Closed Loop Maximum Dilution Limit Control using In-Cylinder Ionization Signal

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ABSTRACT

This paper presents a combustion stability index derived from an in-cylinder ionization signal to control the engine maximum EGR limit. Different from the existing approaches that use the ionization signal values to gauge how much EGR was added during the combustion, the proposed method concentrates on using the ionization signal duration and its stochastic properties to evaluate the end result of EGR on combustion stability. When the duration index or indexes are higher than pre-determined values, the EGR limit is set. The dynamometer engine test results have shown promise for closed loop EGR control of spark ignition engines.

INTRODUCTION

Exhaust Gas Recirculation (EGR) is a well-known practice to improve engine fuel economy and reduce NOx emissions in certain operating regimes. For EGR, a portion of the exhaust gas is either recirculated back to intake manifold through a link between the intake and exhaust manifolds (external EGR) or trapped inside the cylinder through valve timings (internal EGR) for engines having a variable valve timing mechanism in order to mix with the fresh air for the next combustion event. Dilution of the fresh air-charge mixture with the inert exhaust gas lowers the combustion temperature and therefore suppresses the NOx formation.

Currently, the EGR setting for a given engine operating condition is generally pre-determined by extensive engine calibrations and implemented in real time utilizing the stored maps in an open loop control setting. The amount of EGR for each operating condition needs to be determined based on the emission and combustion stability considerations. The addition of EGR not only reduces NOx emissions, but also allows better fuel economy until excessive dilution starts to deteriorate the combustion quality. Generally speaking, as long as the combustion stability is within the desired operating range, the higher the EGR content, the better the fuel economy and the lower the NOx emission results for a steady state condition.

Combustion stability is often measured by the COV of IMEP (COVariance of Indicated Mean Effective Pressure). The lower the COV value, the better the combustion stability. However, there is no direct method to obtain the COV of IMEP for an operating condition without an in-cylinder pressure sensor. Therefore, the closed loop control of EGR, lean limit, idle spark timing, or any other stability related engine control, is challenging in the absence of an in-cylinder pressure measurement. Without having an online measurement, all the settings are pre-calibrated and generally applied as they are for all the engines of the same type during the engine's lifetime. For an SI (Spark Ignition) engine, when the combustion stability is beyond the desired stability limit, the crank angles for the combustion to reach a certain fraction of fuel burned or for the combustion to complete usually become greater compared to a normal combustion event. The standard deviations for the corresponding angles also get larger [1]. Furthermore, both the initial flame development (0-5% burned) and main combustion durations (10-90% burned) increase when EGR increases (see [2], among others). Therefore, the COV of IMEP is not the only indicator of combustion stability for an SI engine, how long the combustion process takes in crank angle degrees could also be an alternative indicator as well. However, the burn duration calculation still relies on an in-cylinder pressure measurement.

On the other hand, in-cylinder ionization signals have recently gained a lot of attention for combustion/engine control purposes. An example of a 300-cycle average ionization signal is shown in Figure 1. It usually consists of two peaks following the ignition pulse. The first peak represents the flame kernel growth and development around spark plug (chemical ionization), and the second peak is the re-ionization (thermal ionization) due to the in-cylinder temperature increase as a result of both pressure increase and flame development in the cylinder. The thermal ionization may disappear at operating conditions with light loads or high EGR rates. Nevertheless, an ionization signal provides a detailed fingerprint about the combustion process. It shows when a flame kernel is formed and propagates away from the spark plug gap, when the combustion is
accelerating rapidly, when the combustion reaches its peak burning rate, and when the combustion ends. Ionization signal has already been used to correlate with pressure signal [3], predict A/F ratio [4], detect misfire and knock [5] and control MBT timing in closed loop [6], among others. The ionization signal has also been utilized for closed loop knock and partial burn/misfire limit controls in a stochastic control framework with experimental verifications ([7], [8]).

