EXHAUST GAS RECIRCULATION STRATEGY IN THE HYDROGEN SI ENGINE

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Abstract

It is known that Exhaust Gas Recirculation (EGR) can be successfully applied not only for reducing NOx content in exhaust gases but also for reduction of combustion knock in SI engines. From this point of view, EGR can be particularly effective for knock elimination in the hydrogen reciprocating engine. Additionally with the application of EGR, the H2-air combustion can be maintained at the stoichiometric ratio enabling highly efficient NOx reduction in catalytic converters. In this paper a strategy of estimating EGR for the naturally aspirated, hydrogen fuelled engine is explained. On the basis of this strategy, the closed loop control system of the EGR was built and was implemented for the single cylinder CFR engine. There is also an outline of the test bed and several examples of in-cylinder pressure courses recorded under various EGR percentages. Next, the impact of EGR on combustion knock in the hydrogen fuelled engine is presented. Finally, conclusions concerning EGR application for hydrogen combustion in the IC engine are presented.

EGR calculation and control scheme, main diagram of EGR calculation, subroutine (Sub-block) for calculating the molecular weight of EGR gases, in-cylinder pressure traces for several EGR levels during hydrogen combustion in the CFR engine, the fluctuating component of in-cylinder pressure during hydrogen combustion with several levels of EGR, peak pressure of fluctuation component of in-cylinder pressure vs. EGR percentage are presented in the paper

***Keywords:** internal combustion engine, hydrogen, exhaust gas recirculation (EGR)*

1. Introduction

The investigation presented in this paper concerns strategy of exhaust gas recirculation for a hydrogen port injected single cylinder engine. The EGR ratio, defined further as the Mass Fraction of EGR (Eq.3), is calculated online on the basis of oxygen content in exhaust gases and oxygen content in the intake manifold. Both oxygen concentrations are measured by wide-band electrochemical lambda sensors (UEGO sensor) (Figure 1).

With respect to Heywood [1], the EGR percentage ratio is defined as the mass of EGR upon the mass m_i delivered to the cylinder from the intake (Eq.1).

$$EGR(\%) = \frac{m_{EGR}}{m_i} \cdot 100 . \tag{1}$$

There is also the alternative definition of percent EGR provided by [1].

