ENERGY-EFFICIENT MARINE ENGINE AND DYNAMIC WING EVALUATION UNDER LABORATORY CONDITIONS TO ACHIEVE EMISSION REDUCTION TARGETS IN SHIPPING

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ABSTRACT

There is a requirement to comply with the forthcoming IMO & EU requirements to reduce ship emissions by at least 40% in 2030 compared to the 2008 levels. Such medium-term emission reduction targets can only be achieved by introducing novel technologies into the shipping industry. The SeaTech H2020 project (seatech2020.eu) introduces two main innovations that can support the same emission reduction objectives. Those innovations consist of integrating an energy-efficient marine combustion engine with a renewable energy recovery device, i.e. dynamic wing. However, these two technologies are not evaluated in an actual environment in a selected ocean-going vessel. On the other hand, various data sets are collected from both innovations and can be used to quantify their energy efficiencies in a data science environment. Furthermore, it is expected that both innovations should interact with each other in the same data science environment as well as in the respective testing platforms, therefore more realistic vessel operational conditions can be introduced. Hence, this study introduces realistic head wave conditions in both innovations, where the dynamic wing creates adequate thrust to push the vessel forward under the same ocean wave conditions. The same thrust and ocean wave conditions have been applied to marine engine testing as the main contribution of this study. Finally, the data sets collected from the engine testing platform under its loading situations for both wave and thrust conditions of the selected ocean-going vessel are presented in this study.

Keywords: Marine engines, dynamic wing, engine testing, energy efficiency, emission reduction, shipping, maritime, ocean waves.

1. INTRODUCTION

The international maritime organization and other authorities, such as the European Commission, are expecting a considerable reduction in ship emissions in the future. Therefore, various rules and regulations on ship energy efficiency and emission reduction have been introduced by the same organizations. As a general target, CO2 emissions from shipping should be reduced and that can further be quantified as at least a 40% CO2 reduction by 2030, with the continued effort towards a 70% CO2 reduction by 2050, compared to the 2008 CO2 levels [1]. The emission reduction rules and regulations can eventually make the path towards zero-emission vessels, where many such vessels will be powered by batteries or renewable energy sources. In addition, CO2 capturing and storing technologies can also help to offset the respective emissions created by fossil fuel-based combustion processes, i.e. marine engines in ocean-going vessels. It is expected that internal combustion engines will stay in the shipping industry for while due to their operational simplicity, moderate maintenance & higher availability of fossil fuels, and the respective delivery infrastructure. However, there is a possibility that cleaner or bio/synthetic fuels that can be used under internal combustion engines may come into the market to reduce the respective shipping emissions. Hence, internal combustion engines can still play an important role in the future of the shipping industry.

Since renewable energy power technologies can play an important role in future zero-emission vessels, adequate procedures to quantify the same technologies should be investigated. It is expected that such technologies will closely be integrated with internal combustion engines since the same technology can play an important role. This study is also interested in achieving the same technology objectives by considering an integration process between energy-efficient marine combustion engines and renewable energy recovery devices, i.e. dynamic wing. These research objectives are proposed under the SeaTech H2020 project (Next generation short-sea ship dual-fuel engine and propulsion retrofit technologies, seatech2020.eu) project to combine the modern technologies of marine engines and propulsion innovative devices to improve vessel energy efficiency and reduce ship emissions.

The proposed marine engine technology consists of a duel-fuel (DF) engine developed by Wartsila with a higher energy conversion efficiency by precise controlling of the engine combustion process. The proposed renewable energy-based propulsion technology consists of an active biomimetic dynamic wing mounted on the vessel bow to harvest wave energy in moderate and heavy sea conditions; see Fig.1. The same propulsion technology can produce extra thrust to increase ship speed and dampen undesirable vessel motions [2], therefore the required engine power can be reduced, considerably. However, the proposed innovations of marine engine and propulsion technologies are evaluated under laboratory conditions and large model scale conditions, where the respective data sets from the proposed innovations are collected.

The proposed marine engine, i.e. SeaTech engine, is developed and tested under laboratory conditions and the dynamic wing is developed and tested under a large model scale in an ocean environment. Both innovations produce large data sets, which should be analyzed in a data science environment. This data science environment should consist of adequate interactions among the respective systems, i.e. marine engine and propulsion technologies, to understand more realistic interactions among the same technologies. Since this study has considered the marine engine and propulsion technologies as the SeaTech innovations, the latter should interact in the same data science environment. The above technology connections in the data science environment should reflect realistic interactions that should mimic realistic ocean-going vessel conditions.

