Carlo method: the parameters of an engine simulation model are varied statistically to produce a spectrum of output [5,6]. One difficulty in this approach is that one has to make educated guesses of the distributions of several input parameters (e.g. the residual gas fraction and equivalence ratio). One objective of this work is to experimentally determine the extent of variations of the charge components.

The approach here is to interpret the fluctuations of an engine output \( y_j \) (e.g. \( y_j \) could be the GIMEP or the 0-10% burn duration) in terms of the fluctuations of the engine input variables \( x_i \) as:

\[
\frac{\delta y_j}{y_j} = \sum_i \left[ \frac{d \ln(y_j)}{d \ln(x_i)} \right] \frac{\delta x_i}{x_i}
\]  

(1)

The prefix \( \delta \) denotes variations of the quantity, for which the mean value is denoted by an over-bar. The higher order terms in the above Taylor expansion are dropped. This approximation will be justified a posteriori by experimental results.

Squaring Eq. (1) and assuming the input variables \( x_i \) are uncorrelated (to be discussed later), the coefficients of variations (COV) of the input and output quantities are then related by:

\[
\text{COV}_{y_j}^2 = \left[ \sum_i \left( \frac{d \ln(y_j)}{d \ln(x_i)} \right)^2 \right] \text{COV}_{x_i}^2
\]  

(2)

To examine the charge component effects, the \( x_i \)'s are \( m_r, m_w, m_0 \). To account for the field effects (fluid motion and charge inhomogeneity) on \( y_j \), Eq. (2) is modified to:

\[
\text{COV}_{y_j}^2 = \sum_i \left[ \frac{d \ln(y_j)}{d \ln(x_i)} \right]^2 \left( \text{COV}_{x_i} \right)^2 + \left( \text{COV}_{\delta} \right)^2
\]  

(3)

where \( \text{COV}_{\delta} \) represents the COV of \( y_j \) due to the field effects. The strategy is to first determine the sensitivity matrix \( \frac{d \ln(y_j)}{d \ln(x_i)} \) by a set of synchronous perturbation experiments. Then single-shot firing experiments with heated artificial residual gas simulating the correct thermal and composition environment are carried out; the charge composition of the firing cycles for these experiments is thus well defined and the measured COV of \( y_j \) for the firing cycles are equal to the values of \( \text{COV}_{\delta} \). Finally, the values for the LHS of Eq. (3) are measured for normal engine idle, and the variations of \( x_i \) at idle can be solved from Eq. (3).

The following four engine output parameters are used for the \( y_j \)'s: GIMEP, and the durations of 0-10%, 10-25%, 25-50%, 50-90% burned mass fraction. Thus Eq. (3) represents an over-determined system of four equations for the three \( \text{COV}_{x_i} \)'s, which are solved by the method of least square.

The above choice of \( y_j \)'s is not unique, nor does the choice guarantee a priori good observability of the \( x_i \)'s. The validity of the procedure lies in the practice: when the experimentally obtained values are used in Eq. (3), the system is well-conditioned and could be inverted easily.

A basic assumption in arriving at Eq. (3) is that the variations of the variables are uncorrelated, or more precisely, the self correlations are much larger than the cross-correlations. In general, the engine variables are all related in a complex manner. For example, the change in fuel mass in one cycle affects the stoichiometry and burn rate, hence the exhaust temperature, which in turn, alters the gas exchange process of the next cycle so that both the air mass and residual mass of the next cycle are changed. On the other hand, variation of residual gas fraction due to the valve timing cyclic variations in an engine fit with hydraulic valve lifters will be statistically independent of the other variables. Without experimental data, it is difficult to assess the extent of the cross-correlations. That they are neglected is perhaps more a necessity out of ignorance.

**EXPERIMENT**

**Apparatus and operating conditions**

Experiments were done in a modern production four-valve per cylinder spark ignition engine (Nissan SR20DE) which was modified for single cylinder operation. The engine specifications are: 8.6 cm bore; 8.6 cm stroke; 9.5 compression ratio; 499.6 cc per cylinder displacement; intake valves open at 13\(^\circ\) BTC, close at 55\(^\circ\) ABC; exhaust valves open at 57\(^\circ\) BBC, close at 3\(^\circ\) ATC. There is a 16\(^\circ\) valve-overlap. The engine was completely warmed up; the coolant temperature was kept at 80-85\(^\circ\)C; the oil temperature at 72-77\(^\circ\) C. The inlet air temperature was at 25-30\(^\circ\) C.

The idle operating condition was at 800 rpm. 0.32 bar intake pressure, and the air/fuel ratio was stoichiometric. The spark timing at 15\(^\circ\) BTC was substantially retarded from MBT timing (at 35\(^\circ\) BTC). The residual gas fraction was at 27% which was measured by sampling the cylinder content in skip-fired cycles.