$$EGR^{*}(\%) = \frac{m_{EGR}}{m_{air} + m_{fuel}} \cdot 100. \tag{2}$$

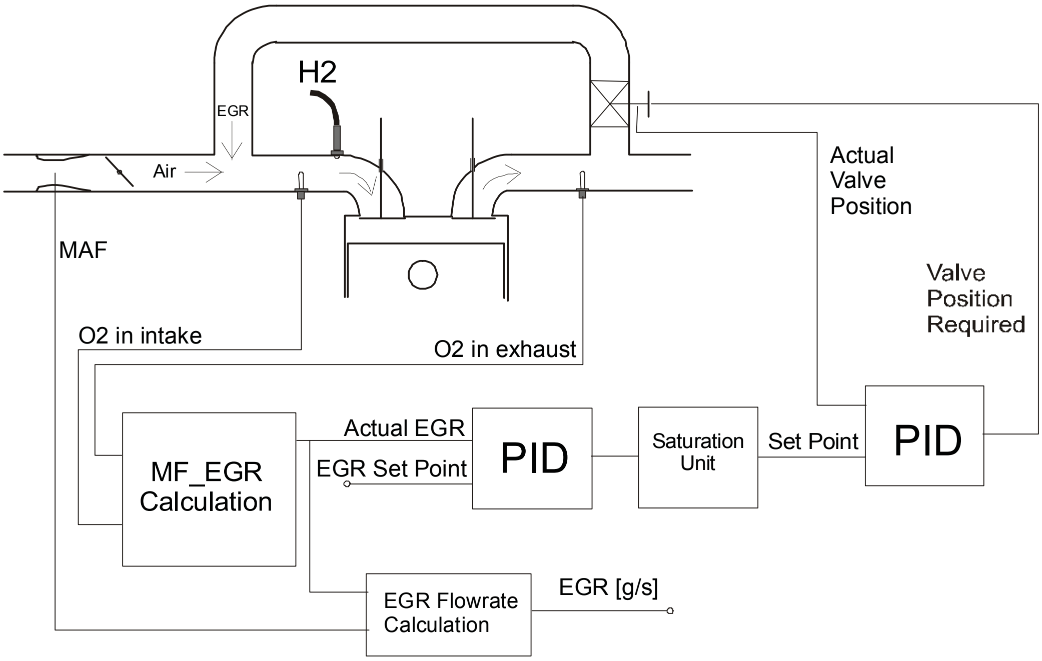

Fig. 1. EGR calculation and control scheme

It is assumed that the m_i charge consists of only the exhaust gases provided by recirculation and the mass of ambient air, as is the case for the gases in the intake manifold before hydrogen injection which provides additional dilution of oxygen. Taking this assumption into account, we introduce Mass Fraction of EGR (MF_{EGR}), which is defined by the following Eq. 3, and we can omit hydrogen dilution effect on oxygen.

$$MF_{EGR} = \frac{M_{EGR}}{M_{EGR} + M_{Air}}. \tag{3}$$

This is important because hydrogen injector is placed in the manifold as close to the inlet valve as possible to reduce the potential of backfires and thus there is insufficient space for installing the UEGO sensor. In addition the UEGO sensor may also induce combustion in the hydrogen rich intake gases.

The MF_{EGR} can be easily converted to $EGR(\%)$ or to $EGR^{*}(\%)$ using through the following:

$$EGR^{*}(\%) = \frac{MF_{EGR}}{1 - MF_{EGR}} \cdot \frac{1}{1 + \frac{1}{34.5 \cdot \lambda}}, \tag{4}$$

$$\frac{EGR(\%)}{100} = \frac{EGR^{*}(\%)}{100 + EGR^{*}(\%)}, \tag{5}$$

where:

λ is the relative air/fuel ratio as measured by the UEGO sensor in the exhaust manifold.

2. Test-bed Description

The engine used for this research is a single cylinder CFR (Cooperative Fuels Research) engine manufactured by the Waukesha Motor Company. The engine was chosen for its versatility and robustness of construction which is important because of the intended study of combustion knock.

Engine control and monitoring was performed using a target-based rapid-prototyping system [2] with the electronic sensors and actuators installed on the engine. Sensors monitored flow rate, pressure, and temperature of the working fluid at various regions of the engine along with engine position determined from a sensor on the crankshaft. Sensors included MAF, manifold pressure (MAP), UEGO, and crank position sensor. Electronic actuators included a digital ignition coil, throttle, EGR valve, and two port fuel injectors for both liquid (gasoline) and gaseous (hydrogen) fuels.

Data from the in-cylinder pressure and engine mounted piezoelectric accelerometer along with an engine crank position sensor were acquired with a National Instruments BN-2111 analog to digital converter. Data for 300 engine cycles at 100 kSamples/second-channel were recorded for off-line analysis.

3. EGR model for the Hydrogen CFR Engine

To calculate the EGR percentage in the intake we should determine as follows: the oxygen molar balance in the plenum

$$n_{O2,Tot} = n_{O2,EGR} + n_{O2,Air} . \tag{6}$$

Next, denote:

X oxygen content in the exhaust gases,
Y oxygen content in the intake before hydrogen injector,
20.9 oxygen content in the ambient air.

As molar fractions are the same as volume fractions, we obtain:

$$\frac{Y}{100} n_{Tot} = \frac{X}{100} n_{EGR} + \frac{20.9}{100} n_{Air} , \tag{7}$$

$$Y \cdot n_{Tot} = X \cdot n_{EGR} + 20.9 \cdot n_{Air} , \tag{8}$$

n_{Tot} moles after premixing EGR with air,
n_{EGR} moles of EGR gases,
n_{Air}moles of air,

$$n_{Tot} = \frac{M_{Tot}}{MW_{Tot}} , \tag{9}$$

$$n_{EGR} = \frac{M_{EGR}}{MW_{EGR}} , \tag{10}$$

$$n_{Air} = \frac{M_{Air}}{MW_{Air}} , \tag{11}$$

where, the molecular weight of air is constant (MW_{Air}=28.97kg/kmol).

