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An experimental investigation of additional actuators on a submarine diesel generator

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A B S T R A C T

Additional actuators and active generator load control have been suggested to improve performance on submarine diesel generators. Until recently, a lack of systematic control design has limited the ability to thoroughly investigate their potential. In this paper, model predictive control is used to produce near-optimal actuator commands for an experimental diesel generator on a test bed capable of producing representative submarine operating conditions. The performance with different actuator subsets is compared against an existing speed governor control architecture over a range of operating conditions. It is demonstrated that a minimum of two actuators may substantially improve generator performance. The study also investigates how model predictive control, when combined with additional actuators, can be used to enforce appropriate operational constraints that may lead to better longevity of the generator.

1. Introduction

Diesel-electric submarine platforms are propelled through the water using electric motors. As illustrated in Fig. 1, these motors source their power from batteries. To charge these batteries while minimising the acoustic and visual signature of the submarine, a submarine will operate its diesel engines while it is several meters below the surface of the water—an operation referred to as “snorting”.

During a snorting manoeuvre, fresh air is consumed by the engines, drawn from the main volume of the ship's hull as illustrated in Fig. 1. A snort mast that protrudes above the surface allows this air to be replenished. Due to the depth at which the engine exhaust is released from the submarine, it experiences a static pressure head. The mean value of this exhaust static pressure head is typically 4–5 m (Buckingham & Mann, 2010; Mann, 2011). However, it will vary with the height of the wave. The result is a time varying back pressure on the diesel engine.

The World Meteorological Organization has published a standard metric for wave heights over a variety of sea conditions. These are referred to as “sea states”. A subset of this data, extended by the Australian Department of Defence to include the period of waves found in oceans around Australia (Australian Department of Defence, 2003), is shown in Table 1. Significant wave height is defined as the mean peak-to-peak wave height of the highest third of waves, though in practise there are a spectrum of wave heights for a given sea condition. Also given in Table 1 is the resulting peak-to-peak exhaust back pressure variation experienced by the engine. Sea states of 6 or less make up 99% of all sea conditions (Mann, 2011).

The effects of increasing back pressure on a turbocharged submarine engine are well understood (Hield, 2011; Jost, 1983; Kirkman & Hopper, 1990; van den Pol, 1992). As the exhaust back pressure increases, the pressure ratio across the turbine decreases and, as a direct consequence, the pressure ratio across the compressor drops as the turbocharger reduces in speed. The drop in intake manifold pressure leads to a reduction in airflow through the engine. This reduction in airflow increases the exhaust gas temperature for a constant fuel rate. The heightened back pressure and reduced intake manifold pressure also increase the pumping work for the engine, resulting in a small engine speed drop. The diesel generator's speed governor responds to this reduced speed by increasing fuel flow to the engine, increasing the exhaust temperature further (van den Pol, 1992). These fluctuations in exhaust gas temperatures have been linked to reliability issues (Kirkman & Hopper, 1990; Hield, 2011). The reduced airflow and increased fuel consumption also lead to decreased air-to-fuel ratios, and smoke production can therefore increase considerably.

Typically, diesel-electric submarines are equipped with fixed geometry turbochargers and constant generator loads, utilising a Single-Input Single-Output (SISO) Proportional-Integral (PI)

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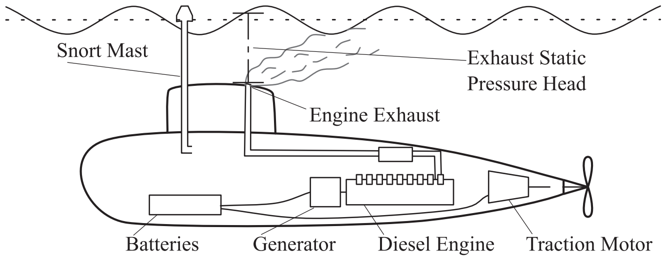

Fig. 1. Diesel-electric submarine during a snorting manoeuvre.

Table 1
Wave characteristics at different sea states.

Sea state		Significant wave height (m)	Average period (s)	Pressure change (kPa)
3	Mean	0.875	6.9	8.8
	Max	1.250	7.4	12.6
4	Mean	1.875	7.9	18.8
	Max	2.50	8.6	25.1
5	Mean	3.2050	9.0	32.7
	Max	4.000	9.5	40.2
6	Mean	5.000	9.9	50.3
	Max	6.000	10.3	60.3
7	Mean	7.500	10.8	75.4
	Max	9.000	11.2	90.5

control approach to adjust the engine's fuel rate in order to maintain a desired speed set-point. This control structure is reactive, since a deviation from the speed set-point is required before the speed governor can vary the fuel rate. Nevertheless, a recent study has demonstrated that with careful tuning, PI based speed governors can reduce engine speed variations in submarines to fall within acceptable tolerances (Hield & Newman, 2013).

