An experimental investigation of additional actuators on a submarine diesel generator

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ABSTRACT

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-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)
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 in submarines to fall within acceptable tolerances (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

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**Table 1 Wave characteristics at different sea states.**

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

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

**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.
temperature sensors throughout the gas path to permit the monitoring of engine performance. The control systems in this paper require measurement of the engine’s speed, intake manifold pressure, VGT position and turbine speed states. While the first three states are available through the engine’s native sensor set, a Garrett turbocharger speed sensor was installed to provide turbine speed. If the turbine speed were not directly measurable, online state estimation would be required as in Ortner, Ferreau, Bergmann, and del Re (2009). To eliminate sub-cycle pressure fluctuations, which are outside the time-scale of interest, the intake manifold pressure reading was filtered by a first order discrete time low pass filter with a time constant of 55 ms, approximately equal to one engine cycle.

The generator is represented by a Horiba–Schenck Titan-T460 transient engine dynamometer. As shown in Fig. 3, the dynamometer control system accepts a reference load torque command as an input.

A dSPACE MicroAutoBox, denoted as MAB-ECU and shown in Fig. 3, takes the place of the engine’s production control unit. The MAB-ECU is tasked with directly controlling all engine sub-systems, including fuel-rail pressure, injection timing and back pressure tracking. The MAB-ECU also logs data at rates of up to 1 kHz. To ensure the time-critical tasks of the MAB-ECU are not interrupted by the relatively processor-intensive control system, a second dSPACE MicroAutoBox is used to implement the control system, denoted MAB-MPC and also shown in Fig. 3. At each time step, the MAB-ECU sends the MAB-MPC the current system state over a CAN bus, which in turn responds with engine and dynamometer input commands. The inputs to the system are summarised as \( u = \{ \delta_f, \tau_{\text{gen}}, \mu_{\text{gen}} \} \), which represents the injection duration, generator load and a VGT actuator command. The MAB-MPC also generates a back pressure reference signal, which is tracked by a control system described in the subsequent section.

2.1. HIL simulation of submarine operating conditions

A butterfly valve was installed in the engine’s exhaust (Fig. 2) to generate back pressures which simulate a submarine operating environment. The butterfly valve generates a pressure differential, which is a nonlinear function of valve position, mass flow rate and gas temperature.

The valve can be characterised using the standard equations representing compressible flow through a nozzle (Heywood, 1988). By treating the exhaust gas as ideal and by assuming no entropy generation, the valve’s mass flow rate as a function of pressure ratio and valve opening can be modelled using

\[
m_v = \frac{p_{\text{up}}}{R_T c_v A_f} \theta \left( \frac{2y}{\gamma - 1} \left[ 1 - \left( \frac{p_{\text{up}}}{p_{\text{in}}} \right)^{\frac{\gamma - 1}{\gamma}} \right] \right)^{-\frac{1}{\gamma}} \tag{1}
\]

where \( m_v \) is the flow through the valve, \( p_{\text{in}} \) is the pressure ratio across the valve, \( \gamma \) is the ratio of specific heats for the exhaust gas, \( R \) is the specific gas constant for the exhaust gas, \( C_D \) a discharge coefficient and \( A_f \) is the equivalent area of the valve, as a function of valve angle. The composite function \( C_D A_f(\theta) \) was identified as a quadratic function of valve angle using steady state data. Based on this valve characterisation, a map which relates the required valve angle as a function of desired back pressure and valve mass flow rate can be generated, shown in Fig. 4.

To enable back pressure tracking, the valve’s map was used as part of a hierarchical model based control system, illustrated in Fig. 5 and implemented on the MAB-ECU. Based on a reference back pressure, a measurement of the exhaust gas temperature and an estimate of valve mass flow, a feed-forward valve reference position is calculated using the valve map (Fig. 4). The valve flow rate is estimated as the summation of the measured fuel and compressor mass flows. Since the valve map and the estimated valve flow rate have errors, integral action is incorporated into the back pressure tracking. The reference valve angle is then passed to a position tracking PID controller. The resulting control system is capable of replicating a wide range of operating conditions. Assuming sinusoidal oceanic waves, Fig. 6 shows the back pressure valve and control system replicating sea states 3–6 mean. The exhaust back pressures shown in Fig. 6 and all subsequent figures are filtered by a moving average filter with a window size equal to the number of samples in an engine cycle, eliminating sub-cycle pressure variations. The wave is reproduced well, with some minor tracking error caused by backlash in the valve actuator. This error is more pronounced near the peak in exhaust pressure as higher pressures are more sensitive to valve position. This error is not anticipated to be a problem, due to the robust nature of the

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**Fig. 3.** Controller hardware configuration.

