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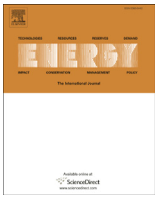

Auto-ignition control in turbocharged internal combustion engines operating with gaseous fuels

Jorge Duarte, Germán Amador, Jesus Garcia, Armando Fontalvo, Ricardo Vasquez Padilla [1], Marco Sanjuan, Arturo Gonzalez Quiroga*

Department of Mechanical Engineering, Universidad del Norte, Km 5 Via Antigua Pto Colombia, Barranquilla, Colombia

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ABSTRACT

Control strategies for auto-ignition control in turbocharged internal combustion engines operating with gaseous fuels are presented. Ambient temperature and ambient pressure are considered as the disturbing variables. A thermodynamic model for predicting temperature at the ignition point is developed, adjusted and validated with a large experimental data-set from high power turbocharged engines. Based on this model, the performance of feedback and feedforward auto-ignition control strategies is explored. A robustness and fragility analysis for the Feedback control strategies is presented. The feedforward control strategy showed the best performance however its implementation entails adding a sensor and new control logic. The proposed control strategies and the proposed thermodynamic model are useful tools for increasing the range of application of gaseous fuels with low methane number while ensuring a safe running in internal combustion engines.

1. Introduction

Knock phenomenon is a real barrier for increasing efficiency and lowering maintenance costs of spark ignition engines. Knocking can cause severe damages in engines, especially in mechanical parts like piston, valves and cylinder head [1]. Nowadays, it is widely accepted that knock is due to auto-ignition in the end gas region of the combustion chamber [2]. One important issue for knocking occurrence in turbocharged internal combustion engines operating with natural gas is the effect of ambient temperature on the auto-ignition tendency of the fuel. Depending on local atmospheric conditions, manual derating of the engine is mandatory to avoid knocking [3]. Actions such as power reduction and spark advance have been implemented to avoid knocking condition [4]. In this context, this paper presents a robust control strategy, implemented in a feedback control loop, for auto-ignition control in turbocharged internal combustion engines operating with gaseous fuels. The capabilities for adapting engine operation to changes in ambient temperature while maximizing output power are explored. The performance of the robust control strategy is compared to a feedforward control strategy.

Some previous research in knocking prevention has been focused on the effect of fuel composition and engine operation mode. It was found that adding inert gases (N_2 and CO_2) causes a significant increase in the knock-limited spark timing (KLST) [5] while thermal efficiency and emissions are slightly affected. It has been reported that mixing fuels with different auto-ignition tendencies (natural gas and heptane) can be used for knocking control [6]. It has also been noted that auto-ignition is promoted by increments in residual gas temperatures and residual gas flow rates [7].

To prevent knocking, it has been proposed to adapt engine tuning according to fuel composition [2]. Authors propose a knocking protection map to set engine parameters based on the results of a computational combustion simulator. It has been proposed using specific combustion chamber depending on fuel, to delay knocking appearance [8]. According to [8], a baseline-type combustion chamber fueled with methanol allows operating with lower knocking intensity without significantly affecting thermal efficiency. Adding hydrogen to natural gas has been highlighted as a way to get a lean combustion extension [9]. Adding oxygen to the

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* Corresponding author. Tel.: +57 5 3509272; fax: +57 5 3509255.
E-mail addresses: jduartee@uninorte.edu.co (J. Duarte), gjamador@uninorte.edu.co (G. Amador), jesusmg@uninorte.edu.co (J. Garcia), aefontalvo@uninorte.edu.co (A. Fontalvo), Ricardo.Vasquezpadilla@csiro.au (R. Vasquez Padilla), msanjuan@uninorte.edu.co (M. Sanjuan), arturoq@uninorte.edu.co, arturo.gonzalez.quiroga@gmail.com (A. Gonzalez Quiroga).
[1] CSIRO Energy Technologies, PO Box 330 Newcastle, NSW 2300, Australia. Tel.: +61 249606293.

