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Experimental evaluation of a solid oxide fuel cell system exposed to inclinations and accelerations by ship motions

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HIGHLIGHTS

- The effect of ship motions on the operation of SOFC systems is tested.
- Oscillations result in fluctuations in voltage and thus power production.
- Design improvements for marine SOFC systems are suggested.
- Solid test procedures are needed to avoid forced oscillation behaviour.

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ABSTRACT

Solid Oxide Fuel Cell (SOFC) systems have the potential to reduce emissions from seagoing vessels. However, it is unknown whether ship motions influence the system's operation. In this research, a 1.5 kW SOFC module is operated on an inclination platform that emulates ship motions, to evaluate the influence of static and dynamic inclinations on the system's safety, operation, and lifetime. The test campaign consists of a static inclination test, a dynamic test, a degradation test, and a high acceleration test. There were no interruptions in the power supply during the different tests, and no detectable gas leakages or safety hazards. Although the SOFC does not fail in any test condition, dynamic inclinations result in forced oscillations in the fuel regulation, which propagate through the system by different feedback loops in the control architecture, leading to significant deviations in the operational parameters of the system. Additionally, for motion periods from 16 to 26 s, reoccurring exceedance of the fuel utilisation results in a gradual reduction of the power supply. Several enhancements are recommended to improve the design of SOFCs and marine fuel cell regulations to ensure their safe operation on ships.

1. Introduction

Maritime transportation significantly contributes to greenhouse gas emissions. The share of shipping to the global anthropogenic emissions has increased from 2.76% in 2012 to 2.89% in 2018 [1]. Moreover, the shipping industry contributed 15% to all nitrogen oxide (NO_X) emissions in Europe in 2017 [2]. In response, the International Marine Organisation (IMO) adopted an emission reduction strategy and corresponding regulations. Since 1 January 2023, it is mandatory for all ships to report their Energy Efficiency Existing Ship Index (EEXI) and Carbon Intensity Indicator (CII) [3]. This forces shipbuilders and shipowners to monitor and gradually reduce carbon emissions from their ships. Furthermore, stringent limits restrict the NO_X emissions from ships, especially in specific emission control areas [4].

Solid Oxide Fuel Cell (SOFC) systems are a high-potential solution for reducing carbon and pollutant emissions [5]. Compared to marine diesel engines, SOFC systems convert fuel with a higher efficiency which contributes to a reduction in carbon emissions. Moreover, SOFC systems emit virtually no NO_X and CO, because combustion is replaced by electrochemical conversion. Furthermore, SOFC technology is characterised by high redundancy and fuel flexibility, which are very beneficial for marine applications [6]. Many research areas that are required for the successful integration of SOFC in ships are already covered. Baldi et al. [6] compared the load-following behaviour of the electrical power and heat production of SOFC systems with the varying energy demand of a tanker and a cruise ship. Kistner et al. [7] focused on the optimisation of spatial design for both centralised

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and decentralised SOFC systems, while taking into account potential component malfunctions. Haseltalab et al. [8] investigated the optimal sizing of components for a dredging ship powered with engines and SOFCs. Rivarolo et al. [9] compared multiple energy management strategies for an SOFC-powered power plant on a cruise ship. However, the effect of ship motions on the operation of SOFCs is not considered in the current literature.

Many ships make deep-sea itineraries with the possibility of encountering large waves and heavy weather. However, most SOFC systems are designed for stationary applications such as domestic, power plants or data centres [10]. All shipboard equipment and machinery must be designed to function properly even when exposed to these inclinations and motions. The conditions the equipment might be exposed to and the regulations currently in place for shipboard machinery are summarised in Appendix A. This is particularly relevant for SOFC systems because one of the benefits is their ability to be installed in a decentralised manner, reducing the size and losses of the power grid, and increasing system reliability [7]. However, this also increases the distance of the SOFC from the centre of rotation of the ship, resulting in increased accelerations that the SOFC system may experience. Despite the growing interest in using solid oxide fuel cells (SOFCs) as a power source for marine vessels, to our knowledge, no other researchers published regarding the effect of ship motions on SOFC systems. There is a need to assess the impact of tilted movements on SOFC systems in order to safely and effectively integrate them into ships.

The authors of this research did an initial inclination test campaign to develop solid test procedures [11]. A 1.5 kW SOFC system was inclined statically and dynamically up to angles of 30 degrees. The dynamic inclination test resulted in forced oscillation behaviour of the operational parameters of the SOFC stack. It was concluded that a larger range of test conditions and longer test durations are needed to determine the cause and the potential harm of the forced oscillation behaviour. The findings of the initial test campaign are used to define an improved second test campaign, which is presented in this manuscript.

The goal of this research is to evaluate the influence of marine conditions in terms of static and dynamic inclinations on the operation, safety and lifetime of SOFC systems. The results will be used to identify safety risks, in order to propose design improvements for SOFC systems and develop well-founded class rules. Using a one-axial oscillation platform, ship motions are emulated up to 30 degrees of inclination. The main contributions of this paper can be summarised as follows:

- The present study introduces a design for a test bench capable of evaluating inclinations and accelerations for fuel cell systems across a wide spectrum of seagoing ship types.
- To the best of our knowledge, this study is a first-of-its-kind assessment of the operability of SOFC systems under inclinations and accelerations.
- This paper gives insight into the possible consequences for the SOFC technology and its Balance of Plant (BOP) components and identifies which components are most critical for inclined operation.
- The present study provides evidence that SOFCs can operate successfully in the marine environment after minor design adjustments and indicates that ship motions have no significant impact on the system's lifetime.

First, the test set-up, test procedures and data acquisition are explained in Section 2. Next, the results and their interpretation for the different tests are shown in Section 3. Then, improvements are proposed for the design of SOFC systems, and for fuel cell regulations in Section 4. Finally, conclusions and recommendations further investigation are given in Section 5.

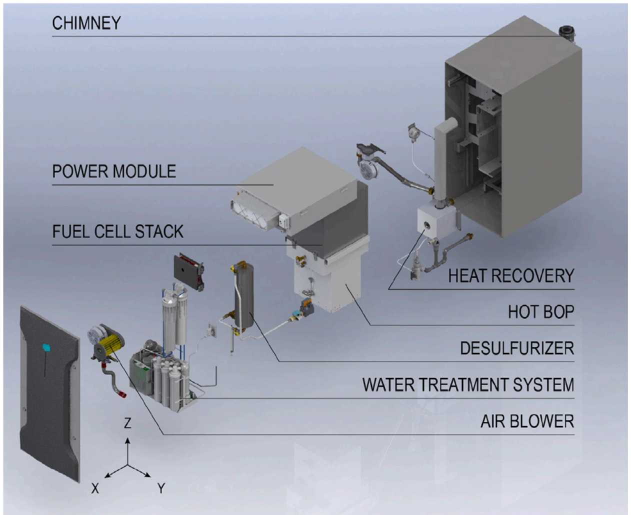


Fig. 1. Visualisation of main components in tested SOFC system and the defined X, Y and Z axes.