**Fig. 4.** Valve position as a function of back pressure and flow rate.

**Fig. 5.** Schematic of back pressure control system.
MPC controller.

2.2. Model predictive control

Maintaining a constant engine speed and maintaining a constant exhaust temperature are considered to be the primary and secondary objectives for the submarine diesel generator respectively. Given that these two objectives are achievable, a tertiary objective is to maximise the power produced by the generator. These objectives can be represented by the stage cost

\[ I(x, u) = (\omega_e - \omega_{1\text{ref}})^2 + \delta_1(T_{cyl} - \bar{T}_{cyl})^2 + \delta_2(t_{gen} - t_{ref})^2 \]

where \( x \) and \( u \) are the system states and inputs; \( \omega_e \) is the engine speed and \( \omega_{1\text{ref}} = 2050 \) rev min\(^{-1} \); \( \bar{T}_{cyl} \) is the cylinder exit temperature as a function of states \( x \) inputs \( u \) and disturbances \( d \); and \( t_{ref} = 750 \) K; while \( t_{gen} \) is the generator load and \( t_{ref} = 300 \) Nm. The weighting \( \delta_1 \) was chosen as 0.1 to emphasise engine speed tracking as the primary objective, while the weighting \( \delta_2 \) was made very small \((10^{-6})\) to emphasise that the tertiary objective was only to be satisfied following satisfaction of the primary and secondary objectives. Since 300 Nm of torque is unachievable given the target exhaust temperature, the third cost term only aims to maximise the torque, and hence power, produced by the generator. The exhaust temperature of 750 K was chosen as it is achievable with all actuators strictly within their limits while the mean back pressure of 140 kPa is applied.

The MPC proposed in Broomhead, Manzie, Shekhar, et al. (2015) was implemented as in Broomhead, Manzie, Hield, et al. (2015) on the MAB-MPC. The cost function, (2), was used with a prediction horizon 1.5 wave periods in length. Engine dynamics were predicted within the controller using a four-state linear model, combined with an estimate of future back pressure disturbances. Due to the controlled environment of the experimental setup, the estimate of future back pressure disturbances could be taken from the disturbance generator, as seen in Fig. 3. In practise though, this estimate would need to be generated by a disturbance estimator. It is worth noting that during the experimental investigation, it was found that errors in the back pressure estimate could be tolerated without a significant impact on closed loop performance.

The linear model was derived from an eleven-state nonlinear mean value engine model using the model reduction procedures described in Broomhead, Manzie, Brear, and Hield (2015). The process exploits time-scale separation within the model, employing regular and singular perturbation techniques to eliminate superfluous states which operate outside the time-scales of interest. Following this model order reduction, standard linearisation and discretisation procedures are applied. The resulting model has states representing the engine speed, the turbine speed, the VGT position and the intake manifold pressure, which can be described as \( x(t) = (\omega_e, \omega_t, N_{\text{vgt}}, P_{\text{int}}) \). Since the system nominally operates about a single operating point, a single linearisation was found to work well, if the system deviated significantly from this operating point however, modelling error may become significant and degrade performance. In such a case, the use of a Linear Time Varying (LTV) model or multiple linear models, as demonstrated in Ortner, Langthaler, Ortiz, and del Re (2006), may improve performance.

The constraints \( \mathcal{Y} \) of the MPC are summarised in Table 2, and include upper and lower bounds on each of the inputs, the engine speed and the allowable exhaust temperature. Also included in the constraints are upper and lower slew rate constraints for the VGT input, which represent physical limitations of the actuator.