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Nomenclature

BTDC	before top dead center
$C(s)$	transfer function
C_p	specific heat capacity [kJ/kgK]
CO	controller output
FFC	feedforward control
FFTF	feedforward transfer function
FI	fragility index
FOPDT	first order plus dead time
IAE	integrated absolute error
K_c	controller gain [%CO/%TO]
KLST	knock-limited spark timing
M_s	process transfer function
M_s	sensitivity
MN	methane number
MVM	mean value model
n_T	polytropic coefficient
NO_x	nitride oxides
p	pressure [kPa]
R	crank-connection rod ratio
r_c	compression ratio
T	temperature [K]
t	time [s]
TO	transmitter output
u	error
V	volume [m^3]

Greek symbols

β	weight factor
λ	lambda tune
ω	signal frequency [rad/s]
ρ	density [kg/m^3]
τ_d	derivative time [*s*]
τ_i	integral time [s]
θ	crank angle [rad]

Subscripts

0	ambient conditions
b	burned
m	air fuel blend
R	residual gas
s	spark point
u	unburned

fuel also reduces the knock tendency; however it increases NO_x emissions [10].

A considerable amount of literature has been published on control strategies for knocking prevention. A knocking detection scheme consisting of multi-feature extraction and neural classification has been proposed [11]. Authors developed a constructive learning algorithm for the cycle-by-cycle knocking detection task. A fuzzy control system, in which different spark advances and timing setting effects were used to determine knocking intensity, has been reported [12]. It was also reported the development of an engine which operates with variable biogas/air ratios and performs a stable operation without knocking [13]. The control algorithm for this engine was designed to adjust variable biogas/air ratios to obtain high efficiency along with low NO_x emissions.

A knocking control strategy based on modifying ratios of high-octane-fuel/low-octane-fuel fed into combustion chamber without changing ignition timing has been patented [14]. It has also been patented an alternative knocking control strategy which uses a delivery system automatically configured to respond to variable operating conditions by feeding a fluid like alcohol or water to at least one of the engine cylinders of a vehicle [15]. Finally, it has been patented a knocking control strategy that uses a pre-combustion chamber with a first spark plug, followed by a chamber with an independent spark plug; depending on operating conditions one or both of the sparks work [16].

The most common knocking control strategies for modern engines have been based on the Feedback principle, with the drawback that knocking is belatedly corrected. It is possible to implement knocking control strategies based on the feedforward principle, however it entails characterization of the disturbance, and for internal combustion engines there are many disturbances that lead to auto-ignition. This paper focuses on a robust PID control strategy based on the feedback principle [17] but including a sensitivity factor which allows faster responses to a disturbance. The first section of this paper presents the development and the validation of a model for predicting temperature at the ignition point. Based on this model, the following section present Feedback auto-ignition control strategies, testing its performance in terms of robustness and controller fragility. The next section presents a feedforward auto-ignition control strategy focused on common disturbances. The final section compares and discusses the performance of the developed auto-ignition control strategies.

2. Model for predicting temperature at the ignition point

2.1. Model description

To evaluate the performance of the control strategies addressed in this paper, a model for predicting temperature at the ignition point was developed, fitted and validated. The model describes the compression process of a four-stroke turbocharged engine taking into account volume, pressure and temperature of air-fuel-unburned and residual-exhaust gases in the combustion chamber. It was considered simultaneous mass and heat transfer between air-fuel-unburned gases coming from the aftercooler and residual-exhaust gases remaining in the combustion chamber. A MVM (Mean Value Model) approach was chosen because of its reasonable precision and low computational complexity [18]. MVM are control oriented models with time as the independent variable, where the discrete nature of the engine is neglected and the evolution of variables are assumed to be continuous in an average sense over the cycle.

The process begins with an air-fuel mixture entering the mixing chamber. The mixture is fed into the turbocharger where an increase in pressure produces a rise in temperature. The valve in the supply line regulates the amount of fuel fed into the mixing chamber and the aftercooler reduces air-fuel mixture temperature to 40 °C. Then, the air-fuel mixture is fed into the combustion chamber where simultaneous mass and heat transfer between air-fuel-unburned and residual-exhaust gases mixture takes place. The mixture follows a polytropic compression process until reaching the ignition point. At this point, the temperature of the mixture should be below auto-ignition temperature to avoid knocking. A schematic diagram of the engine detailing the aforementioned processes is shown in Fig. 1.

The proposed model relates gases mixture temperature to its experimental polytropic coefficient. An experimental dataset from a large commercial engine was employed to determine the