Table 1
Main characteristics of tested SOFC system.

Characteristic	Value	Unit
Width	1200	mm
Depth	550	mm
Height	1014	mm
Mass	250	kg
Electrical output	0.5 to 1.5	kW
Nominal net electric efficiency	57	%
Heat loss to environment	0.1	kW

2. Methodology

2.1. Tested SOFC system

The tests are conducted with a 1.5 kW SOFC system manufactured by SolydEra S.p.A. The fuel cell module comprises of a stack composed of 70 anode-supported planar cells, an integrated heat exchanger, a pre-reformer, and a combustor. The cold balance of plant is made up of a desulphuriser, an air supply system, a water treatment system, power conditioning equipment, and a waste heat recovery unit, see Fig. 1. The fuel channels through the stack follow the negative Y direction, while the gas, water, and air channels follow various directions towards the stack. It is an integrated independent system, meaning that the control architecture and safety mitigation are included in the module. The main characteristics of the module can be found in Table 1. The system is designed for stationary applications and was not yet operated before while exposed to dynamic inclinations.

2.2. Experimental set-up

A uniaxial harmonic oscillation platform induces both static or dynamic inclinations, enabling a wide range of ship motions to be simulated by adjusting the inclination and oscillation period. The SOFC system is secured to the inclination platform using a steel frame and lashing straps. Fuel, water, electricity, and exhaust piping are mounted flexibly. The process air is directly extracted from the environment. The hydraulic platform is electrically controlled, and the operating data of the SOFC module and BOP components are recorded every second. An inclination sensor is installed to also record the instantaneous angle every second. The SOFC module and its connections can be rotated with respect to the platform to be able to test rotations around the X and Y-axis of the module.

Table 2
Test conditions of different experiments.

	Axes [–]	Inclination setting [°]	Roll period OR COG acceleration [–]	Steps [–]	Duration per step [min]	Total duration [h]
Static test	X, Y	−30 to 30	–	13	12	5.2
Dynamic tests						
- Full load test (100%)	X, Y	15, 22.5, 30	≈8 to 80 s	19	10	19
- Part load test (50%)	X, Y	30	≈8 to 80 s	19	10	6.3
- Degradation test	X	30	8 s	–	–	190
- Acceleration test	X	30	0.16 to 0.88 m/s^2	12	3	0.6

Room temperature during testing varies from 15–20 °C.
Pressure of natural gas line is 17 mbarg.
Volumetric composition of used natural gas: 94.3% CH_4, 3.2% C_2H_6, 0.8% C_3H_8, 0.2% C_4H_{10}, 0.5% CO_2, 1.0% N_2

2.3. Test conditions

Table 2 shows the conditions that are used for the different tests. The test conditions are based on an analysis of possible ship motions and, although not limited to, current regulations on motions and accelerations of shipboard equipment, see Appendix A.

The static test subjects the SOFC system to an inclination range spanning from −30° to 30°, with a step size of 5°, with each inclination lasting 12 min. The static inclination test is performed around the X and Y axis.

The dynamic testing employs harmonic oscillations, as an electric motor with a crank connection drives the platform. For the full load and part-load test 19 oscillation periods between 8 and 80 s are used, to include a wide variety of ship types (see Table A.1). The full-load test is conducted at inclinations of 15°, 22.5°, and 30°, while the part-load test is solely performed at an inclination of 30°. The SOFC is operated for a duration of 10 min at each distinct combination of test conditions. Because power modulation is time intensive, solely one part-load condition is taken into account, namely 50% power production. The full-load and part-load tests are also executed for two rotational axes.

In order to investigate the impact of dynamic inclinations on the lifetime of the SOFC system, the module is operated under nominal conditions for a total of 190 h, of which 64 h are under dynamic inclinations. The dynamic inclinations are solely performed around the X-axis, with an outer inclination setting of 30 degrees. The shortest motion period of 8 s is used because this results in the highest number of cycles and impose the highest structural loads.

When the SOFC system is positioned far from the centre of rotation on a ship, roll and pitch motions can expose the system to significant accelerations. To assess the suitability of the system for decentralised power production, it is subjected to high acceleration testing. It is noteworthy that current regulations for fuel cell testing do not mandate any acceleration tests. Consequently, the acceleration test parameters are based on prior studies that reported simulated or measured accelerations, as indicated in Table A.2, although the maximum acceleration was limited by the capability of the platform. The accelerations range from 0.1 to 0.88 m/s^2, distributed over 12 discrete steps.

2.4. Degradation rate prediction

The SOFC module is designed to maintain constant power output. Therefore, as voltage decreases due to degradation, the current increases to compensate and deliver the same power output. This in turn further decreases voltage along the polarisation curve of the SOFC stack. Hence, the absolute degradation rate (as expressed by Eq. (1)) is determined based on the decrease in system efficiency and not voltage, as this is a more representative parameter for system-level testing [12].

$$deg\ [\eta_{net}/\mathrm{kh}] = \left(\eta_{net,start} - \eta_{net,end}\right) \cdot \frac{1000}{t_{end} - t_{start}} \tag{1}$$

Accurate estimation of the degradation rate in the SOFC module requires extensive testing hours, owing to small variations in its operation, continuous deviations by control feedback, and noise generated by sensors. According to Gemmen et al. [13], operation for at least 10,000 h is required for reliable results when the experimental noise is 1% and the nominal voltage degradation rate is 0.5%/kh, which is typical for commercial stacks. In this paper, we propose Gaussian process regression (GPR) to predict the net electric efficiency to estimate the range of degradation rates that can be concluded from this relatively short degradation experiment. GPR makes use of a probability distribution over an infinite number of functions that coincide with the used data points. The mean and covariance of all these functions form the prediction, which makes it possible to reflect the uncertainty in the prediction. GPR has also been successfully used by Zhu and Chen [14] and Deng et al. [15] to predict the degradation of fuel cells. The net electric efficiency is estimated by $f(x)$ and a noise term:

$$\eta_{net} = f(x) + \epsilon \tag{2}$$

of which the signal term $f(x)$ is a collection of functions, following a Gaussian process:

$$f(x) \sim \mathcal{GP}(m(x), k(x_i, x_j)) \tag{3}$$

The noise term reflects the inherent randomness in the observations, which is assumed to be normally distributed:

$$\epsilon \sim \mathcal{N}(\mu, \sigma^2) \tag{4}$$

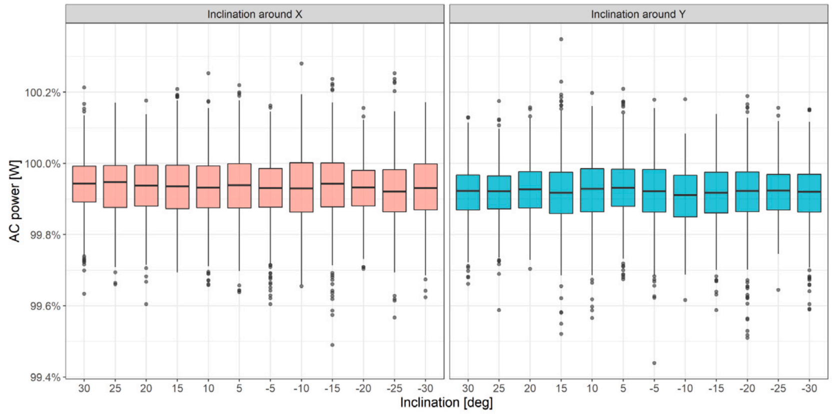
The kernel is a function that measures the similarity of two inputs. A suitable kernel needs to be selected to calculate the covariance matrix of the Gaussian process. Because cell degradation is often simplified to a quasi-linear process over time, a combined linear and constant kernel is used for the GPR model, as expressed by Eq. (5). Some other composite kernels were also tested, such as RBF (Radial basis function) + periodic + linear and linear + RBF·periodic + RBF, but these combined kernels matched the measurement data less well.

$$k = k_C(x_i, x_j) + k_L(x_i, x_j) = \sigma^2 x_i^\top x_j + C \tag{5}$$

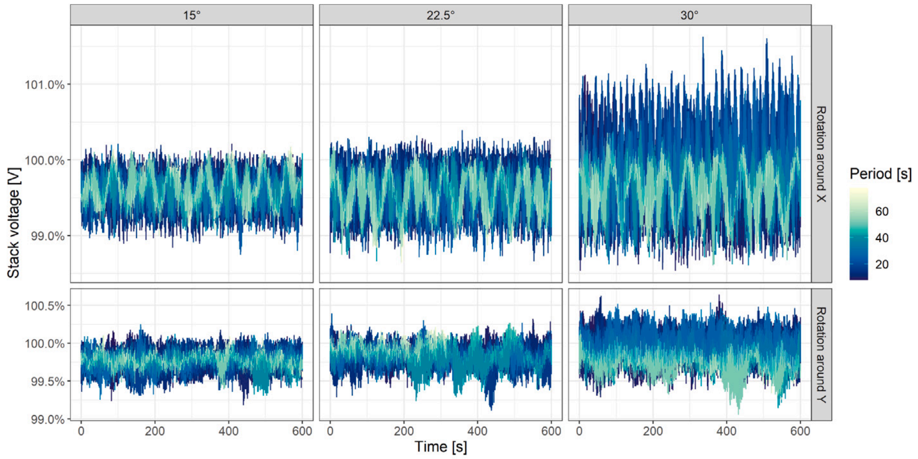
where x_i and x_j are input vectors. The variance σ^2 and constant C form the hyperparameters of the model, which are used to tune the kernel. These are optimised using maximum likelihood estimation to achieve an accurate fit of the measurement data. The measurement data during the 190 h of the degradation experiment are used to train the model to estimate a 95% confidence interval for the net electric efficiency after 10,000 h of operation, from which the expected degradation rate can be derived.

3. Results & discussion

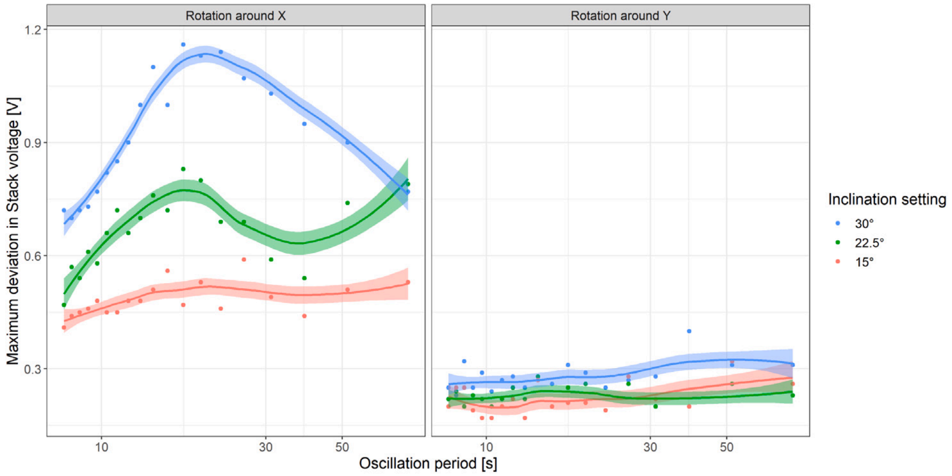
The SOFC module delivers power over the full test duration, and no gas leakages or safety hazards are detected. Moreover, there is no indication of cell defects or delamination of the air electrodes. Nevertheless, small water leakages occur at inclined positions, possibly due to the overflowing of the condensate discharge system. Furthermore, some level sensors measure values that differ from the actual values due to the inclined or sloshing level surface.



(a) Normalised delivered AC power during static test.

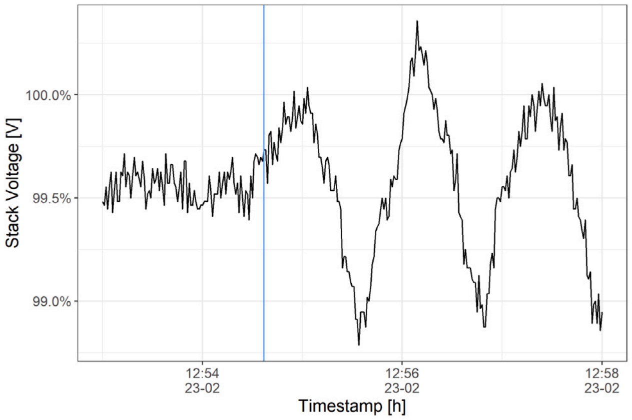


(b) Normalised stack voltage of full load dynamic experiment plotted over testing time for different combinations of test conditions.

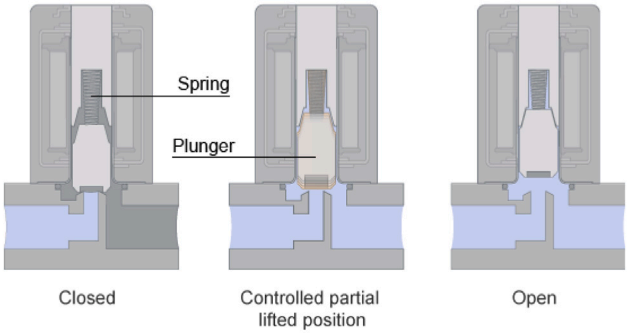


(c) Maximum deviation in stack voltage caused by platform oscillations. The solid line shows a trendline including a 75% confidence interval.