Next, substitute to obtain:

$$Y\frac{M_{Tot}}{MW_{Tot}} = X\frac{M_{EGR}}{MW_{EGR}} + 20.9\frac{M_{Air}}{28.97}\,. \tag{12}$$

Now after applying the mass balance:

$$M_{Tot} = M_{EGR} + M_{Air} \tag{13}$$

and rearranging Eq. 12, yields:

$$\frac{M_{EGR}}{M_{Air}} = \frac{\dfrac{20.9}{28.97} - \dfrac{Y}{MW_{Tot}}}{\dfrac{Y}{MW_{Tot}} - \dfrac{X}{MW_{EGR}}} = \beta\,. \tag{14}$$

So, the EGR Mass Fraction MF_{EGR} can be expressed as:

$$MF_{EGR} = \frac{M_{EGR}}{M_{Tot}} = \frac{M_{EGR}}{M_{EGR} + M_{Air}} = \frac{1}{1 + \dfrac{M_{Air}}{M_{EGR}}} = \frac{1}{1 + \dfrac{1}{\beta}} = \frac{\beta}{\beta + 1}\,. \tag{15}$$

For calculations, we need *MW_{Tot}* and *MW_{EGR}*. For *MW_{Tot}* we can determine this from an overall balance of moles in the intake before the hydrogen injector:

$$n_{Tot} = n_{EGR} + n_{Air}, \tag{16}$$

$$\frac{M_{Tot}}{MW_{Tot}} = \frac{M_{EGR}}{MW_{EGR}} + \frac{M_{Air}}{28.97}\,. \tag{17}$$

We substitute:

$$M_{EGR} = MF_{EGR} \cdot M_{Tot}\,, \tag{18}$$

$$M_{Air} = \left(1 - MF_{EGR}\right) \cdot M_{Tot} \tag{19}$$

and finally obtain:

$$MW_{Tot} = \frac{1}{\dfrac{MF_{EGR}}{MW_{EGR}} + \dfrac{1 - MF_{EGR}}{28.97}}\,. \tag{20}$$

To solve these formulas (Equations 14, 15, 20) we can apply an iterative calculation. With this and after 4 steps of iteration cycles, we obtain an appropriate value of *MF_{EGR}* with relative error less than 0.5% in comparison to the exact solution.

MW_{EGR} is calculated from the reaction of hydrogen combustion in compliance with equations as follows. For hydrogen combustion with excess air:

$$2H_2 + \lambda(O_2 + 3.78N_2) = 2H_2O + (\lambda - 1)O_2 + \lambda\, 3.78N_2\,. \tag{21}$$

Derive molar fractions for the each product species:

Oxygen:
$$\chi_{O2} = \frac{\lambda - 1}{2 + \lambda - 1 + 3.78 \cdot \lambda} = \frac{\lambda - 1}{1 + 4.78 \cdot \lambda}\,. \tag{22}$$

Water:
$$\chi_{H2O} = \frac{2}{2 + \lambda - 1 + 3.78 \cdot \lambda} = \frac{2}{1 + 4.78 \cdot \lambda}\,. \tag{23}$$

Nitrogen:
$$\chi_{N2} = \frac{3.78 \cdot \lambda}{2 + \lambda - 1 + 3.78 \cdot \lambda} = \frac{3.78 \cdot \lambda}{1 + 4.78 \cdot \lambda} . \tag{24}$$

Thus MW_{EGR} yields:

$$MW_{EGR} = \chi_{O2} MW_{O2} + \chi_{H2O} MW_{H2O} + \chi_{N2} MW_{N2} , \tag{25}$$

$$MW_{EGR} = \frac{4 + 137.84 \cdot \lambda}{1 + 4.78 \cdot \lambda} . \tag{26}$$

4. Modeling Electronic Control Unit (ECU)

Developing the software for the ECU was performed in MathWorks Simulink environment. In Figure 2, the main Simulink based algorithm for online MF_{EGR} calculation is presented. In this figure there are 3 main blocks for calculating (1) molecular weight of EGR gases, (2) molecular weight of total combustible mixture and (3) beta. To provide iterative calculations, a delay element is placed in a feedback line linking the output with the block for MW_{Tot} determination. As a further example, Figure 3 shows the sub-block for calculating the molecular weight of the EGR gases.