A calibration gasoline (indoline) was used as the normal fuel. In the fuel perturbation experiments, the liquid fuel was augmented by propane which served as the perturbation increment.


Synchronous perturbation of charge composition

To determine the sensitivity of output $y_j$ with respect to a particular input $x_k$, the engine was operated at idle condition. Then the $x_k$ value was perturbed by a small known amount once every $(N-1)$ non-perturbed engine cycles (see Fig. 1). The value of $N$ is chosen large enough to make sure that the engine returns to "normal" after the perturbation so that subsequent-cycle-effects are eliminated, and small enough so that there is good data collection efficiency. The analysis is to synchronously average the difference between the $y_j$ values of the perturbed cycle (cycle 1) with the preceding unperturbed cycle (cycle $N$ of the previous sequence) over $M$ sequences. Since the signal-to-noise ratio $\sim \sqrt{M}$, good accuracy could be obtained by choosing a large $M$.

![Diagram of synchronous perturbation scheme](image)

Fig.1 Schematic of synchronous perturbation scheme. The perturbation is introduced once every 4 cycles in this illustration.

For determining the sensitivity matrix, the above synchronous detection is required over a procedure using the difference of the results from two steady state operating points. This is because there is significant engine run-to-run non-repeatability; the associated errors will substantially affect the accuracy of the results. More important is the fact that the engine thermal and gas exchange environment is changed when the steady state operating point is altered. Thus the derivatives obtained from steady state experiments are not applicable for assessing the effects of engine input variable fluctuations on engine output parameters. This difference is illustrated in Fig. 2. In this figure, the sensitivity of the GIMEP to the fuel quantity obtained from steady state experiments and from synchronous perturbation experiments are compared. For a 1% increase in fuel energy, the steady state results give a 1.87% increase in GIMEP; the corresponding value from the synchronous perturbation is 3.18%. Because of this substantial difference, the synchronous perturbation experiments are necessary.

Preliminary experiments with various $N$ and $M$ values were used for selection purpose. A good compromise between accuracy and data collection efficiency was obtained at $N=4$ and $M=500$.

The amplitude of the perturbation was chosen to be small enough so that the engine response linearly, and large enough for good signal-to-noise ratio. There is no a priori determination of the optimal amplitude. Perturbations were therefore done at two levels to ensure that the engine response was in the linear range (see results later).

The composition perturbations were done by gas injection at the intake port very close to the intake valve. For air perturbation, pressurized air was used. For residual gas perturbation, an artificial residual of $N_2$ and $CO_2$ mixture with the molar specific heat matched to the exhaust gas was used [4]. For fuel perturbation, propane was used as an augmentation to the normal liquid fuel injection. This procedure was necessary to avoid the complication of the port liquid fuel dynamics and the difficulty of metering a small fuel increment. The amount of fuel perturbation is therefore done based on fuel energy rather than fuel mass.

The perturbation gas was injected via a fast-response solenoid during the intake valve open period. Care was taken to ensure that all the injected gas was ingested by the engine and that the normal gas exchange process was disturbed minimally. This could be especially severe for the case of air mass perturbation because the injected air was substantial (up to 4% of the normal air) and significant amount of the normal intake air may be displaced (the throttle position was fixed). To check the displacement effect, the engine was first ran without air injection at a relative air/ fuel ratio ($\lambda$) = 1.0. Then air was injected at every cycle during intake-valve-open at an amount corresponding to 5% of the original intake air flow rate. The air flow rate through the throttle was found not to change, and the exhaust $\lambda$ increased to 1.05 (measured by an UEGO sensor). Finally to demonstrate the displacement effect, the same amount of air was injected during intake-valve-close. The air flow through the throttle decreased and the exhaust $\lambda$ value went back to 1.0. These results support that the injection scheme performed satisfactorily.

Another concern about the perturbation experiment is that only one-way perturbation is possible: there are only positive increments of $m_a$, $m_b$, and $m_c$. While the engine behavior is expected to be linear with respect to $m_a$, the engine may response non-linearly in the fuel rich region. (Fundamentally the laminar flame speed peaks at $\lambda \sim 0.9$; fuel is also not completely oxidized to $CO_2$ and $H_2O$ in the...
rich range.) To assess this effect, the GIMEP as a function of \( \lambda \) (at constant intake manifold pressure) is shown in Fig. 3. In the lean range (\( \lambda > 1 \)), the dependence is linear; for \( \lambda < 1 \), the data points deviate from the straight line. Our results will later show that the air and fuel fluctuations at idle is \(< -5\%\). Therefore an upper bound measure for the non-linear error (estimate using the difference between the value of the GIMEP at \( \lambda = 0.95 \) and the linearly extrapolated value from the lean range) is \(< 4\%\).