Fig. 2. Main results of full load static and dynamic test.



(a) Normalised stack voltage during dynamic inclinations with period of 78 seconds around the X axis up to 30°.



(b) Principle of a proportional solenoid valve that regulates fuel flow (Tameson, 2023).

Fig. 3. Effect of oscillation motion and cause forced oscillation behaviour (See [16]).

3.1. Static inclination test

In the static experiment, no extraordinary observations are made, and the system operation does not significantly differ from non-inclined operation. Fig. 2(a) illustrates the power production measurements taken during the experiment at various static inclination angles. The power production remains highly stable and shows minimal variance for higher inclination angles.

3.2. Dynamic inclination tests

Dynamic inclinations have a significant influence on the operational parameters of the SOFC module. Fig. 3(a) illustrates that upon the onset of platform oscillations (indicated by the blue vertical line), the stack voltage shows forced oscillation with the same period as the platform. The magnitude of these oscillations surpasses the noise level observed during normal operational conditions.

3.2.1. Full load

The stack voltage measurements in full load under varying test conditions are presented in Fig. 2(b). The deviations are most prominent at a combination of large inclinations and rotation around the X-axis. This forced oscillation behaviour is also observed for stack current, burner temperature, fuel utilisation, fuel flow, and steam flow. Consequently, these variations also occur in power production and electric efficiency. This also results in significant changes in the steam-to-carbon ratio, ranging from 1.6 to 2.2, although no carbon deposition is observed. Ultimately, it is discovered that the forced oscillation behaviour in system parameters is caused by the fuel regulation valve. The used proportional solenoid valve (shown in Fig. 3(b)) acts as a mass–spring-damped system. The forced oscillation of the plunger leads to variations in the fuel feed. According to the Nernst equation below, variations in $y_{H_2,an}$ and $y_{H_2O,an}$ have a direct effect on the reversible cell voltage at position x along the fuel channel. Because the module's control architecture is aimed at producing a constant power, these voltage fluctuations result in a response by the before-mentioned system parameters.

$$V_{rev,x} = V_{rev,0} + \frac{RT}{2F} \ln \left(\frac{\sqrt{y_{O_2,ca}} \cdot y_{H_2,an}}{y_{H_2O,an}} \cdot \sqrt{p_{cell}} \right) \tag{6}$$

where $V_{rev,0}$ is the standard reversible voltage, R the universal gas constant, T the temperature, F is the Faraday constant, y_j the molar concentration of species j, and p_{cell} the cell pressure.

During rotation around the X-axis, the plunger experiences the largest acceleration, hence the larger deviations for this direction. Fig. 2(c) illustrates that the deviations in stack voltage are largest in the 16 to 26-s period range, which indicates that the natural frequency of the valve is in this range. It is confirmed that the valve causes the forces oscillation behaviour by temporarily positioning the valve such that the plunger has no acceleration component during oscillations. This completely eliminates the enhanced deviations in fuel flow and consequently in all operational parameters.

For the motion periods with high deviations (16 to 26 s), the forced oscillation in operational parameters results in a gradual but significant power decrease. The oscillations in fuel flow result in changes in the fuel utilisation of ±2%. As excessive fuel utilisation could oxidise the nickel catalyst, this is undesirable in the SOFC system. Therefore, a safety mechanism is built into the system to prevent high fuel utilisation. The stack current is promptly reduced whenever the fuel utilisation limit is surpassed, as shown by the red line in Fig. 4. However, during oscillations, the limit is periodically exceeded, allowing insufficient time for the current to recover. As a result, the current and subsequently the power gradually decline. Given that the necessary stack current regulates the amount of fuel supplied to the stack, the reduction in current does not alleviate the fuel utilisation quickly enough, leading to a continued decrease in power. Moreover, the effect was tested over a 40-min period, demonstrating a sustained reduction in power, albeit at a diminishing rate of decline up to a decrease in power of 7%.

3.2.2. Part-load

To investigate whether the oscillation effects are similar or whether new phenomena emerge under partial load conditions, the 30° dynamic inclination experiment is also conducted at 50% part load. Regulation valves typically exhibit non-linear responses to changes in their opening, which can also alter their response to different periods. Therefore, the absolute deviations in fuel flow and air flow are not expected to reduce proportionally with the power. Subsequently, part load conditions may yield distinct behaviour. The deviations in fuel utilisation (±3%) are larger than in full load (±2%), as is visualised with density plots of the measurement data in Fig. 5. This phenomenon can be attributed to the fact that an absolute deviation in fuel flow would represent a larger proportion of the fuel utilisation at lower fuel flow rates. This is especially relevant since it was pointed out in the previous section that changes in fuel utilisation can have a significant impact on the operation of the system. Nevertheless, the power reduction observed in Fig. 4 is absent under part-load conditions. This is the case because, at 50% load, the SOFC system operates at 75% fuel utilisation (see Fig. 5) instead of 85% fuel utilisation. This strategy is used by the SOFC system manufacturer to increase the amount of fuel in the anode off-gas flowing into the afterburner. This ensures that the burner receives sufficient fuel to maintain the temperature of the stack, which can be a challenge at 50% part-load operation. At 75% fuel utilisation with deviations of ±3%, the fuel utilisation limit is never exceeded.

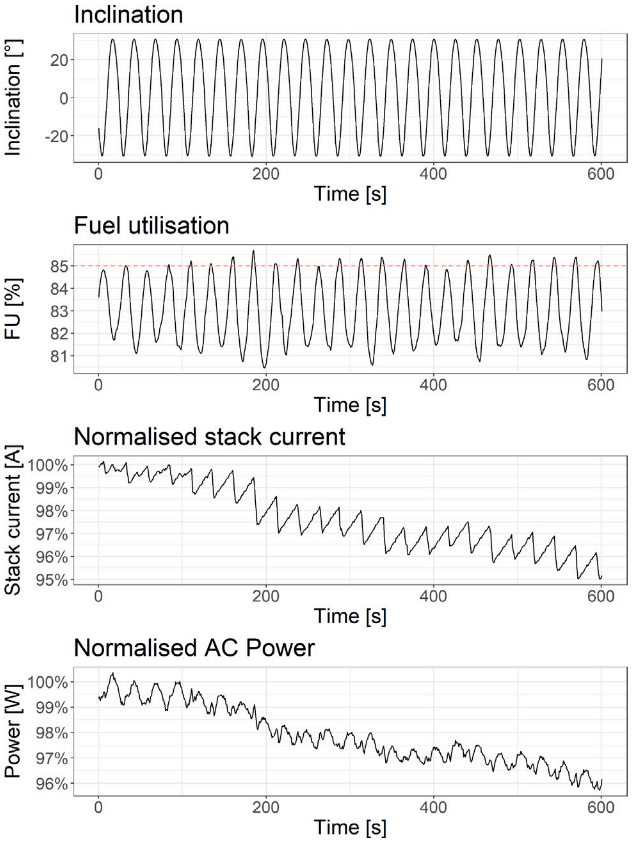


Fig. 4. Inclination, fuel utilisation, stack current and AC Power over testing time for the dynamic experiment using rotation around X-axis, an angle of 30 degrees and a period of 27 s. The stack current and AC power are given as a percentage of their nominal value.