![Figure 1: A typical cycle-average ionization signal](image)

There have been several attempts at using an ionization signal to predict the rate of EGR or correlate the ionization signal with combustion stability. In [9], the magnitude of the first peak, the location of the first peak, and the area under the first peak were correlated with the EGR percentage by linear relations. However, an EGR limit based on these correlations was not stated. In [10], the COV of ionization integral and the coefficient of the variation of the ionization integral were correlated with the COV of IMEP. However, the correlation was satisfactory only at low load conditions and failed to correlate at higher load conditions.

Both of these approaches heavily depend on the ionization signal magnitude instead of the critical events during the combustion process, such as the flame kernel formation, flame propagation, and the end of combustion. The ionization signal derived from the spark plug or ionization sensor has very close relationship with the combustion process. Although its magnitude depends on combustion mixture contents, spark plug types, and the details of associated electronics, its basic shape is merely an indicator of the present operating condition. A good combustion or a stable combustion requires these events to occur at specific locations in the crank angle domain. An unstable combustion will result in irregular ionization signal, delayed flame formation and propagation. However, the ionization signal magnitudes change at the above mentioned conditions and the changes could be significant at conditions where the combustion stability has not reached the unstable limit yet. Using the ionization magnitudes to define the combustion quality due to EGR rate, tremendous calibration efforts will still be needed to implement any closed-loop control strategy.

This paper proposes to use an ionization signal duration parameter defined by the crank angle duration from spark timing for its integral to reach a certain percentage and its associated stochastic properties as the combustion stability indicator for closed loop EGR control. Spark timing is also controlled online to maximize EGR in a multivariable control setting.

**COMBUSTION EFFICIENCY AND EMISSIONS WITH EGR**

Although, the effects of EGR on engine performance, emissions and combustion stability are quite well-known, this section provides a brief summary of an experimental EGR-spark sweep study as illustrated in Figure 2 to Figure 5 in order to formalize the EGR control objective. Specifically, data for these figures was from a 3L, V-6 engine operated at 1500 RPM with 2.62 bar BMEP for different EGR and spark timing settings. For each EGR level, throttle and fuel injection amount were adjusted to keep the engine torque output about the same level while air-to-fuel ratio is maintained at stoichiometric and spark timing was set to provide the maximum torque possible for that particular EGR setting (that is, Maximum Brake Torque (MBT) timing). The spark timing was then swept and several emissions and performance variables were recorded.

![Figure 2: NOx at MBT for different EGR settings](image)
It is observed that NOx formation heavily depends on EGR rate and spark timing as expected. As shown in Figure 2, both EGR and spark retard effectively decreases the NOx emissions by reducing the peak combustion pressure and flame temperature. Since MBT spark is the optimal spark setting for fuel economy, EGR is left as the most suitable remaining control variable for NOx emissions. The amount of reduction in NOx is almost 90% when spark is kept at MBT based on Figure 2 and Figure 3.

Moderate EGR also improves the fuel economy since adding EGR reduces the pressure difference between exhaust and intake manifolds and in turn the pumping loss at light loads. Reduction in combustion temperature also minimizes the heat loss through the walls and improves the thermal efficiency as shown in the BSFC (Brake Specific Fuel Consumption) plot of Figure 3. However, excessive EGR halts the normal combustion progress and hence increases the fuel consumption. HC formation is also adversely affected by EGR. As shown in Figure 3 and Figure 4, HC emission is almost doubled at 17% EGR when the spark is kept at MBT.

While EGR is increased, MBT spark timing moves in the advanced direction as illustrated in Figure 3. Since EGR reduces the combustion speed, the earlier initiation of combustion allows more time for combustion to progress and complete, which in turn provides more efficient combustion in terms of torque output.