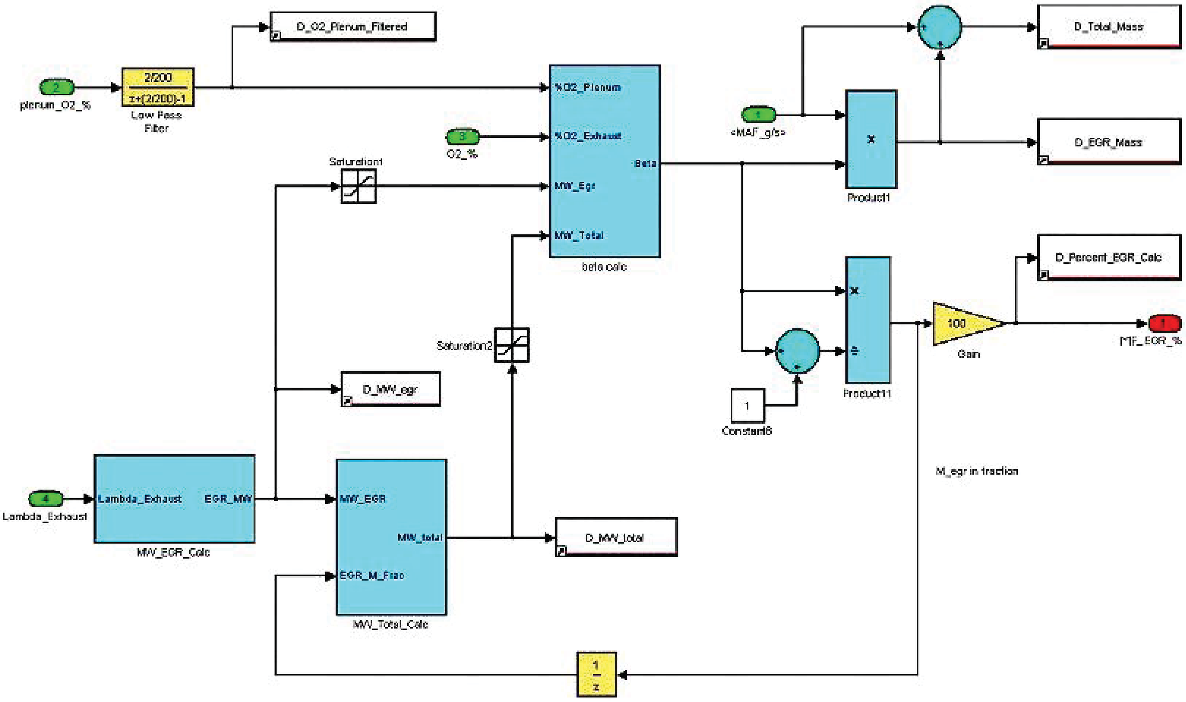

Fig. 2. Main diagram of EGR calculation

5. Results

There are four in-cylinder pressure traces presented as examples of different MF_{EGR} ratios:
0, 0.113, 0.225 and 0.306 which correspond to EGR(%) of 0%, 11%, 22% and 30% respectively.

These tests were done for parameters as follows:

- Engine speed = 900 rpm,
- Compression ratio = 8,
- Spark timing 5° before TDC,
- Combustible mixture at stoichiometric ratio ($\lambda = 1$),
- Hydrogen dose = constant (8 ms of injection duration at 4.8 bar).

In Figure 4 these pressure traces for the four levels of EGR, recorded under these conditions, are presented. Next, the pressure traces were filtered using a high pass digital Butterworth filter with cut-off frequency of 4 kHz. Figure 5 presents the high-frequency or fluctuation component of the in-cylinder pressure for the EGR percentages using the high-pass filtered pressure signals.