3.3. Degradation test

Repositioning the fuel regulation valve to eliminate acceleration components during platform motion prevents the oscillation behaviour of system parameters in this particular experimental setup. However, ship motions are more intricate, and accelerations may arise in various directions. Consequently, it is necessary to evaluate whether extended exposure to forced oscillation behaviour results in SOFC damage or accelerated degradation.

During the 190 h of the degradation test the module produced power stably and nothing extraordinary is observed besides the forced oscillation behaviour. Fig. 6 shows the prediction of the net electric efficiency from the degradation experiment using GPR. The estimated net electric efficiency after 10,000 h of operation is 53.55% ±1.37%, corresponding to a degradation rate of 0.30 ±0.14%./kh. The figure also shows the anticipated net electric efficiency in red according to the nominal degradation of this system, which is roughly 0.2%./kh. Nevertheless, the nominal degradation also varies slightly per SOFC stack, especially at the beginning of the lifetime of the stack. Consequently, it can only be concluded from this test that the degradation during oscillations with a fast period of 8 s and an outer angle of 30° is in the same order of magnitude as in normal operation. Nevertheless, there is an indication of enhanced degradation. Thus, it is recommended to do long-term dynamic inclination experiments to accurately quantify the degradation rate to make sure the lifetime of the system will not be shorter when the system is operated on a ship.

3.4. Acceleration test

For this test, the platform is oscillated at high speeds to let the SOFC system experience high accelerations. The acceleration test is completed without noticeable safety hazards. The frequency of the oscillations in voltage becomes high for high acceleration speeds, because of the forced oscillation behaviour of the fuel regulation valve. However, the amplitude of the deviations in voltage and power production remains steady at high accelerations, see Fig. 7. At high accelerations, the deviations in power production are smaller than at slower accelerations. This is the case because, at high accelerations, the motion frequency deviates more from the natural frequency of the fuel regulation valve, resulting in a smaller amplitude for the variations in fuel feed.

3.5. Comparing normal and inclined operation

As indicated in the preceding sections, the oscillations of the platform cause deviations in several system parameters. In normal operation, there are also small fluctuations in system parameters due to the noise of the sensors and continuous feedback from the control system. Fig. 8 compares the amplitude of the fluctuations during normal operation with those observed during the presented test conditions. The figure shows that the static inclinations do not lead to a significant increase in the amplitude of the fluctuations compared with normal operations for most system parameters. However, dynamic inclinations result in a substantial amplification of the amplitude in all of the shown system parameters.

4. Recommendations for SOFC development and regulations

The results of the inclination experiments are used to propose design improvements for SOFC systems and develop well-founded class rules. First, it is discussed how representative the testing of this specific SOFC system is for SOFC systems in general. Following, guidance is given to stack developments to withstand inclinations and accelerations. Next, improvements to the design and control of SOFC systems are proposed to make them less prone to marine inclination conditions. Finally, the test results are compared with current marine fuel cell regulations to identify current gaps. The recommendations are summarised in Table 3.

4.1. Generalisability of experiment

The presented results are specific to the tested system and its operational and control strategies. For instance, the natural frequency period of fuel oscillations observed in the system could manifest differently in other systems. However, the test methods and design recommendations are applicable to SOFC systems in general, because the system components are very similar. This holds as well for larger high-power systems, which are expected for marine applications. Although, it might be more difficult to expose the whole system to dynamic inclinations.

4.2. Implications for stack development

The exposure of SOFCs to inclinations and accelerations presents opportunities for the development of cell materials and SOFC stacks. It becomes essential to design materials that can withstand these dynamic conditions while maintaining their electrochemical performance. Optimising the microstructure of the anode material can enhance its stability and prevent the formation of cracks or degradation during inclination or acceleration conditions [17]. The interconnect, which connects individual fuel cells in a stack, should also be designed to withstand increased mechanical stresses. Anode materials with enhanced mechanical properties, such as higher fracture toughness and resistance to mechanical deformation, can help withstand the stresses.

Because the ship motions can result in fuel feed fluctuations, the tolerance of high fuel utilisation in SOFCs could be enhanced. For instance, Futamura et al. [18] achieved high performance and stability at fuel utilisation up to 95% by co-impregnating noble metal catalyst

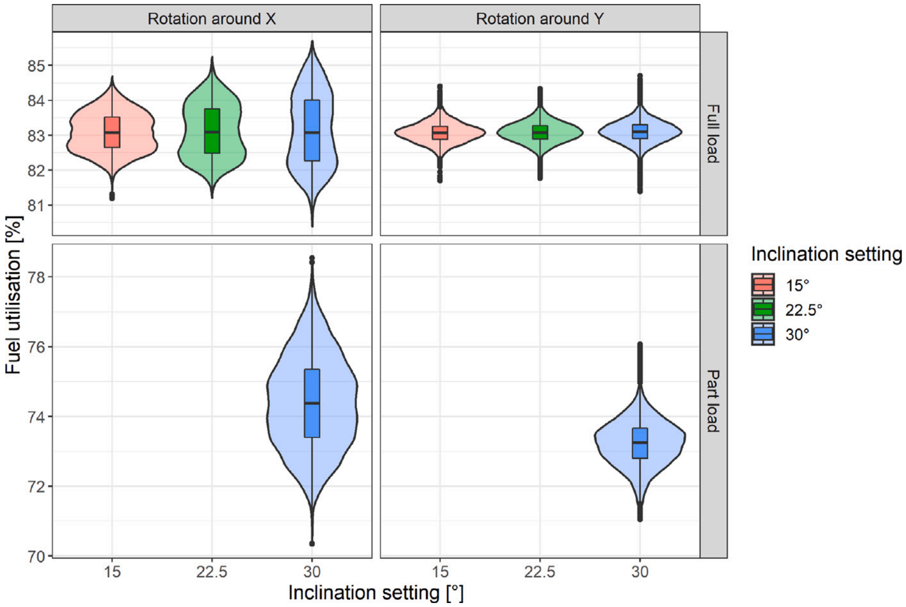


Fig. 5. Fuel utilisation at full load and part load for two rotation directions and different outer angles.