It is expected that these vessels fitted with the proposed dynamic wing should navigate in moderate to high sea conditions. This is due to the reason that the dynamic wing is a wave energy harvesting device, therefore the respective vessels should be navigated in appropriate wave fields. However, while such vessels are considered to navigate with several speeds in wave fields, various undesirable motions, i.e. roll and pitch motions, can be introduced. It is expected that the dynamic wing can dampen some of the undesirable vessel motions. However, the same wave fields can introduce additional loading conditions into the main marine engine. Therefore, these interactions between both technologies should be considered in quantifying the efficiency of the proposed innovations. One should note that that can be done under the proposed data science environment and that consists of various machine learning (ML) algorithms to develop artificial intelligence (AI) applications to analyze the respective data sets.

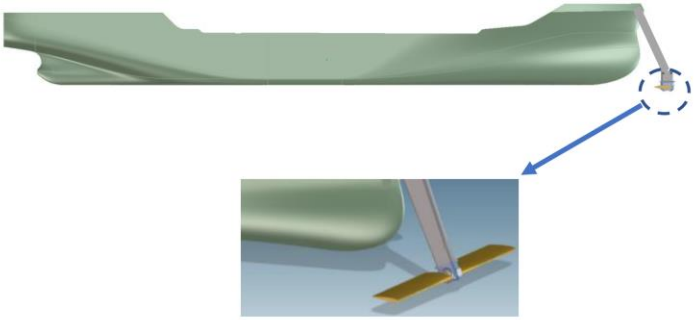

FIGURE 1: DYNAMIC WING ARRANGED AT THE BOW OF A SMALL CHEMICAL TANKER 95000TON DWT

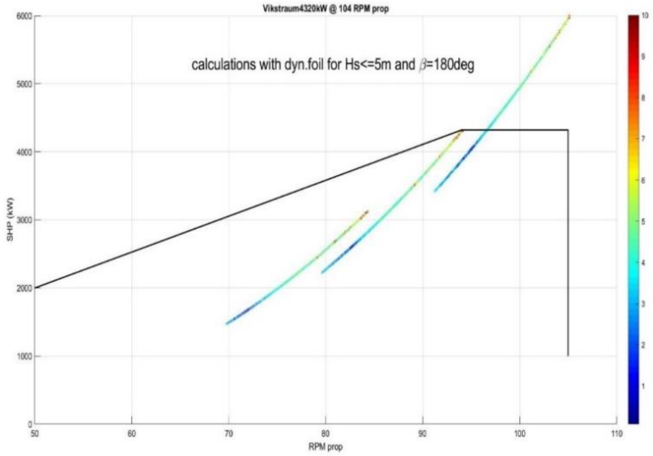

FIGURE 2: ENGINE-PROPELLER COMBINATOR DIAGRAM IN THE CASE OF A SHIP OF FIG.1 WITH THE EFFECT OF DYNAMIC WING

The development of the data science environment consists of the following steps and which have been published in previous studies as a theoretical study of the engine propeller combinator diagram with and without the dynamic wing; see Fig.2. One should note that the engine propeller combinator diagram combines both engine and propeller characteristics and that can make the basis for the proposed data science environment; see also [3]. Furthermore, the performance of the dynamic wing can also be integrated into the same engine propeller combinator diagram combines, where the performance of the SeaTech innovations can be quantified. The respective technology quantification can consist of the life cycle cost analyses (LCCA) to evaluate the proposed technologies from the long-term life-cycle perspectives [4-6].

The initial energy efficiency gain and reduction in fuel consumption at the SeaTech engine have been estimated as a part of the same project [7-8]. The same energy efficiency gain and reduction in fuel consumption at the SeaTech engine is verified under laboratory testing conditions, in a later study. These laboratory testing conditions can be divided into two parts: 1) engine operations without the dynamic wing effect and 2) engine operations with the dynamic wing. These test conditions with and without the dynamic wing have been implemented under the engine loading conditions and are described in the following section. One should note that under these two parts, the interactions between the SeaTech engine and dynamic wing are considered under a data science environment., where the data sets collected from the engine testing conditions have been utilized.

2. MARINE ENGINE TESTING ENVIRONMENT

This section describes a reasonable operational environment for the SeaTech engine that has been tested under laboratory conditions. One should note that there are additional engine tests to be conducted by considering the outcome of this study. These laboratory testing conditions consist of various engine loading conditions, i.e. as results of wave conditions and responses in ship routes, that have been introduced into the engine testing conditions. It is expected that these wave conditions should be favorable towards the bio-mimetic dynamic wing, since that can produce additional thrust to improve performance during the navigation situations of the respective vessel.