![Graph showing GIMEP vs relative air fuel ratio (\( \lambda \)) at idle.](image)

**RESULTS**

**Sensitivity of cyclic variations to charge composition at Idle**

The synchronous perturbation experiments were carried out at two levels of perturbations (see Table 1). The pressure data are synchronously averaged over 500 sequences of perturbations.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Composition</th>
<th>Perturbation (\text{(low/high)})</th>
<th>% Perturbation (\text{(low/high)})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>90 mg</td>
<td>2.25 / 3.60 mg (per cycle)</td>
<td>2.5 / 4.0</td>
</tr>
<tr>
<td></td>
<td>(per cycle)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Residual</td>
<td>36.3 mg</td>
<td>1.10 / 1.80 mg (per cycle)</td>
<td>3.0 / 5.0</td>
</tr>
<tr>
<td>Fuel</td>
<td>6.17 mg indolene</td>
<td>0.15 / 0.23 mg propane (fuel energy)</td>
<td>2.5 / 4.0</td>
</tr>
</tbody>
</table>

Typical results of the perturbation experiments are shown in Fig. 4. In this figure, the changes of GIMEP are well behaved and are linear with respect to the level of perturbation; thus the amplitudes of the perturbation were appropriate. The behavior of the other engine output quantities (0-10, 10-50 and 50-90% burn durations) are similar [8]. It will be shown later that the variations of air, residual and fuel at normal engine idle are within this linear range and therefore the whole procedure is self-consistent.

The sensitivity derivatives were obtained from the slope of the least square fit (forced fit through the origin) to the data typical of Fig. 4. (A discussion of the signal-to-noise ratio which determines the error bars of the data points and the computation of the uncertainty in the slopes can be found in the Appendix.) The sensitivity derivatives \(dE(x)/dE(y)/dE(x)\) are shown in Table 2: for example, the results show that if the fuel energy is increased by 1\%, the GIMEP will change by 3.18\%.

For all the perturbations, there is an increasing sensitivity to the input variations as combustion progresses.

![Graph showing GIMEP change vs percent perturbation of Air, Residual and Fuel.](image)
For example, the 50-90% burn duration is more sensitive than the 10-50% burn duration, which in turn, is more sensitive than the 0-10% burn duration. This behavior is a result of the dependence of the flame development with respect to the combustion phasing: when a flame has a fast start, the subsequent combustion occurs earlier and thus happens at a higher pressure and temperature environment. Because of the non-linear temperature dependence of the laminar flame speed, the burn duration for the later portion of the combustion is shortened more than the earlier part. Thus there is an increase in the sensitivity of the "later-burn" parameters to the perturbation.

The charge perturbations influence the combustion in two different ways: they change the burn rate, and they change the total charge energy. Air and residual perturbations primarily affect the burn rate (although they do influence the charge energy somewhat), while fuel perturbation significantly influence both the burn rate and the total charge energy. The charge energy affects the engine behavior because (i) it changes the energy output per cycle, and (ii) it changes the burned gas temperature, which affects the unburned gas temperature via end gas compression. The unburned gas temperature then affects laminar flame speed and the combustion process. Because of this multiplicity of effects, the sensitivity derivative of the engine output variables to the fuel perturbation is larger than 1 (in absolute value), and is substantially higher than the sensitivity to the air and residual perturbations.

It is observed that the burn parameters are less sensitive to the air perturbation than the residual gas perturbation. This observation may be explained by that when the air mass is incremented, the residual gas as a fraction of the total charge mass decreases. The laminar flame speed is a function of both the air equivalence ratio $\lambda$ and the residual gas fraction. For the air perturbation, the combined effect is that the flame speed actually increases slightly even though $\lambda$ increases. (See Ref.8 for numerical values. In the range of our experiment, $\lambda < 0.9$ and the flame speed at a fixed residual gas fraction is a monotonic decreasing function of $\lambda$.) Although this small increase in flame speed is more than offset by the reduction in adiabatic flame temperature, hence the end-gas compression, with the extra air dilution, the net effect is that the reduction in burn rate is less than the corresponding perturbation with residual gas.

### Extent of charge composition variations at idle and their contributions to the engine cycle variations

The COV of the engine parameters obtained from the experiments are shown in Table 3. The values for the composition variations were obtained by the least-square inverting of Eq. (3). The air mass, residual mass and fuel mass variations at idle were respectively 5.5, 4.4 and 0.64 percent.

The contribution of these variations to the total variations of the engine output parameters is shown in Fig. 5. Note that the plot is in terms of $\text{COV}^2$ since only the squared values are additive. The field variations (flow fluctuations and charge inhomogeneity) constitute a large part of the fluctuation of the burn rate, but the contribution to the GIMEP is about half (54%). Of the charge composition variations, the residual gas fluctuation contributed the most. In particular, it contributes to $\sim 1/3$ of the GIMEP variation ($\text{COV}^2$) which is the quantity of most interest. The air and fuel variations contribute to a much less amount: 7.5% and 4.6% respectively. It is noted that although the engine output parameters are most sensitive to fuel fluctuations (see sensitivity matrix in Table 2), the fuel amount does not vary much and the overall effect is not as large as the residual mass and air mass fluctuations.