At time \( k \) and current state \( x(k) \), the MPC optimisation problem solved online is given by:

\[
\mathcal{P}(x(k)):\min_{u} \sum_{j=0}^{N_P} I(x_j^k, u_j^k) + \sum_{j=N_P}^{N-1} y_j^k - \bar{y}_j^k \]

\[
\text{s. t. } x_0^k = x(k), x_{N_P}^k = x_{N_P-1}^k, \quad y_j^k \in \mathcal{Y}_j, \quad \forall \ j \in \{0,1,...,N-1\}.
\]

where the control law is implicitly defined as \( x(k) = u_k^F \). The second summation in the cost function represents a terminal cost, which is used to ensure stability of the closed loop system. See Broomhead, Manzie, Shekhar, et al. (2015) for further information about the control system and (Broomhead, Manzie, Hield, et al., 2015) for its implementation.

3. Submarine actuator sets

In the following sections, six different control systems will be demonstrated on the diesel generator as it operates under submarine conditions. Additional constraints are added to the MPC

<table>
<thead>
<tr>
<th>Table 2</th>
<th>MPC constraints.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bound States</td>
<td>Inputs</td>
</tr>
<tr>
<td>( \omega_e (\text{rev/min}) )</td>
<td>( \delta_1 (\text{ms}) )</td>
</tr>
<tr>
<td>Lower</td>
<td>1950</td>
</tr>
<tr>
<td>Upper</td>
<td>2150</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 3</th>
<th>Summary of actuator combinations.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input</td>
<td>Controller</td>
</tr>
<tr>
<td>Fuel injection duration</td>
<td>I</td>
</tr>
<tr>
<td>Generator load</td>
<td>x</td>
</tr>
<tr>
<td>VGT position</td>
<td>x</td>
</tr>
</tbody>
</table>
formulation described in the previous section to restrict the use of particular actuators. This allows insight into the achievable performance for a given actuator combination. A summary of these actuator combinations is given in Table 3.

### 3.1 Fuel injection duration control

A fuel governor was developed on the MAB-MPC to establish baseline performance. The fuel governor is represented by a PI controller.

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**Fig. 7.** Performance of single-input control strategies under sea state 6 mean operating conditions.
controller with injection duration (in units of ms) as its controlled input. For a given engine speed, the injection duration input is equivalent to the fuel rate input used in Hield and Newman (2013). The fuel governor aims to minimise tracking error from a speed set-point of 2050 rev/m. The closed loop performance of the fuel governor under a sea state 6 mean operating condition is shown in Fig. 7. Controllers I and II represent two different controller tunings, with gains summarised in Table 4.

Controller I was tuned to keep the fuel rate relatively constant, allowing the natural forcing of the back pressure disturbance to be shown. The peak-to-peak engine speed and exhaust temperature variations are 125 rev/m and 84 K respectively.

Controller II shows the performance of a fuel governor where the gains are carefully tuned to minimise engine speed variations at the given operating point. The resulting engine speed and exhaust temperature variations are 34 rev/m and 117 K respectively. To achieve the performance seen in Fig. 7, controller II had to be tuned aggressively. In practice, such an aggressive tuning would not provide an acceptable level of robustness, and so the controller would be detuned. In Hield and Newman (2013), the investigators found that the speed governor’s PI gains significantly impact engine speed and exhaust temperature variations. The authors demonstrated that within certain regions of the PI map, engine speed variations were effectively eliminated. While some regions also reduced exhaust temperature variations, they could not be significantly reduced like the engine speed variations. The same result was found during the tuning of the PI gains for this investigation. Comparing controllers I and II, the 73% reduction in engine speed variation causes an increase in exhaust temperature variation of 40%.

Also shown in Fig. 7 is the performance of the developed MPC controller, denoted as controller III, performing the task of a fuel governor under sea state 6 mean conditions. Like the fuel governor, the only controllable input is the injection duration and the weighting $\delta_1$ was changed to $10^{-4}$, to further emphasise minimisation of engine speed variation as the primary objective. In this case, the closed loop performance is very similar to that of the aggressively tuned fuel governor, with 27 rev/m of peak-to-peak speed variation and exhaust temperature variations of 116 K peak-to-peak.

The similarity in performance between the near-optimal MPC and fuel governor indicates that an aggressively tuned fuel governor is capable of fully utilising the single input, given that there are no additional operational constraints. This is not unexpected as the PI structure has been carefully tuned for the current operating point. Whilst such tuning is possible for the SISO system considered here, it becomes significantly more complicated as additional degrees of freedom are incorporated into the problem, as will be considered in the Multiple-Input Multiple-Output (MIMO) cases in the following sections.