As the first step of this engine testing process, the wave conditions of a selected vessel are of the main interest. The main reason is that the same wave conditions can be implemented into the marine engine testing environment at Wartsila, therefore the fuel consumption and emissions on the existing vessel's main engine and SeaTech engine can be compared. The comparison results can eventually be used for the LCCA on the SeaTech engine and that can also be used to make the decisions on retrofitting of such engines to existing vessels. The respective wave conditions of the selected vessel have been further investigated in the following sections. The environmental/ weather data (i.e. significant wave heights and mean or peak periods and wave directions) from the Copernicus Program [8] are downloaded by considering the selected vessel position and time information. The selected vessel particulars and data are listed in Table 1, where also the respective ship performance and navigation data sets are collected:

TABLE 1: VESSEL PARTICULARS

Parameter	Particulars
Ship Type	Chemical Tanker
Ship length	135m
Ship beam	20m
Gross tonnage	14000tons
Deadweight (at designed draft)	9500tons
Main engine type	Dual fuel engine with MCR 4320 (kW) at 720 (rpm)
Gearbox Reduction Ratio	6.9:1
Propeller type	One 4-bladed Controllable Pitch Propeller with a diameter 5.2m.

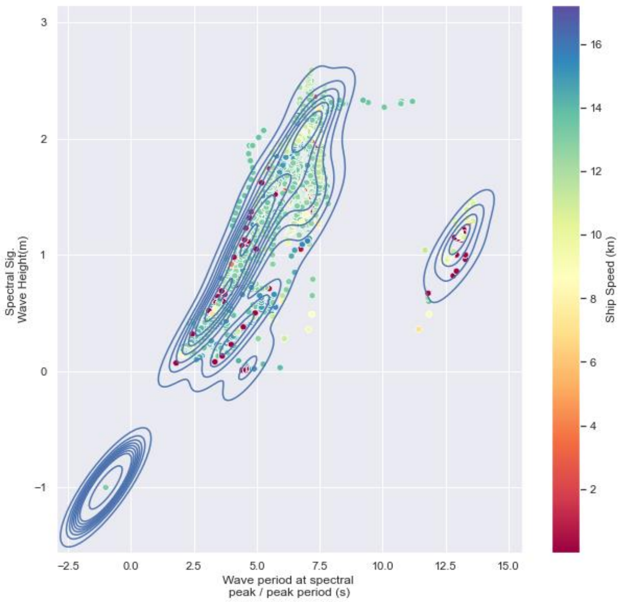

FIGURE 3: SPECTRAL SIG. WAVE HEIGHT VS WAVE PERIOD AT SPECTRAL PEAK PERIOD

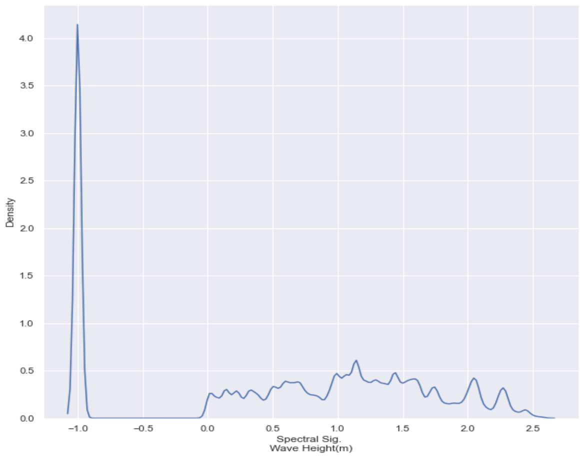

FIGURE 4: SIGNIFICANT WAVE HEIGHT

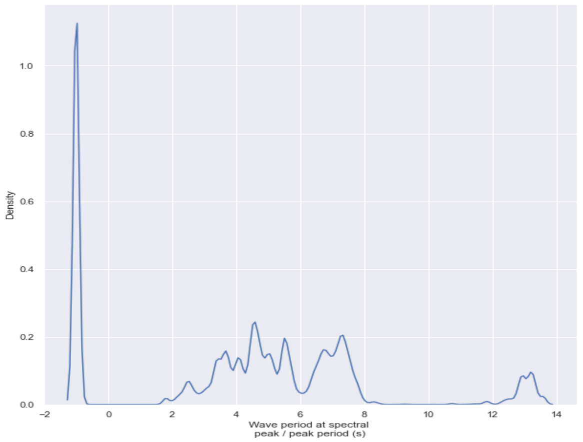

FIGURE 5: WAVE PERIOD AT SPECTRAL PEAK PERIOD

2.1 Full-Scale Ship Performance and Navigation Data

In this section, the encountered wave conditions of the selected vessel are analyzed to understand the respective operational profile of the vessel. The wave condition information, i.e. significant wave height and peak wave periods, are presented in Figs. 3, 4, and 5, where also information concerning the frequency of encountered wave conditions is presented. One should note that the vessel speed of 13knots represents 60% of the operational profile in the same figure.