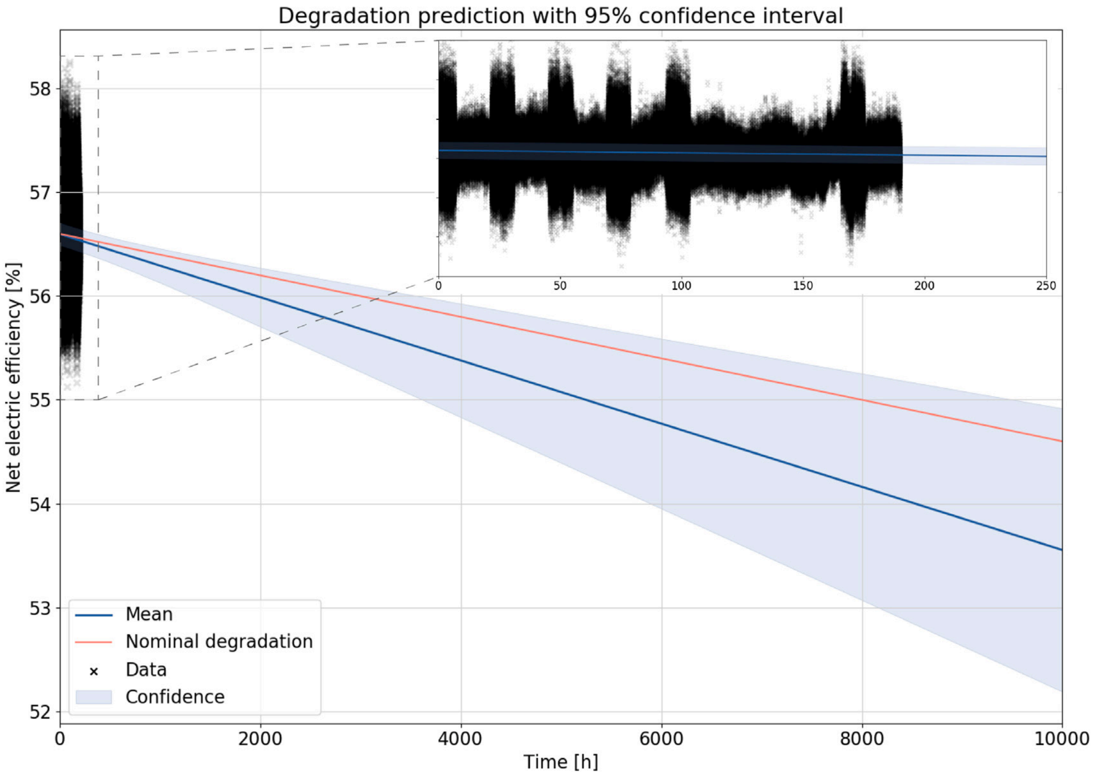


Fig. 6. Net electric efficiency during degradation experiment with oscillation around X axis at a period of 8 s up to 30 degrees. The red line shows the nominal degradation rate in system efficiency during its lifetime, which is 0.2%./kh.

nanoparticles with a conventional cermet anode. Moreover, this stimulates the development of anodes that are less prone to re-oxidation, such as perovskite oxide supported cells [19]. The fluctuations in fuel utilisation also offer an interesting topic for future research. Extensive understanding and modelling of the effect of fluctuations in oxidants and fuel flow fields in stack models are necessary to predict the effect of fuel feed fluctuations. The effect of recurring variations in fuel utilisation on the microstructure of SOFCs is to the knowledge of the authors not yet investigated and could be tested with SOFC cells and short stacks.

4.3. Implications for system operation

4.3.1. Forced oscillation behaviour

Although the tests did not result in experimental evidence that the instability of the fuel regulation causes direct damage to the cells, the degradation test did indicate the possibility of an enhanced degradation rate. Fuel fluctuations and stack instabilities are often concluded as causes of accelerated degradation [20]. Fluctuations in fuel utilisation and current result in increased local temperature variations. Moreover,

Table 3
Recommendations on stack, system and ship level for reducing negative consequences of marine inclinations conditions to SOFC systems.

Level	Aim	Recommendation
Stack development	Improve resistance to motions	Development of anode materials with higher fracture toughness and resistance to mechanical deformation
	Improve tolerance to temporary increased fuel utilisation	Co-impregnating noble metal catalyst nanoparticles with a conventional cermet anode
		Use of anodes that are less prone to re-oxidation such as perovskites
	Improve knowledge on effect of fuel utilisation fluctuations	Including fluctuations in fuel reactants and oxidants in flow field modelling for stacks
		Stack testing on the effect of fuel utilisation fluctuations on SOFC microstructure
System operation and control	Prevent fuel flow fluctuations	Tune natural frequency of fuel regulation valve
		Use valve that is not affected by accelerations, such as stepper motor valve
	Limit effect of fuel fluctuations on system operation	Increase fuel utilisation limit
		Use advanced control of fuel utilisation to reduce the effect of fuel fluctuations, such as: time-delayed feedback, feedforward control, or model predictive control
		Maintain fuel flow rate when current is reduced by safety mechanism
	Prevent leakage or backflow of liquids	Use non-gravity based check valves
		Adapt level sensors to inclined or sloshing level surfaces of liquids
Ship design and regulations	Limit acceleration experienced by SOFC	Evaluate the acceleration experienced by the SOFC in relation to the distance to the centre of rotation of the ship
	Improve marine fuel cell regulations	Mandate dynamic inclination test on full range of motion periods of dedicated application
		Mandate to test the effect of inclinations on stack and BOP

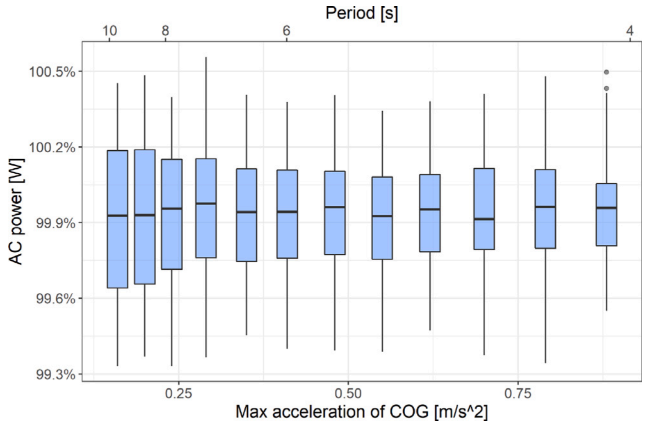


Fig. 7. Normalised power production during acceleration experiment for different acceleration speeds. The acceleration speed represents the maximum acceleration during the given oscillation period as experienced by the centre of gravity (COG). AC power is given as a percentage of its nominal value.

fuel starvation and nickel oxidation can subsequently increase mechanical stress in the cells. In case of fuel overconsumption, it can lead to a significant drop in cell potential, possibly modifying the anode microstructure irreversibly by re-oxidisation. Irreversible damages in the microstructure often result in an accelerated degradation rate. In short, it would be preferred to prevent or limit fluctuations in the fuel feed as much as possible.