It is worth noting that the calibration effort for the MPC was less than that required for the PI controller, but this reduction in controller calibration needs to be weighed against an increased cost in system identification. A significant advantage of the MPC based control system is that, under certain assumptions, it comes with guarantees of stability and constraint adherence which are critical in a submarine. The validity of these assumptions for a diesel generator in a submarine environment are demonstrated and discussed in Broomhead, Manzie, Hield, et al. (2015).

3.2. Active generator load control

Controller IV represents the MPC where access to both injection duration and the generator load torque is permitted. In Fig. 8, the performance of controller IV is compared with its single-input counterpart, controller III, under sea state 6 mean operating conditions. Using controller IV, engine speed variations are effectively eliminated, while exhaust temperature variation is reduced to 38 k peak-to-peak, representing a 67% reduction from controllers II and III. Since the diesel generator represents a highly coupled MIMO system, systematic tuning of a PI based control system for these two inputs would be very challenging, but the MPC was able to handle the additional control input with comparable calibration effort to the single input cases.

The reasons for the remaining temperature variation relate to modelling error and inter-sample dynamics, as discussed in Broomhead, Manzie, Hield, et al. (2015). It is postulated that with improved prediction models or online model estimation, the remaining temperature variation can also be effectively eliminated, since the actuators are not being saturated. The average generated power when using controller IV is slightly reduced at 38.1 kW when compared to the 38.8 kW produced when using controller III. Since the peak exhaust temperatures have been reduced, the average power output may be increased by increasing $T_{\text{ref}}$.

Controller IV utilises the injection duration input in a different manner to controllers II and III. As seen in Fig. 7, controllers II and III have a peak in injection duration closely following the peak in exhaust pressure, whereas in Fig. 8, controller IV is shown to minimise injection duration during the peak in exhaust pressure. This behaviour can be attributed to the second term in the cost function, where in order to minimise exhaust temperatures during the peak in back pressure, the fuel rate must be reduced, rather than increased. It can also be noted that the generator load torque moves in phase with the injection duration, which minimises engine speed variation.

The generator torque commands given by controller IV may be considered aggressive, with peak-to-peak torque variations of 82 Nm representing a 47% variation in generator load. Further reduction in exhaust temperature would require even more aggressive control inputs, since the peak in exhaust temperature still corresponds to the peak in back pressure. This aggressive and periodic actuation may increase the risk of fatigue failure. Given access only to injection duration and generator load, it is postulated that restricting the allowable variation in torque will yield a response with performance somewhere between that of controller III and controller IV. Limiting the allowable variation in load torque is investigated further in Section 4.

3.3. Variable geometry turbocharger control

Controller V represents the MPC where access to both injection duration and the VGT position is compared with controllers III and IV. In order for the VGT to be in its usable range for the desired exhaust temperature of 750 K, the fixed generator torque had to be reduced to 163 Nm, compared with 180 Nm used in controller III. While the performance of controller V is a significant improvement over controller III, with 33 rev/m and 46 k respectively, its performance is worse than that of controller IV. This reduced disturbance rejection capability may be attributed to the VGT moving between its upper and lower limits.
Despite active generator load control providing better disturbance rejection, the use of a VGT is an attractive proposition, due to its relatively low cost and the relatively short down-time required to retrofit existing diesel generators. There are known reliability issues for VGTs operating under submarine operating conditions though, due to the temperature at which they operate.

**Fig. 8.** Performance of single- and dual-input control strategies under sea state 6 mean operating conditions.
An alternative solution may be to use a waste-gate, which has the potential to achieve similar performance to the VGT with a reduced number of moving parts in the hot exhaust flow (von Drathen, 2013).

3.4. **Full engine actuation**

Controller VI represents the MPC, where access to all actuators is given. In Fig. 9, the performance of controller VI is shown, where
the diesel generator is subjected to sea state 6 mean operating conditions. The performance of controllers III and IV is replicated in Fig. 9 for reference. Notably, despite having access to all actuators, the MPC utilises only the injection duration and generator load inputs, keeping the VGT at its maximum position. As a result, the performance between controllers IV and VI are effectively identical.