In particular cases of data anomalies (e.g. ship at port, data acquisition system errors, etc) are indicated as missing values (using -1). As presented in the above figures, the vessel is operating around somewhat calm-to-moderate weather conditions, i.e. the significant wave height is less than 2.5m. This is an obvious expectation, due to the main reason that ship navigators prefer to operate vessels under calm weather conditions, and has also been reflected in the data sets. However, these navigation conditions may not be favorable for the bio-mimetic dynamic wing, which gains energy from the ship's responses in waves and contributes more significantly when the respective vessel is navigated under higher wave heights and the system is able to harvest an adequate amount of wave energy to support vessel propulsion thrust.

2.2 Favorable Navigation Conditions

One should note that favorable wave conditions for the bio-mimetic dynamic wing should be implemented in the marine engine testing environment, therefore actual vessel performance of the SeaTech engine integrated with the flapping thruster can be observed, relevant data sets can be collected and performance can be quantified with the same data. In particular, a rectangular wing arranged at the bow is considered submerged at a draft below the free surface is considered (see Fig,1), with main dimensions: span=18m, chord=3.5m, and its aspect ratio is *AR*=5.2 for this engine testing conditions.

Since the wave conditions observed in the selected vessel are not favorable for the bio-mimetic dynamic considered for the particular vessel wing [8], the following additional wave conditions are derived to understand the vessel performance under several wave conditions. It is expected that future vessels with dynamic wings should be recommended to navigate in moderate to high wave fields as selected in this study. The wave conditions considered for this study are divided into 3 cases and the respective data concerning significant wave heights, peak wave periods, vessel speed, wave encounter angles, and foil thrust (calculated) are presented in Table 2:

TABLE 2: WAVE CONDITION CASES

cases	Hs (m)	Tp (sec)	Vs (kn)	β(deg)
1	2.2	7.5	13 (*)	180 (head waves)
2	1.2	12.5	13 (*)	180 (head waves)
3	2.5	8.0	14.6	180 (head waves)

(*) Vessel speed 13kn represents 60% of the operational profile.

