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Statistical Engine Knock Control

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Abstract: A new statistical concept of the knock control of a spark ignition automotive engine is proposed. The control aim is associated with the statistical hypothesis test which compares the threshold value to the average value of the maximal amplitude of the knock sensor signal at a given frequency. Control algorithm which is used for minimization of the regulation error realizes a simple count-up-count-down logic. A new adaptation algorithm for the knock detection threshold is also developed. Confidence interval method is used as the basis for adaptation. A simple statistical model which includes generation of the amplitude signals, a threshold value determination and a knock sound model is developed for evaluation of the control concept.

Keywords: Engine Knock, Six Sigma, Threshold Adaptation, Spark Ignition Engines

1. INTRODUCTION

Engine knock in a spark ignition automotive engine results in restriction of the ignition advance and is the main limitation to the torque output performance and a fuel economy improvement. Statistical knock control method proposed in this paper introduces a new concept of the engine knock control where the achievement of the control aim is associated with the rejection of the null statistical hypothesis that the average value of the maximal amplitude of a knock sensor signal at a certain frequency is equal to the target value.

The performance of the knock sensor signal and hence the average value of the maximal amplitude at a certain frequency and its standard deviation might change with time due to aging of engine components. Erroneous knock detection might occur if the average value of the maximal amplitude and standard deviation increase and the threshold value is not updated. Therefore the engine knock threshold value should be updated if the average value of the maximal amplitude or standard deviation deviate from the pre-calibrated values. Main idea of adaptation is a presentation of the knock detection threshold using a confidence interval and holding the same significance level for new and aged engines.

This paper also develops a simple statistical model for evaluation of the control concept. The model consists of three parts: generation of the amplitude signals, a threshold value determination and a knock sound model. A Volvo six cylinder prototype engine equipped with cylinder pressure and block vibration sensors was used in the experiments. External microphone was used for the knock sound measurements.

2. STATISTICAL MODEL OF THE KNOCK SENSOR

Statistical models for the knock sensor and microphone signals are designed via calculation of the frequency contents of the signals using trigonometric interpolation method. The distribution of the maximal amplitudes of the knock sensor signal at the most suitable frequency for knock detection is close to the lognormal distribution (it has a longer tail on the right-hand side). Therefore the maximal amplitude signal at a given frequency is generated using lognormal random numbers with the average value and standard deviation calculated using trigonometric interpolation method (Zhu *et. al.* [2005]).

The model is completed by assigning a threshold value for the maximal amplitude signal of the knock sensor. If a maximal amplitude of the knock sensor signal exceeds this threshold value the knock is judged to occur. This threshold value is the function of ignition timing.

3. ENGINE KNOCK CONTROL

Suppose that the amplitude of the knock sensor signal is measured at a certain frequency as an output of the band-pass filter and the maximum of the amplitude is calculated over the knock window. Since maximal amplitudes follow lognormal distribution the logarithm of the maximal amplitude signal is taken, converting the data to normally distributed data. Maximal amplitude signal A_k, (k is the cycle number) which is normally distributed is the input for the control algorithm.

Define the following regulation variable

$$T_k = \frac{(A_t - \overline{A}_k)\sqrt{w-1}}{s_k} \tag{1}$$

where $\overline{A}_k = \dfrac{1}{w} \sum\limits_{i=k-(w-1)}^{i=k} A_i$, is the value of the maximal amplitude averaged over the window of a size w, s_k is a standard deviation given by $s_k = \sqrt{\dfrac{1}{w-1} \sum\limits_{i=k-(w-1)}^{i=k} (A_i - \overline{A}_k)^2}$, A_t is a knock threshold value, T_k is a regulation variable, which defines the

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[1] This work was done within the Volvo Six Sigma programme

difference between A_t and $\overline{A}_k$.

The achievement of the control aim is associated with the rejection of the null statistical hypothesis H_0 that the average value of the amplitude is equal to the target value. The null hypothesis is tested against the alternative statistical hypothesis H_A that the average value of the amplitude is smaller than the target value, i.e.,

$$H_0 : A_t = \overline{A} \tag{2}$$

$$H_A : A_t > \overline{A} \tag{3}$$

The control aim is to find the ignition timing such that

$$T_k \rightarrow T_d \quad as \quad k \rightarrow \infty \tag{4}$$

where T_d is the desired value of the statistic T_k, $T_d = T_t + \Delta$, where T_t is the value in the Student distribution look-up table $T_{1-2\alpha,w-1}$ for degrees of freedom $w-1$, and Δ is small positive number. If $T_k \rightarrow T_d$ as $k \rightarrow \infty$ then

$$\frac{(A_t - \overline{A}_k)\sqrt{w-1}}{s_k} > T_t \quad as \quad k \rightarrow \infty \tag{5}$$

The achievement of the control aim (5) guarantees that asymptotically H_0 is rejected in favor of H_A with a certain significance level α (specified by the designer). Desired value of the statistic T_d and α-risk should be chosen by taking into account customer related data.