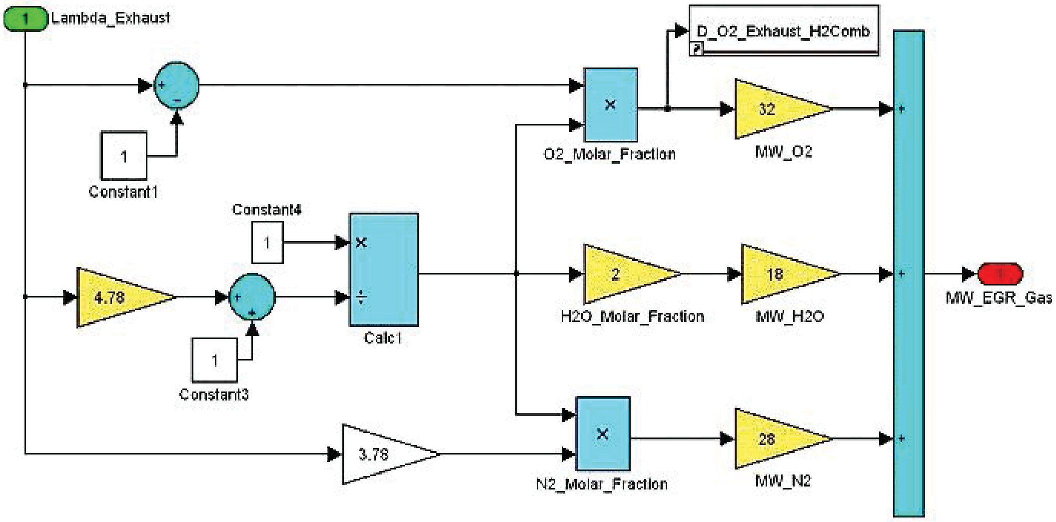

Fig. 3. Subroutine (Sub-block) for calculating the molecular weight of EGR gases

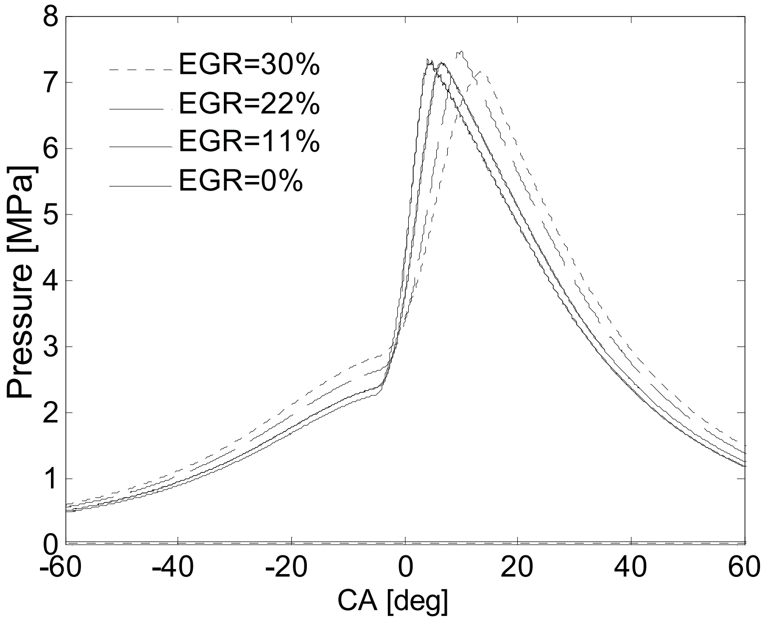

Fig. 4. In-cylinder pressure traces for several EGR levels during hydrogen combustion in the CFR engine

As can be seen in Figure 5, the pressure pulsations express the combustion knock intensity as the result of combustion of hydrogen in the engine cylinder as the EGR level is changed. It is also noticed that rapid combustion knock indicted by an increase in pressure starts almost at the same time when combustion process is initiated through ignition at the lower levels of EGR, this is more extensively examined by Szwaja et al. [4]. For evaluating the combustion knock level there are several metrics for expressing its intensity presented by J.Naber et al. [3]. Peak Pressure (PP) is one of the metrics for evaluating the effect of knocking, and it is also applied here. It is defined as the maximal absolute amplitude of the fluctuating pressure pulsations in an engine position window. Figure 6 shows PP metrics, determined from the pressure traces in Figure 5, vs EGR percentage for stoichiometric hydrogen combustion.