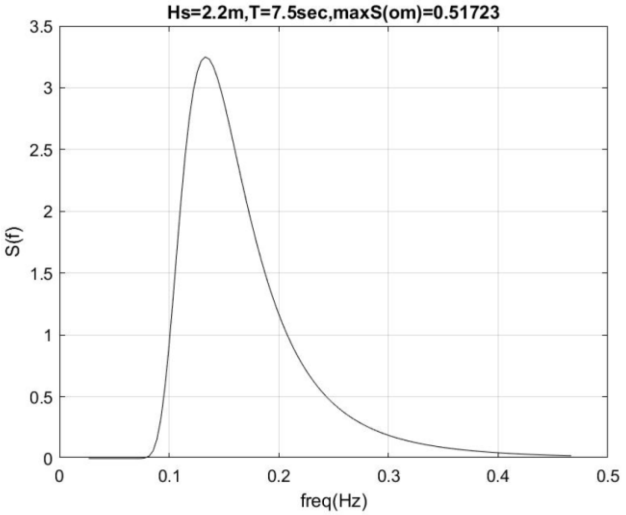

FIGURE 6: WAVE SPECTRUM FOR CASE 1

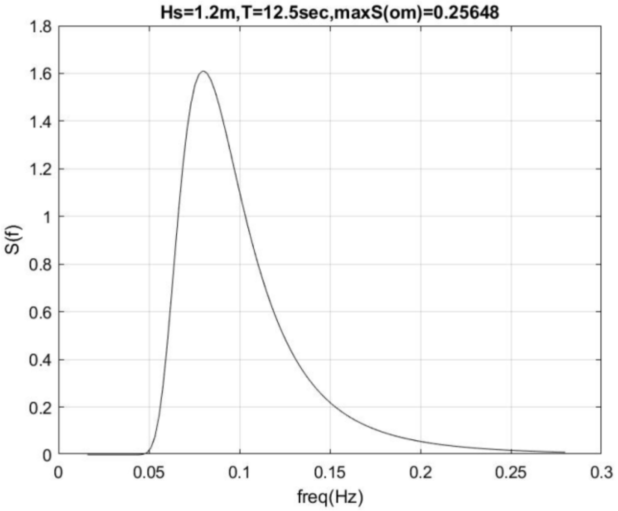

FIGURE 7: WAVE SPECTRUM FOR CASE 2

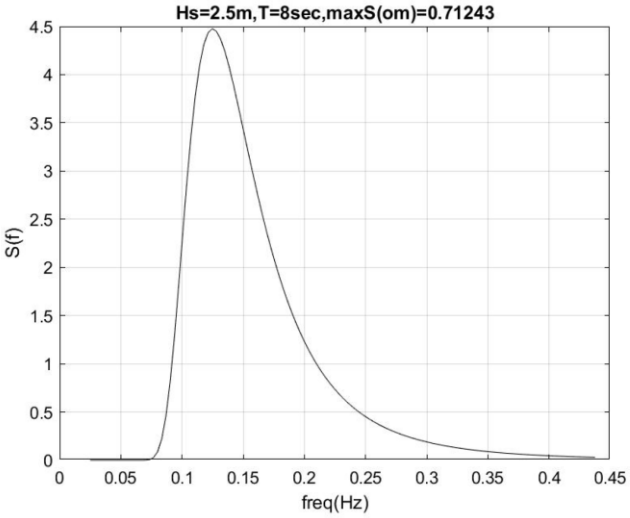

FIGURE 8: WAVE SPECTRUM FOR CASE 3

2.3 Wave Spectrums

The wave spectrum with respect to each of the above cases is derived from the following equations, and that has been developed by using the Bretschneider model:

$$S(\omega) = \frac{1.25}{4}\frac{\omega_m^4}{\omega\omega^5} H_s^2\, exp\left(-1.25\frac{\omega_p^4}{\omega^4}\right) \tag{1}$$

where H_s is the significant wave height and $\omega_p = 2\pi / T_p$ the peak frequency corresponding to the peak period T_p, respectively. The spectra are then converted to the ship frame of reference by the following equations:

$$S^U(\omega_e) = S(\omega)\frac{d\omega}{d\omega_e} \tag{2}$$

$$d\omega = d\omega_{en}\left(1 - \frac{2\omega U}{g} cos\,\beta\right)^{-1} \tag{3}$$

where U (m/s) is the ship speed and β denotes the wave direction with respect to the ship's long-axis (and thus, β=180deg corresponds to incoming head waves). The modeled frequency spectra for the three test cases considered are presented in Fig. 6, 7 and 8, for cases 1, 2 and 3, respectively.

In the case of head waves, the spectra of Figs. 6, 7 and 8, have been used in the engine testing platform as the inputs that relate the load profiles of the SeaTech engine in the corresponding assumptions. There are several assumptions that are made during this process: 1) the vessel is moving at a constant speed without any yaw motion and no time delay in the system responses and 2) the marine engine is running under constant RPM conditions, while the respective loading conditions can be changed appropriately.

In the following step, the respective simulations of the marine engine for the selected vessel, with and without the operation of the dynamic wing, are conducted. The following observations are noted concerning the simulation results:

- In case 1- foil reduces the average engine load by 1.24%
- In case 2- foil reduces the average engine load by 4.9%
- In case 3- foil reduces the average engine load by 3.7%

Hence, it is expected these simulated conditions will be compared with the results of the engine testing conditions. One should note that actual vessel navigation encounter wave conditions can vary considerably, therefore ocean-going vessels can encounter large speed fluctuations due to the large variations in added wave resistance. Therefore, the same speed fluctuations should be reflected on the engine load profile. However, instant load fluctuations of more than 10% can be problematic for engine testing conditions. In addition, such load fluctuations can introduce additional challenges in implementing such propulsion technologies in onboard vessels in actual ocean environments with various wave conditions.

Furthermore, the large load fluctuations in marine engine testing can introduce additional noise conditions in the sensor measurements, i.e. data sets, therefore the measurement values can be degraded, i.e. the data quality can be reduced. That can affect the emission measurements with various data anomalies, especially in transient conditions. Due to such limitations related to data quality in the engine testing conditions, a shorter period of the received load profiles, and keeping the same frequency of load oscillations are feedback into the engine testing conditions. One should note that inserting the load profile into the testing conditions for the SeaTech engine can be a time-consuming and resource-demanding process, due to the repeating procedures of the engine testing procedure.