The ignition timing is defined according to the conventional knock controller which is widely used in industry and realizes count-up/down logic as follows

$$I_k = \begin{cases} I_{k-1} - \delta_{down} & if \quad e_k < 0 \\ I_{k-1} + \delta_{up} & if \quad e_k > 0 \end{cases}$$

$$e_k = T_k - T_d \tag{6}$$

where e_k is the regulation error, I_k is the ignition timing, δ_{down} and δ_{up} are positive constants (count down/count up gains).

In the case of the knock occurrence the amplitude exceeds the threshold value and therefore the ignition timing should immediately be retarded.

4. ADAPTATION OF THE THRESHOLD VALUE

The knock detection threshold should be updated for aged engines preventing erroneous knock detection.

First, pre-calibrated threshold value at a certain ignition timing is presented using confidence interval as follows:

$$A_t = \overline{A} + t_{\alpha_t/2,n-1} s \sqrt{\frac{n+1}{n}} \tag{7}$$

where $\overline{A}$ and s are average amplitude and standard deviation respectively, n is the sample size, $t_{\alpha_t/2,n-1}$ is the value taken from the Student distribution look-up table for a significance level α_t and degrees of freedom $n-1$, A_t is the threshold value. Equation (7) is resolved with respect to the significance level α_t for each ignition timing.

If the averaged value $\overline{A}$ or standard deviation s deviate from the pre-calibrated values the knock threshold value should be adapted. New values of the detection threshold are calculated as follows using the significance level α_t

$$A_{tim} = \overline{A}_{im} + t_{\alpha_t/2,w_t-1} s_{im} \sqrt{\frac{w_t+1}{w_t}} \tag{8}$$

where $\overline{A}_{im}$ and s_{im} are the average value and the standard deviation calculated over window of a size w_t, $i = I_1, I_2, ...$ is the ignition angle, A_{tim} are newly calculated values of the threshold. The difference ε_i between pre-calibrated A_{ti} and new values A_{tim} of the knock threshold $\varepsilon_i = A_{ti} - A_{tim}$ is approximated as follows:

$$\hat{\varepsilon} = \varphi^T \theta \tag{9}$$

$$\varphi = [1 \quad I \quad I^2 \quad I^3 \quad ...]^T \tag{10}$$

$$\theta = [\theta_0 \quad \theta_1 \quad \theta_2 \quad \theta_3 \quad ...]^T \tag{11}$$

where $\hat{\varepsilon}$ is a polynomial approximation of ε_i, I is the ignition angle, θ_j, $j = 0, 1, ...$ The model is constructed using a step-wise regression method, where the contribution of each term θ_0, $\theta_1 I$, $\theta_2 I^2$ is reviewed, to ensure that it remains statistically significant, using the following variance

$$V_j = \frac{1}{(N-j-1)} \sum_{i=1}^{N} (\varepsilon_i - \theta_0 - \theta_1 I_i - \theta_2 I_i^2 - \theta_3 I_i^3 - ... - \theta_j I_i^j)^2 \tag{12}$$

where j is the order of the polynomial and N is the number of measured points. The process is stopped if the variance V_{j+1} does not get significantly smaller than the variance V_j. The variances V_{j+1} and V_j are compared using the *Test for Equal Variances* (Picard, [2002]). The coefficients (11) are calculated recursively using a least-squares method (Stotsky [2007]).

As soon as the coefficients and the optimal order of the polynomial are found that defines the model $\hat{\varepsilon}$, the values of the compensation term are calculated and added to the values in the nodes of the pre-calibrated look-up table of the threshold.

5. CONCLUSION

New statistical knock control concept that allows the connection of the control algorithm parameters with the probability of the knock occurrence and customer related data is proposed and verified by simulations. The robustness of the concept is guaranteed via a suitable adaptation of the knock detection threshold. Statistical simulation model which can be used for testing different control concepts and calibration of control algorithms was developed.

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