In Figure 5, the covariance (COV) of IMEP was computed from pressure measurements and plotted against different EGR and spark timing settings. Holding spark timing constant and increasing EGR degrades the combustion stability by slowing down the combustion. For a given EGR level, it is shown that the relation between the spark timing and COV of IMEP is mostly a convex function similar to a typical spark/torque curve, i.e.; there is an optimal spark timing which would provide the minimum covariance and changing the spark in either direction would increase the covariance.
EGR LIMIT DETECTION FROM ION SIGNAL

Based on Figure 2, NOx emissions can be greatly reduced by increasing EGR amount. Fuel economy is also improved with EGR at partial load conditions. Therefore, maximizing EGR amount is a desirable objective unless the engine is operated at certain conditions such as full load or idle since EGR reduces maximum torque output and combustion stability. Towards this goal, this section presents how ionization signal can be utilized as a feedback signal to enable maximum dilution control.

Figure 6 to Figure 8 show in-cylinder ionization signals and their scaled integrals starting from the end of spark event (scaled for plotting purposes) for three EGR settings: no EGR, moderate EGR and excessive EGR. The use of ionization integration is considered as a fairly robust way of assessing the ionization and alternatively the combustion duration as originally introduced in [7]. Due to slow convergence of integral signal to its maximum, the duration at which a certain percentage of maximum (scaled) integral is achieved, provides a better measure for combustion stability comparison purposes. With no EGR, the ionization signal activity dies around 60 degrees from the end of spark event and 90% integration duration is reached slightly after 40 degrees. Note that the ionization signal does not include a significant thermal component (around 45 degrees from spark event) due to light load conditions and its shape is more irregular compared to an average mid-load ionization signal in Figure 1. With moderate EGR, the chemical ionization part starts slowing down slightly and 90% integral duration extends to a bit over 50 degrees as shown in Figure 7. However, the ionization signal (an individual cycle snapshot) is still similar to the no EGR case shown in Figure 6. The difference, if any, is in the range of variability of a typical ionization signal with no EGR. Figure 8 shows a sample ionization signal when the EGR is increased to 17%. Note that, the ionization signal stretches irregularly along a considerably wider window. The initial combustion delay (notice the first 30 degrees of ionization signal) is quite common with high EGR rates due to the effect of dilution on burn rate.

The variability of combustion with EGR can be visualized from Figure 9 to Figure 11, where the statistical distribution of 90% integral duration from 300 consecutive cycles under the same operating conditions is plotted. Without any EGR, the histogram of 90% integral duration behaves similar to a Gaussian random variable (Figure 9). With increased EGR, more and more cycles start having longer combustion durations as shown in Figure 10 and Figure 11 where the statistical distributions of 90% integral durations are plotted. Note that, partial burn and/or misfire cycles can be identified as the ones causing the distribution to skew towards the high combustion duration ranges.

It is also important to note that the variability of ion integral duration even without any EGR is high compared to a typical in-cylinder pressure parameter (for example, COV of IMEP).
ionization integral duration is more than the normalized covariance. This is mainly due to the fact the ionization signal is relatively higher variation than in-cylinder pressure signal since ionization signal provides local combustion information around the spark plug. However, an SD value of 6% is comparable to a 3% COV of IMEP number at least for this particular engine, which is usually regarded a good combustion stability limit value.

Figure 8: In-cylinder ionization signal with 17% EGR

Figure 9: Ionization duration statistics (0% EGR)

Figure 10: Ionization duration statistics (7% EGR)

Figure 11: Ionization duration statistics (17% EGR)

Figure 12 and Figure 13 illustrate how the statistics of 90% integral duration vary with EGR and spark timing (ST) along with the COV of IMEP computed from pressure signal for a given cylinder. A slow burn count parameter, which is basically the number of cycles with integral durations more than a threshold is included as well (threshold was selected as 50 degrees for these plots). In Figure 12, the ST was held at 32 DBTDC (Degrees Before Top Dead Center) while EGR is varied. At this spark timing, COV of IMEP reaches 3% with about 7-8% EGR, although more EGR could be allowed by advancing the spark timing as discussed before. Note that, the mean, standard deviation (SD) and slow burn count from ionization show qualitatively the same trend with the COV of IMEP number. Standard deviation of the
information both from ionization and pressure signals and spark timing has a convex shape. On the other hand, for a fixed spark, all the parameters increase with increased EGR. It’s also interesting to note that the difference between the stability numbers for two different EGR levels seem to decrease while spark is advanced. In other words, the stability plots of two different EGR levels start to converge with more spark advance to a certain EGR level and this behavior is observable from both pressure and ionization signal statistics.