3. ENGINE LABORATORY IMPLEMENTATION

The SeaTech engine is tested in a laboratory environment with some selected conditions as discussed before. The marine engine is operated around a specific RPM value, where the respective loading conditions can be changed. A heading direction incoming wave conditions for cases 1, 2 and 3 are considered for these laboratory tests. Therefore, the ship resistance due to surge motions, incoming waves (added ship resistance), and added thrust due to the dynamic wing have also been calculated and applied in the engine testing conditions. These calculations were done under moving average data points in intervals of around 4-5 (sec). The SHP (Shaft Horse Power) is then calculated from the propeller curves. The resulting impacts on engine load operations of different wave loading cases are graphically represented in the following figures.

Case 1: The following conditions are considered in the engine testing platform, as presented in Table 3, where the calculated average foil thrust is included, as well as the total ship resistance including the wave-added resistance. The respective testing information is presented in Figs. 9 and 10.

TABLE 3: WAVE CONDITION CASE 1

cases	Hs (m)	Tp (sec)	Vs (kn)	β(deg)	Foil thrust (N)	Rtot (N)
1	2.2	7.5	13 (*)	180 (head waves)	3680	251620

Figure 9 shows that the respective average load of 51.75% is applied to the SeaTech engine under the above wave conditions. The engine performance, i.e. shown using the orange line is considered as the SeaTech engine performance, of the selected vessel under the respective head wave conditions without the dynamic wing. The thrust power created due to the dynamic wing is presented by using the red line in the same figure. Finally, the reduced engine load due to the thrust from the dynamic wing is presented using the blue line and that represents an average 2.06% reduction (i.e. engine average load of 49.69%) in the engine load. Therefore, a reduction in fuel consumption and emission due to the same engine load reduction is expected in this case. The respective engine load fluctuations for the same situation are also presented in Fig 10.

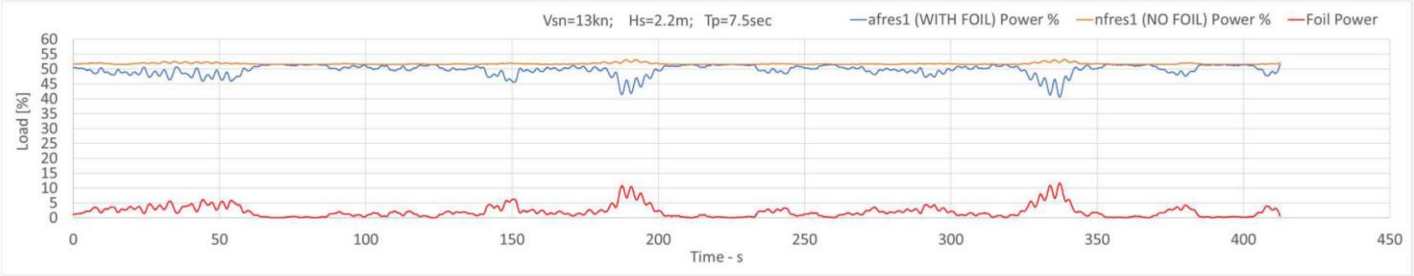

FIGURE 9: ENGINE TESTING RESULTS FOR CASE 1.

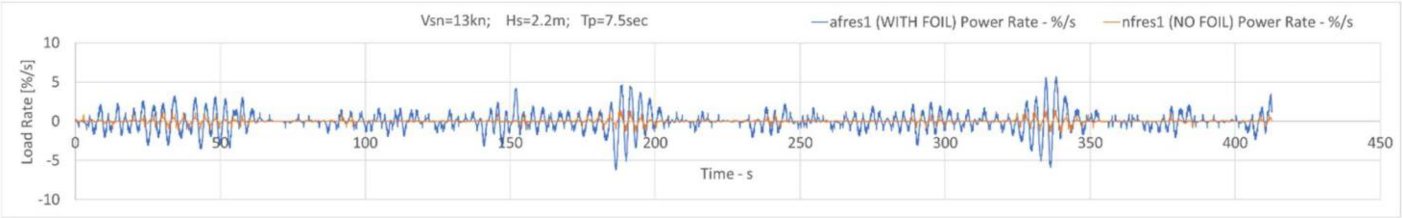

FIGURE 10: ENGINE LOAD FLUCTUATIONS FOR CASE 1.