From steady state analysis, it is known that the maximum VGT position corresponds to a maximisation of airflow through the system, minimising exhaust temperatures for a given fuel rate. As such, this selection of VGT position allows a maximisation of fuel flow through the system for a given exhaust temperature, which therefore maximises the engine brake torque and generator power.

This result indicates that only two inputs are required in order to remove engine speed and exhaust temperature variations. Further, if only targeting the minimisation of engine speed and exhaust temperature variations, then injection duration combined with active load control provides the most control authority. As will be discussed in Section 4, this result changes when additional constraints are considered.

3.5. Effects of sea state on engine performance

Each of the six developed control systems, as summarised in Table 3, were tested on a range of back pressure waves. Fig. 10 shows the peak-to-peak and mean values of key system inputs and outputs for three waves, sea state 4 mean, sea state 6 mean and sea state 6 max (fast). Sea state 6 max (fast) was designed as a highly aggressive test case with an amplitude corresponding to sea state 6 max, but with a period of 4 s. To maximise performance and ensure stability of the PI based speed governor, the PI gains were retuned for each sea state, as summarised in Table 4. In practise, the fuel governors used on submarines utilise a single, but less aggressive, set of gains for all sea states (Hield & Newman, 2013).

As seen in Fig. 10, the less aggressive sea state 4 mean resulted in smaller variations in engine speed and exhaust temperature, and these reductions were achieved with significantly less actuation. Interestingly, while sea state 6 max (fast) was intended as a highly aggressive test case, each of the control systems actually outperformed their sea state 6 mean counterparts. While part of this improvement may be attributed to the smaller sample time achievable with a faster wave, it can be seen from Fig. 10 that each of the actuators is actually utilised less in sea state 6 max (fast) when compared to sea state 6 mean. This reduced actuation is caused by the engine's inertia becoming significant with respect to the time-scale of the disturbance. As the diesel generators used on submarines have much larger inertias than the diesel generator used in these experiments, further damping of the oscillations, and consequently improved performance, may be achievable in full scale testing.

In general, the performance trends seen in detail for sea state 6 mean in Figs. 7–9 are seen across each of the waves in Fig. 10. In particular, it can be seen that when a second input to the system becomes available (controllers IV and V) the ability to reject exhaust temperature variations significantly improves. Furthermore, for each of the back pressure waves tested, the performance did not notably improve with the addition of a third control input.

4. Additional operational considerations

While the previous section demonstrated the achievable performance of a submarine diesel generator with different actuator capabilities, only simple operating constraints were considered. In
Fig. 11. Measured engine outputs and inputs (solid black) under sea state 6 mean operating conditions and additional constraints (dashed grey).
this section, additional operating constraints will be added to the MPC (controller VI) that are representative of desirable operating characteristics that promote longevity of the engine and actuators.

4.1. Maximum rated brake torque

The first operational consideration is the maximum load rating of the diesel generator. The diesel engines onboard submarines have a maximum rated torque in order to ensure their safety and reliability. Implementing active load control with input constraints using a coupled PI based control system would be challenging. PI based control systems are not well suited to input and state constraints and the use of an input saturation may result in engine speed variations. In an MPC framework though, this consideration can be made simply by adding an additional constraint. To demonstrate this principle, controller VI was modified to include an upper bound of 200 Nm on the diesel generator’s load torque. The performance of this controller can be seen in column 2 of Fig. 11. The load torque constraint was continuously adhered to throughout the experiment.

Interestingly, while the nominal controller in column 1 of Fig. 11 only utilises two of the control inputs, all three inputs are utilised when this additional constraint is considered. The load constraint becomes active during the trough in back pressure. Injection duration, and hence torque, is normally maximised at this point, since the exhaust temperature would otherwise decrease. Since the additional constraint prevents this from happening, the VGT position must be decreased to prevent a significant drop in exhaust temperature.