During the experiment, forced oscillation behaviour in the system parameters is eliminated by repositioning the fuel regulation valve. However in a ship, completely removing the acceleration component may not be feasible due to its motions in different directions. As an alternative, the spring stiffness of the fuel regulation valve (see Fig. 3(b)) could be modified, changing the natural frequency to prevent a response at the motion periods in the dedicated ship applications. Alternatively, a fuel regulation mechanism that is unaffected by any accelerations, such as a motor stepper valve, could be used. This was tested at the end of the test campaign for different dynamic inclination conditions. During this test, there were no increased fluctuations in operational parameters compared to normal operation, meaning that the fluctuations in fuel feed were completely resolved.

4.3.2. Gradual power decrease

The gradual power decrease that results from periodical exceedance of fuel utilisation is induced by the system's control software. In the case periodical fluctuations in system parameters by ship motions cannot be prevented, there should be a robust control system in place that ensures the effects do not propagate through the whole system. In this specific case, there are several possibilities to prevent this:

- Increase the fuel utilisation limit for which the current is reduced. It is commonly acknowledged that 85% single-pass fuel utilisation is a feasible limit for the operation of planar SOFC stacks. At 90% fuel utilisation, there is a much higher contribution of concentration polarisation and a significant risk of fuel starvation, causing oxidation mainly at the end of the fuel channel [21]. In practice, SOFC systems have a fuel utilisation limit between 85% and 90% at which the current is reduced to prevent damage to the cells. However, the consequence of shortly exceeding this limit might not be that high, meaning there is some leeway in the setting of the fuel utilisation limit when experiencing quick fuel flow deviations, as in this experiment. Especially when combined with anode with materials that tolerate higher fuel utilisation (as discussed in Section 4.2), the fuel utilisation limit could be increased.
- Use of more sophisticated control strategies for fuel utilisation. A time-delayed feedback control would make sure that a very short exceedance of the fuel utilisation limit does not immediately lead to a change in the operation of the fuel cell system. Time-delayed feedback is an easy and effective method to maintain stability and prevent unnecessary actions in systems with complex dynamics and disturbances. Alternatively, feedforward control or model predictive control could be used to limit the fluctuations by using the ship motions to predict fuel feed fluctuations. However, this would lead to complex control architecture and it might be easier to prevent the fuel feed fluctuations.

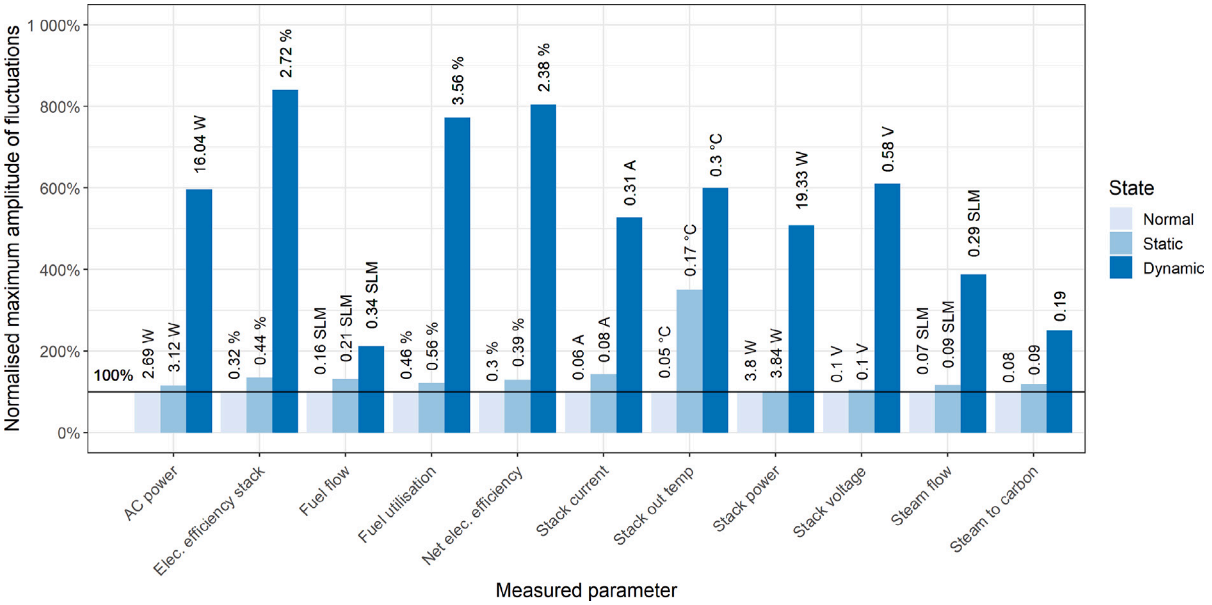


Fig. 8. Comparison in the maximum amplitude of system parameter measurements between normal operation, static and dynamic operation. The data labels are absolute values of the amplitude while the vertical axis is normalised to be able to show the different parameters on one axis.

- Maintain fuel flow rate when current is reduced as a response to the fuel utilisation exceedance. This approach would marginally lower fuel utilisation, thereby avoiding repeated breaches of the fuel utilisation limit. Nevertheless, such an approach would result in a decrease in the nominal system efficiency during scenarios where the stack current is reduced. In order to address this issue, a distinct control loop could be established that identifies instances where current reduction occurs as a safety mechanism rather than intentional power regulation. However, implementing such a control loop would generally be complex, as it would require handling special cases where the loop is always active.

4.3.3. *Flow of liquids*

Liquid flows and tanks should be designed such that they do not overflow or backflow during inclined operation. Especially gravity-based components to prevent backflow, such as air gaps or siphons can cause problems when the system is inclined. Level sensors and their control architecture should be designed such that they work properly for inclined or sloshing level surfaces. For large inclinations, the low-level sensor could be positioned higher than the high-level sensor, which the control architecture should be able to understand. Moreover, intakes should be designed such that the inflow of the liquid is guaranteed under the inclination conditions.

4.3.4. *Structural support*

The implications of static and dynamic inclinations should be integrated early in the design process of the system. Although there were no structural failures in the tested system, the SOFC stack is a heavy component which can exert significant forces on the structural components during accelerations. The supporting structural components should be designed for these loads, especially if the direction of these loads change to the lateral direction.

4.4. *Implications for ship design and regulations*

Although there are static and dynamic inclination regulations in place for marine fuel cell systems, the results of this research show that they need further development. According to the regulations, a single motion period is prescribed for dynamic inclination testing. Nonetheless, our experiment reveals that the system's response is significantly influenced by the motion period. Therefore, it is advisable to conduct the dynamic inclination test with the motion periods present in the dedicated application or to perform the test within the range of 8 to 50 s for type approval purposes, thus encompassing a broad spectrum of seagoing ships.