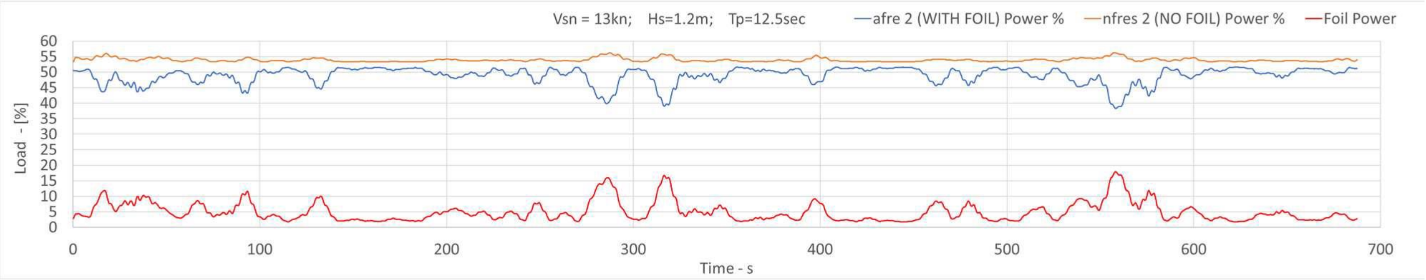

FIGURE 11: ENGINE TESTING RESULTS FOR CASE 2.

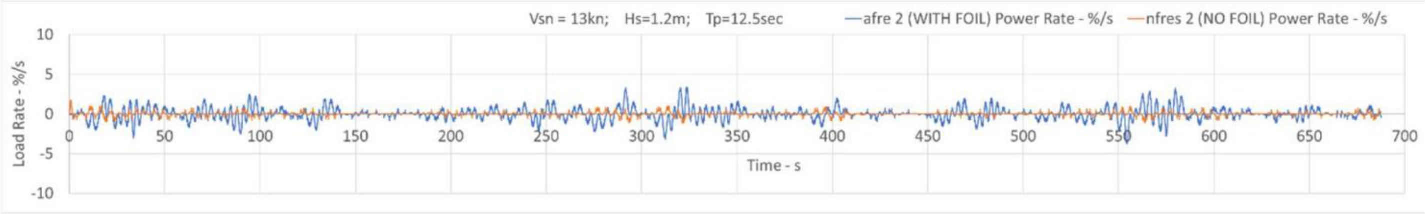

FIGURE 12: ENGINE LOAD FLUCTUATIONS FOR CASE 2.

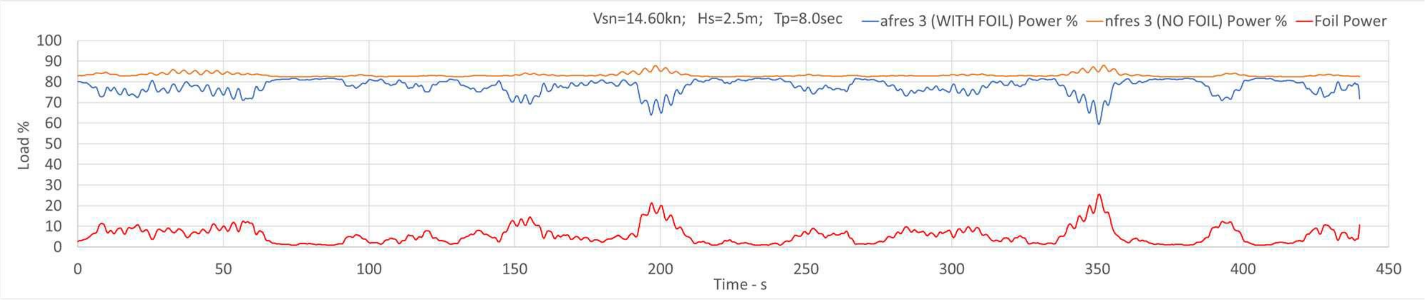

FIGURE 13: ENGINE TESTING RESULTS FOR CASE 3.

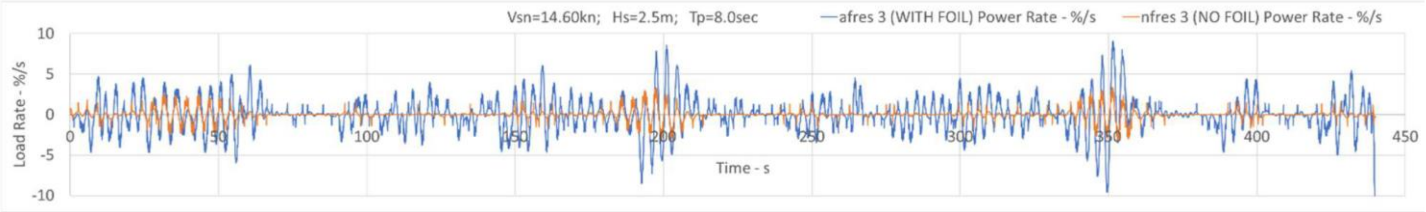

FIGURE 14: ENGINE LOAD FLUCTUATIONS FOR CASE 3.