### Table 3: Coefficient of variations for the engine parameters

<table>
<thead>
<tr>
<th>COV$_{y_i}$ (%)</th>
<th>COV$_{f_i}$ (%)</th>
<th>COV$_{r_i}$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>y$_1$=0-10% burn duration</td>
<td>9.0</td>
<td>7.5</td>
</tr>
<tr>
<td>y$_2$=10-50% burn duration</td>
<td>15.8</td>
<td>13.3</td>
</tr>
<tr>
<td>y$_3$=50-90% burn duration</td>
<td>22.4</td>
<td>20.3</td>
</tr>
</tbody>
</table>
| y$_4$=GIMEP | 9.1 | 7.1 | | |}

Fig. 5. The contributions of the fuel, residual and air mass fluctuations to the $\text{COV}^2$ of the engine output parameters. The contribution of the field variations (flow and charge inhomogeneity) is also shown.
CONCLUSIONS

A new technique was developed to assess the contributions of the charge composition fluctuations to SI engine cycle-to-cycle variations at idle. Through a set of perturbation experiments, the sensitivity of the engine output parameters to the variations of the charge composition was determined. Then the observed variations of the burned durations and Gross Indicated Mean Effective Pressure at idle were used to back-compute the charge composition variations. At idle, the variations of the air, residual and fuel masses respectively are 5.5, 4.4 and 0.64%. Of the composition variations, the residual gas mass contributes to ~1/3 of the GIMEP variations (in terms of the fraction of the COV²). The air and fuel fluctuations contribute much less: 7.5 and 4.6% respectively. The remaining 54% is attributed to the variations in the flow field and charge inhomogeneity.

NOMENCLATURE:

CCV Cycle-to-cycle Combustion Variations
COV Coefficient of variation
COV_f Coefficient of variation of the engine output variable y due to the field (flow and inhomogeneity) effects
GIMEP Gross Indicated Mean Effective Pressure
m_a Air mass in charge
m_f Fuel mass in charge
m_r Residual mass in charge
M In the perturbation experiment, there are M sequence each of N cycles. See definition of N.
MBT Maximum Brake Torque
N In the perturbation experiment, engine is perturbed 1 cycle and not perturbed for N-1 cycles in each sequence
x_i engine input variables
y_i engine output variables
λ Air/Fuel ratio relative to stoichiometric value

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REFERENCES


APPENDIX

Synchronous perturbation experiment signal-to-noise ratio

There are two sources of noise in the perturbation experiments: the instrument error and the natural fluctuation of the physical quantities to be measured. For the pressure measurement, the instrumental error is small compared to the natural fluctuation. Thus the detectability of the perturbation depends on the size of the resulting change of signal due to the perturbation compared to the size of the natural cycle-to-cycle fluctuation. If y_0 and y_i are the unperturbed and perturbed observations (e.g., the IMEP), the quantity we are interested in is \( \Delta y = \bar{y}_i - \bar{y}_0 \). The noise for M observations is then:

\[
\text{Noise} = \left[ \left( \left( \{ y_i - \bar{y}_i \}^2 \right) + \left( \{ y_0 - \bar{y}_0 \}^2 \right) \right)/2M \right]^{1/2} \quad (A1)
\]

Thus the signal to noise ratio is

\[
S/N = \Delta y \sqrt{M} \sqrt{\left( \{ y_i - \bar{y}_i \}^2 \right) + \left( \{ y_0 - \bar{y}_0 \}^2 \right)/2} \quad (A2)
\]

Note that all the quantities in Eq.(A1) and (A2) can be obtained from processing the data, hence the uncertainty of the measurement could be assessed. The error bars in Fig. 4 were determined in this manner.

Uncertainty in the slope for a forced fit through the origin

For a set of data points \((x_i, y_i)\) with error bars \(\sigma_i\), the least square fit to the line \(y = bx + a\) has the solution:

\[
b = \frac{\sum_i (x_i y_i/\sigma_i^2)}{\sum_i (x_i^2/\sigma_i^2)} \quad (A3)
\]

The uncertainty in b is:

\[
\sigma_b = \sqrt{\left[ \frac{\sum_i (x_i^2/\sigma_i^2)^2}{\sum_i \frac{1}{\sigma_i^2}} \right] - 1} \quad (A4)
\]

The uncertainty in \(\sigma_b\) is:

\[
\sigma_{\sigma_b} = \frac{1}{\sum_i \frac{1}{\sigma_i^2}} \quad (A5)
\]