While it was demonstrated in Hield and Newman (2013) that engine speed variations can be effectively eliminated, it was concluded that a different control structure would be required in order to also significantly reduce exhaust gas temperature variations. Variable Geometry Turbochargers (VGT), waste-gated turbochargers and active generator load control have been suggested as useful actuators for reducing exhaust temperature variations (Hield, 2011; Hield & Newman, 2013; Swain, 1994; Swain & Elliott, 1994; von Drathen, 2013). While these additional actuators show promise for reducing exhaust temperature variations, it is not clear how to systematically incorporate these additional actuators into the speed governor control system.

Previous studies have investigated control approaches for active load control and VGTs. In Hield, Zadeh, Harris, Tregenza, and Newman (2013) the authors propose a modification to the existing speed governor control system to allow active generator load control. An additional control loop with feed-forward and feedback components was added to actively vary the engine load. The engine load was varied to keep the engine at a safe operating conditions, including maximum exhaust temperatures. While the developments ensured that the engine remained in a safe operating mode, it did not notably reduce variation in exhaust temperature. In Swain and Elliott (1994), the authors developed a fuzzy logic based control system to actively vary the generator load and the VGT position in a simulated submarine environment. Since the control system did not take into account system dynamics, unstable engine behaviour resulted. The authors also tried a feed-forward based control system, which demonstrated promise for the additional actuators. Compared to a fixed geometry turbocharger, the addition of the VGT allowed an effective increase in power of over 25% (Swain & Elliott, 1994).

A robust control system which is able to systematically incorporate additional system inputs while minimising variation in engine speed and the exhaust temperature is therefore required. The control system must also be able to handle constraints in a systematic way. Model Predictive Control (MPC) is a multi-input model based control strategy that is capable of optimising an objective while keeping the engine within constraints. In Broomhead, Manzie, Shekhar, and Hield (2015) a robust MPC scheme is proposed, which explicitly handles the approximately periodic disturbances found in the submarine environment. This control system provides guarantees that constraints will not be violated and that the system will be stable, given that system disturbances are within a predefined limit. The controlled system was validated under submarine-like operating conditions in Broomhead, Manzie, Hield, Shekhar, and Brear (2016), Broomhead et al. (2015), where exhaust temperature variations were reduced significantly. However, while this study was successful, it is not clear how many or which actuators are required at a minimum to substantially reduce engine speed and exhaust temperature variation. Further, additional operational considerations, such as the maximum torque rating of the engine, were not considered.

This paper therefore uses the controller proposed in Broomhead, Manzie, Hield, et al. (2015) to evaluate the potential performance of different actuator combinations on a submarine diesel generator. This includes consideration of how additional operating constraints can be rigorously enforced, using the combination of MPC and additional actuators. The test bed commissioned for this work is described in Section 2, where the control system's formulation and implementation is also detailed. A speed governor is implemented on the test bed to establish baseline performance, detailed in Section 3, before the performance of various actuator combinations is investigated. These actuator combinations are tested over a variety of back pressure disturbances. In Section 4, the impact of additional operational constraints will be investigated using the additional actuators, before the results of the study are discussed in Section 5.

2. Test bed setup

To investigate the impact of different engine actuators and constraints in a submarine environment, a scaled test bed was commissioned at The University of Melbourne's Advanced Centre for Automotive Research and Testing (ACART), shown in Fig. 2. The test bed consists of a 4-cylinder, 3.0 l diesel engine, equipped with common rail electronic fuel injection and a VGT. The engine's native sensor set has been supplemented with pressure and

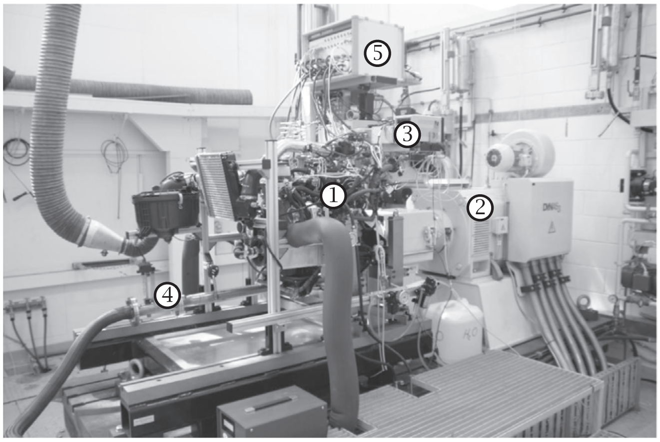

Fig. 2. Diesel engine at ACART dynamometer facility. (1) Automotive diesel engine. (2) Horiba–Schenck transient dynamometer. (3) dSPACE MicroAutoBox. (4) Exhaust back pressure valve. (5) Pressure and temperature sensors.