Case 2: The following conditions are considered in the engine testing platform in Table 4 including the calculated average foil thrust and the total ship resistance including the wave-added resistance, and the respective testing information is presented in Figs. 11 and 12.

TABLE 4: WAVE CONDITION CASE 2

cases	Hs (m)	Tp (sec)	Vs (kn)	β(deg)	Foil thrust (N)	Rtot (N)
2	1.2	12.5	13 (*)	180 (head waves)	7200	246040

Figure 11 shows that the respective average load of 53.89% is applied to the SeaTech engine under the above wave conditions. The engine performance is shown in the orange line and is considered as the SeaTech engine performance of the selected vessel under the respective head wave conditions without the dynamic wing. The thrust power created due to the dynamic wing is presented in the red line in the same figure. Finally, the reduced engine load conditions due to the thrust from the dynamic wing are presented in the blue line and that represents an average 4.96% reduction (i.e. engine average load of 48.93%) in the engine load. Therefore, a reduction in fuel consumption and emission due to the same engine load reduction is expected in this case. The engine load fluctuations for the same situation are also presented in Fig 12.

Case 3: The following conditions are considered in the engine testing platform in Table 5, including the calculated average foil thrust and the total ship resistance including the wave-added resistance., and the respective testing information is presented in Figs. 13 and 14.

TABLE 5: WAVE CONDITION CASE 3

cases	Hs (m)	Tp (sec)	Vs (kn)	β(deg)	Foil thrust (N)	Rtot (N)
3	2.5	8.0	14.6	180 (head waves)	10600	359720

Finally, Fig. 13 shows that the respective average load of 83.27% is applied to the SeaTech engine under the above wave conditions. As before, the engine performance is shown in the orange line and is considered as the SeaTech engine performance of the selected vessel under the respective head wave conditions without the dynamic wing. The thrust power created by the operation of the dynamic flapping thruster is presented in the red line in the same figure. In this case, the reduced engine load conditions due to the thrust from the dynamic wing are presented in the blue line and that represents an average 5.63% reduction (i.e. engine average load of 77.64%) in the engine load. Therefore, a reduction in fuel consumption and emission due to the same engine load reduction is expected in this case. The engine load fluctuations for the same situation are also presented in Fig 14.

Based on the above results it is observed that the load fluctuations are somewhat larger in all three cases, where the SeaTech engine is operating under the dynamic wing. One should note that these load fluctuations are related to the wave conditions, as mentioned before. Even though the trust force due to the dynamic wing has been calculated and considered during the engine testing phase, the vessel stability gain due to the dynamic wing has not been incorporated in the same test platform. Therefore, it would be expected that the actual load fluctuations could be lower and smoother than the values presented in the relevant figures. Furthermore, the SeaTech engine should be adequately synchronized with the smooth load fluctuations with the motions of the dynamic wing, and that way the efficiency of the respective SeaTech innovations can be further estimated from the available data sets. Additional combined engine-propeller-dynamic thruster system operating features, like keeping constant engine torque or additional advanced engine control mechanisms, will also be investigated in the future. Furthermore, having additional flexibility in the dynamic wing or advanced active control mechanisms in the dynamic wing to reduce the respective fluctuations should also be investigated.

4. CONCLUSION

Performance quantification in new engine and propulsion innovations that can be utilized to support the zero-emission shipping strategy is an important component in the future of the shipping industry [10-13]. Since many novel innovations are under laboratory conditions, these qualification approaches can be studied and optimized under a data science-type environment and implemented into real-world technology innovations. This study presents such a case study, where the favorable operational conditions for a selected innovation of a dynamic wing, acting as a flapping thruster gaining energy from the ship responses in waves and offering dynamic ship stabilization, have been applied in complementarity to another innovation of the SeaTech duel fuel engine. The combined performance of the system is simulated and tested under laboratory conditions to collect the required data sets.

The respective head wave conditions that would be expected to encounter by an ocean-going vessel that has both innovations of the SeaTech engine and dynamic wing are considered during these laboratory testing. Therefore, the respective thrust and wave conditions created under realistic head wave conditions are applied to the engine testing platform in this study. As the final outcome, the engine loading conditions are reduced due to the dynamic wing and those observations are also reported under the same data sets. A considerable reduction in fuel consumption up to almost 6% has been observed. However, additional load fluctuations are also noted during the testing conditions, and the respective solutions have also been proposed that will be studied in more detail in future work.

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