The reason for difference with excessive spark advance is probably due to the fact that in-cylinder pressure signal is less sensitive to the first 10% MFB (Mass Fraction Burned) than the ionization signal. Normally, the flame development around spark plug gap is very sensitive to excessive spark advance, which effects ionization signal more than in-cylinder pressure signal. Nevertheless, the 3% COV of IMEP contour is quite similar with the 6% SD of ionization integral duration. Furthermore, along a constant stability contour, spark timing versus EGR curve keeps its convexity over the whole ST-EGR map. This feature is beneficial in controlling EGR and spark timing in a multivariable fashion to maximize EGR.

A contour plot of SD of ionization integral duration as a function of both spark timing and EGR is presented in Figure 14. Note that, despite the differences at high spark advance region, the stability levels shown in Figure 14 are quite comparable with those of Figure 5.
Figure 16: Combustion stability info comparison (cly. 5)

Figure 15 and Figure 16 show stability contour plots for two different cylinders of the engine operated at the same condition. Note that, the general shape of the contours differs from cylinder to cylinder. This is mainly due to differences of air and EGR distributions, fuel injection mismatches and the relative location of EGR loop with respect to individual cylinders. However, the shapes of the contours are quite similar for a given particular cylinder, independent of whether the stability information is obtained from pressure or ionization measurements.

MULTIVARIABLE EGR/SPARK TIMING CONTROL

This section details a multivariable EGR/ST control system for maximum dilution control. The overall system architecture is depicted in Figure 17. The ionization signals from each combustion event are sampled with one crank degree resolution and 90% ionization duration measure is computed from each combustion event. The standard deviation of the ionization duration is then computed online over a moving data buffer of a user-specified length. A closed loop control system uses this information to adjust the EGR amount and spark timing of the engine. Since new feedback information arrives at the end of each combustion event, the spark timing and EGR commands are updated at each firing event in an event-based actuation setting. A V-6 engine equipped with ionization coils and having a pneumatic EGR valve was run at a steady-state engine dyno. Spark and EGR were controlled by a rapid prototyping system whereas fuel and throttle position are set by the dyno controls. An adjustable vacuum regulator for the EGR valve is included in the set-up and controlled by the rapid prototyping system to actuate the pneumatic EGR valve.

Although the employed EGR actuation has inherent vacuum generation and large transport delays, which could be alleviated by alternative actuation mechanisms (such as a stepper motor), it is still considered to be sufficient for initial control system evaluations.

Based on the previous analysis, the main limiting factor for the EGR amount is the acceptable level of degradation in the combustion stability. If the stability limit is specified as 3% COV of IMEP as an example, the admissible operating regime is confined by the 3% covariance contour as shown in Figure 18 and the ideal operating point for the maximum dilution is the one with the maximum EGR rate along the 3% covariance contour. As discussed before, the ionization duration provides this stability information through ionization feedback and an ionization duration SD of 6-7% is found to be practically equivalent to 3% COV of IMEP by data analysis.

Figure 17: System Architecture

Figure 18: Control/Optimization Directions

The proposed multivariable EGR/ST control system is devised to regulate the stability output to a target level by adjusting EGR and spark timing simultaneously. With
no EGR, the MBT spark timing (36 DBTDC) is naturally inside the stability limit contour as shown in Figure 18. An EGR increase with fixed spark timing subject to stability limit clearly would not provide the maximum possible dilution. Instead, an adjustment of spark timing and EGR along a direction depicted by the regulation arrow in Figure 18 would provide a response close to the ideal operating point. The optimization arrow in Figure 18 illustrates an additional degree of freedom on the system for seeking purposes.