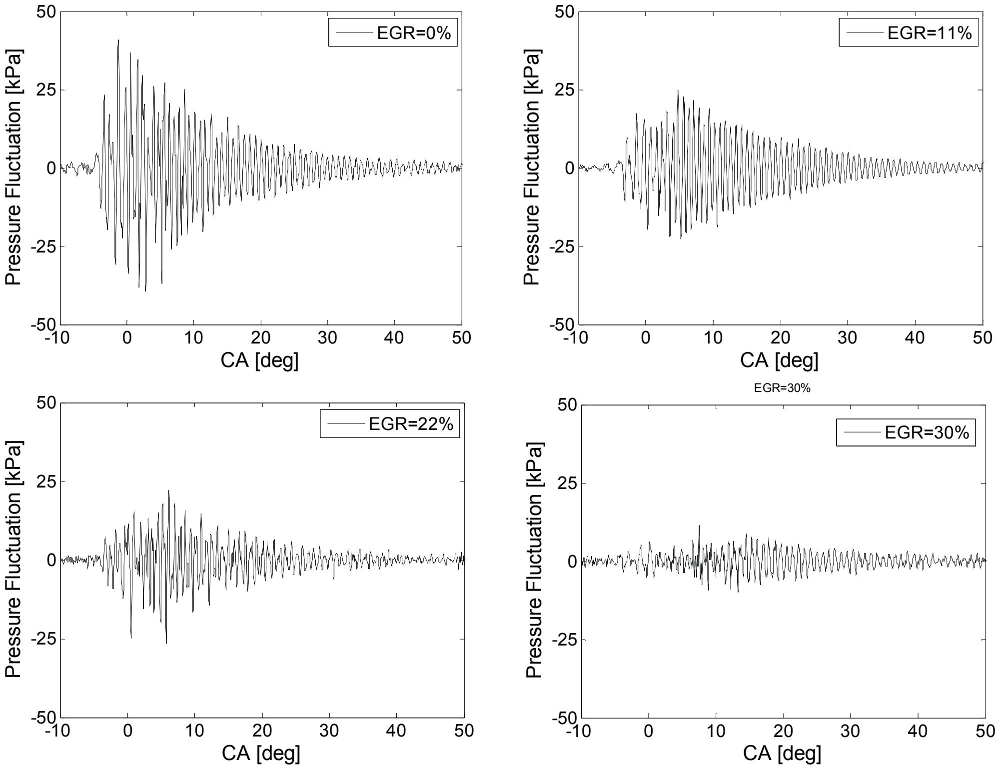

Fig. 5. The fluctuating component of in-cylinder pressure during hydrogen combustion with several levels of EGR

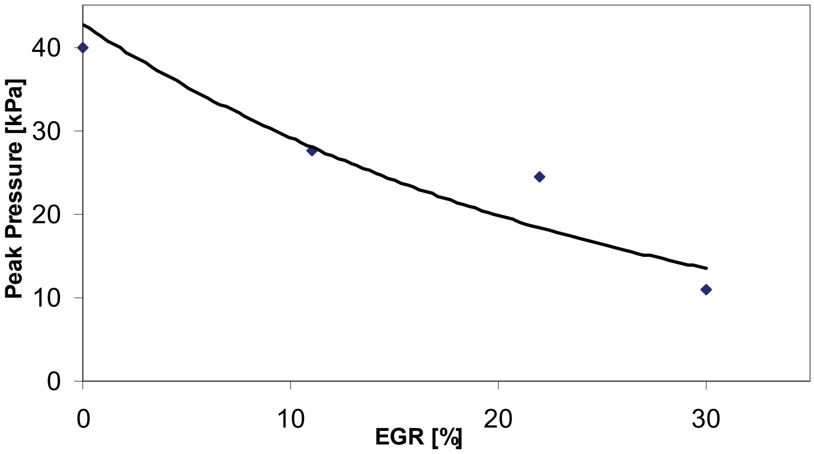

Figure 6. Peak pressure of fluctuation component of in-cylinder pressure vs EGR percentage

6. Conclusions

1. The model of the EGR ratio as a function of oxygen content in intake and exhaust as measured by two UEGO sensors provides a real-time measure with good accuracy for online determination of EGR.
2. The model for EGR ratio can be applied to enable fast and stable feedback for closed-loop-control of a proportional valve to maintain stable EGR levels over a wide range for research purposes.
3. High frequency in-cylinder pressure fluctuactions, generated by improper combustion processes causing knocking, decrease when EGR ratio increases for the conditions examined.
4. Combustion knock intensity expressed by the maximum peak of the fluctuating component of the in-cylinder pressure shows a strong negative correlation with the EGR ratio for stoichiometric hydrogen combustion under the conditions examined.

Acknowledgements

We would like to acknowledge the support of Michigan Technological University's Mechanical Engineering - Engineering Mechanics Department and the Research Office for support of this work.

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