4.2. Generator load variation

As illustrated in column 1 of Fig. 11, the generator load torque can vary by up to 28 Nm between successive inputs commands. This represents an aggressive actuation of the generator which may increase the risk of fatigue failure. To address this concern, controller VI was modified to limit the slew rate of the generator load command to 15 Nm/s. The performance of this controller can be seen in column 3 of Fig. 11, where the slew rate constraint is continuously respected. In addition to limiting the rate at which the generator load can change, the slew rate constraint also reduced torque variation from 82 Nm to 60 Nm peak-to-peak. As a result of the rate constraint on generator load, the VGT needs to become active during the troughs in back pressure to ensure the exhaust temperature is kept relatively constant.

Limiting the slew rate on the generator load control is one of several approaches which could be taken to reduce its variation. An alternative approach would be to tighten the upper and lower generator load torque limits or to include a term in the cost function which penalises the use of the generator’s load as an input. While costing generator load torque would likely work, determining an appropriate weight for this term, relative to the other objectives, may prove challenging.

4.3. Maximum in-cylinder pressure considerations

The next consideration investigated is that of maximum allowable in-cylinder pressures. In-cylinder pressures which exceed some allowable limit pose a threat to the diesel engine’s reliability. One way to effectively limit the peak pressures in a diesel engine is to limit the induced volume of air, which is a function of the intake manifold pressure. A maximum intake manifold pressure constraint of 180 kPa was imposed on a modified version of controller VI. The performance of this controller is shown in column 4 of Fig. 11, where the constraints are adhered to at all times.

The intake manifold pressure naturally tends to peak during the trough in exhaust back pressure, as seen in column 1 of Fig. 11. Therefore, in order to constrain the intake manifold pressure at this time, the VGT position must be reduced. A similar behaviour is likely to be achievable using a waste-gated turbocharger in place of the VGT.

4.4. Emissions considerations

The International Maritime Organization (IMO) does not directly enforce Particulate Matter (PM) limits on submarines (International Maritime Organization, 2008). However to reduce the visual signature of the submarine (Goodenough & Greig, 2008), the diesel generators must limit their production of PM. Particulate matter is known to correlate with the engine’s air-to-fuel ratio, with increased PM produced at low air-to-fuel ratios. Fig. 10 shows the measured variation in normalised air-to-fuel ratio for controllers I to VI under the three operating conditions. It can be seen that controllers IV and VI, which utilise injection duration and generator load inputs, result in higher air-to-fuel ratios with less variation.

While not explicitly considered as a constraint in this study, the engine-out emissions of a diesel generator can be directly constrained using the MPC, as demonstrated in Broomhead, Manzie, Hield, et al. (2015). When these constraints become active, it is expected that all three actuators will be needed to reject engine speed and exhaust temperature variations as demonstrated with the other constraints.

5. Conclusion

In this paper, the performance of a submarine diesel generator with additional actuators was investigated experimentally. Both a conventional speed governor control system and model predictive control system were demonstrated. The MPC framework allowed a systematic study into the impact of additional actuators, including generator load control and a VGT, while taking into account system constraints and dynamics.

For the single input system, the MPC based control system did not significantly outperform the tuned PI based speed governor. There are a nonetheless several advantages in using an MPC system. The MPC system is able to guarantee stability and constraint adherence of the closed loop system. The calibration of the MPC was easier than that of the PI based control system, though this improvement must be weighed against the cost of model identification.

Tuning a PI based control system for the multi-input case would be challenging as the diesel generator represents a coupled MIMO system. In contrast, the MPC control system used in this work provides a relatively straightforward development process, where closed loop results can achieve near-optimal performance. Using the MPC framework, it was demonstrated that the inclusion of either a VGT or active generator load control results in a significant reduction in exhaust temperature variation. This result was demonstrated over a wide range of sea-states. The use of all three inputs did not result in further improvement, indicating that only two inputs are required to simultaneously minimise variations in the engine speed and the exhaust temperature if no additional operating constraints were considered.

The impact of additional operational constraints was then explored. These represented a maximum engine brake torque, a restriction of the generator’s load variation and a maximum allowable in-cylinder pressure. Such constraints allow engine operation to be restricted to regions which maximise engine longevity and can be enforced in a straightforward way using the MPC framework. The closed loop system was demonstrated to respect these
additional constraints while continuing to minimise engine speed and exhaust temperature variations. However, all three actuators were required to achieve the same level of performance within this stricter constraint setting.

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References