The proposed EGR and spark timing control block diagram is shown in Figure 19. The standard deviation of the ionization duration is computed in the SD calculation block. The EGR stability target is an acceptable variation of this parameter based on the combustion stability requirements. For regulation purpose, spark and EGR inputs are used cooperatively. The main regulation feedback loop for EGR is structured as a PI controller with a feed-forward term depending on the operating point (EGR regulation loop) and the nominal spark input is adjusted based on the EGR input through a nonlinear map (spark regulation loop). Note that, this nonlinear function quantifies the cooperative control gradient for regulation as shown in Figure 18 and provides a spark advance correction as a function of EGR input. Since the EGR dynamics are much slower than spark, a lag term is also inserted to the spark regulation loop to be able to match the dynamic responses of spark and EGR (not shown in Figure 19). Without this delay term, spark would be advanced abruptly when EGR input starts to increase. However, in this case NOx would increase right away due to immediate spark advance since spark becomes effective at the next combustion, whereas it takes time for EGR to be effective.

The proposed maximum dilution control system has been tested in an engine dyno using a V-6 engine equipped with ionization feedback coils. A rapid prototyping control system was used for control strategy implementation. During the closed loop control operation, engine was initially brought to 1500 RPM and 2.62 bar BMEP with no EGR and the same throttle angle and fuel pulse-widths were used while EGR and spark timing were adjusted by the proposed control system. Note that the addition of EGR is going to affect the air loop and therefore, throttle and fuel also need to be adjusted such that the engine is operated at the same BMEP level with stoichiometric air-to-fuel ratio.

To characterize the system for control calibration purposes, the response of the system to a step EGR command voltage is shown in Figure 20. Based on steady state data analysis, the applied EGR voltage level generates an EGR amount about 14%. However,
at this voltage level, SD of 90% ionization duration increases to around 12% with fixed spark timing, which exceeds the desired combustion stability level. Figure 21 shows the system behavior when an additional step change was applied to spark timing in the advanced direction to illustrate the coupling between spark timing and EGR in terms of combustion stability. Note that, the SD of 90% ionization duration converges to around 6 to 7% due to the spark advance accompanying the EGR increase. The dynamic behavior of the combustion stability to responses also provides insight about the current EGR setup. The rising and falling transient response times of feedback parameter against step inputs are observed to be slightly more than 10 seconds based on Figure 20 and Figure 21, which limits closed loop system bandwidth. The large delay is mainly due to the EGR pneumatic valve actuation mechanism. Variations on the feedback parameter are also noticeable even at fixed EGR/ST setting due to combustion variability.

**CONCLUSION**

A combustion stability indicator derived from ionization signal is proposed for EGR limit detection and control. Based on experimental data, it is shown that EGR limit can also be regulated from the ionization signal. Some preliminary control performance are also illustrated where the EGR rate and spark timing are adjusted in a closed loop setting based on the measured ionization signal to maximize EGR as long as combustion stability is preserved.

**REFERENCES**

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DEFINITIONS, ACRONYMS, ABBREVIATIONS

**SI:** Spark Ignition  
**IMEP:** Indicated Mean Effective Pressure  
**BMEP:** Brake Mean Effective Pressure  
**COV:** Covariance  
**EGR:** Exhaust Gas Recirculation  
**MBT:** Maximum Brake Torque

**BSFC:** Brake Specific Fuel Consumption  
**MAP:** Manifold Absolute Pressure  
**PDF:** Probability Density Function  
**RPM:** Revolutions Per Minute  
**DBTDC:** Degrees Before Top Dead Center  
**PI:** Proportional and Integral  
**ST:** Spark Timing  
**SD:** Standard Deviation