Given the expected high power output of marine solid oxide fuel cell (SOFC) power plants, the imposition of static and dynamic inclinations presents a challenge due to the potential size and weight of the systems. As a consequence, recent regulations mandate inclination tests solely for the stack technology [22]. Nevertheless, the experiment results prove that the BOP components and their interface with the stack have a considerable influence on the operational performance of the stack. Hence, we recommend that type approval testing includes the response to marine conditions by the SOFC stack and BOP as well as their mutual influence. Further development of marine fuel cell regulation could include guidelines for the design of the system including suitable components, regulators and materials to withstand marine inclination conditions.

Finally, although high accelerations did not result in direct damage or operational troubles to the SOFC system, locating the SOFC system far away from the centre of rotation of the ship might result in even larger accelerations than are tested in this study. The position of SOFC systems in the ship should be evaluated with respect to the experienced and allowable accelerations of the SOFC system.

5. Conclusion

SOFC systems could reduce emissions from seagoing ships, but, it is unknown whether motions from waves or other sources influence the safety, operability, and lifetime of SOFC systems. In this research, a 1.5 kW SOFC module is operated on an inclination platform that emulates ship motions, to evaluate the influence of marine conditions in terms of static and dynamic inclinations on the safety, operation and lifetime of SOFC systems. The module is inclined statically and dynamically around two horizontal axes of rotation up to an outer angle of 30°, including motion periods between 8 to 50 s.

The module is tested successfully without any notable hazards during all different test conditions. Furthermore, there is no indication of cell defects or cathode delamination. While static inclinations do not impact the operation of the SOFC module, dynamic inclinations result in adverse effects. The fuel regulation valve acts as a mass–spring system, causing significant fluctuations in fuel flow to the fuel stack and resulting in deviations in fuel utilisation, power production, and efficiency. These deviations are largest at motion periods between 16 and 26 s, where fuel utilisation deviations of ±2% cause a gradual decrease in power output as the fuel utilisation limit is periodically exceeded. From the 190-h degradation test, the degradation rate is estimated to be 0.32 ±0.14 %./kh. This degradation rate indicates an enhanced degradation rate when compared to the nominal degradation rate (0.2 %./kh), although long-term testing is needed to accurately determine how much the degradation increases.

Based on the experimental results, the following recommendations are proposed for the design and regulation of marine SOFC systems:

- Besides the stack technology, the exposure of BOP components to static and dynamic inclinations and their influence on the SOFC system should be evaluated. The use of flow regulation valves that are affected by accelerations should be avoided or, alternatively, verify that their natural frequency is adequately distant from the anticipated periodic motion that can occur at the application site.
- Control feedback should be designed to mitigate expected forced periodical deviations in operational parameters from affecting the proper operation of the system.
- Liquid-containing systems should be designed to prevent overflow or leakage during inclination, and level sensors should take into account any inclined or sloshing surface level.
- Power producing systems should be tested over a wide range of dynamic motions with periods between 8 and 50 s.

Some practical engineering solutions are proposed to prevent the negative consequences on SOFC systems by ship motions. Nevertheless, future research is needed to understand the effect of fluctuations in oxidants and fuel reactants on the microstructure of the cells and stack. Furthermore, it should be confirmed whether motions result in an amplified degradation rate by exposing the system to motions for a long continuous period. For accurate degradation tests, it is recommended to do this testing on stacks instead of an integrated SOFC system. Additionally, forthcoming demonstration projects of SOFC systems on ships present an opportunity to collect data to evaluate the SOFC system's performance under actual ship motions in six degrees of freedom.

Although dynamic inclinations affect the operation of the tested SOFC module, these issues can be addressed through relatively simple design changes. Therefore, inclinations and ship motions do not pose a significant challenge to the integration of SOFCs in seagoing vessels.

CRediT authorship contribution statement

B.N. van Veldhuizen: Conceptualization, Methodology, Formal analysis, Writing – original draft. **E. Zera:** Methodology, Investigation, Writing – review & editing. **L. van Biert:** Conceptualization, Methodology, Writing – review & editing. **S. Modena:** Resources, Project administration. **K. Visser:** Supervision, Funding acquisition. **P.V. Aravind:** Supervision, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential

Table A.1
Minimum, maximum and typical roll periods for common sea-going ships [24].

Shiptype	Roll period [s]		
	Min	Max	Typical
Bulk carrier	8	16	–
Container vessel	10	40	–
Cruise vessel	14	25	–
Ferry	10	25	15
General cargo	10	20	–
Naval ship	10	15	12
OSV/PSV	8	16	11
Tanker	10	20	–
Overall	8	40	–

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Appendix A. Marine inclination conditions and regulations

Seagoing ships experience ship motions in all degrees of freedom induced by waves, wind and manoeuvring, which can be significant. The following influence the ship motions [23]:

- Ship type and dimensions
- Loading conditions
- Sea state at operating location
- Ship speed and manoeuvring

Generally, the inclinations are the largest in the roll direction. Table A.1 gives an overview of common roll periods for different ship types. The accelerations that the equipment experiences are also dependent on the position on the ship. This is additionally relevant for the evaluation of SOFC for ships, because installing them decentralised is seen as a beneficial option [7]. Table A.2 shows measured or simulated accelerations for different ship types.

All shipboard equipment and machinery must be designed to function properly even when exposed to these inclinations and motions. The regulations by different class societies for inclinations for shipboard machinery are summarised in Table A.3. The test conditions in the experiments of this study are derived from the shown marine conditions and regulations.

Appendix B. Data processing

Cleaning and filtering of data

The tested system is available for commercial purposes and thus includes operational strategies such as occasional filling of the steam dosing tank, hourly toggling of the airflow, and a 12-h surge in fuel and air flow to verify their regulation. These strategies and safety operations have a temporary influence on the system's stable operation and are therefore excluded from the collected data

Normalisation of data

Because of intellectual property considerations of the SOFC manufacturer, the shown data is normalised. Some of the shown data is normalised to the nominal conditions of the system at the beginning of the experimental campaign:

$$x'(t) = x(t)/x_{nominal} \tag{B.1}$$

Table A.2
Maximum measured or simulated acceleration for different ship types in sea waves up to sea state 8.

Shiptype	At location	Lateral acceleration m/s^2	Vertical acceleration m/s^2	Study type	Source
OSV	Anywhere	2.58	5.51	Measured	Jamal et al. [25]
Large passenger	Passenger area	1.00	2.00	Measured	Lawther and Griffin [26]
Small passenger	Bow	–	1.9	Simulated	Cakici [27]
Small passenger	Bow	–	1.62	Simulated	Kucukdemiral et al. [28]
Cruise	Anywhere	–	1.40	Simulated	Kim and Kim [29]
Training ship	After deck	0.49	1.08	Measured	Shigehiro et al. [30]

Table A.3
Requirements for inclination testing of shipboard equipment and machinery for different class societies [31–36].

Equipment	Class	Heel angle			Trim angle			Simultaneous	Minimum time
		Static	Dynamic		Static	Dynamic		–	[min]
		[°]	[°]	[s]	[°]	[°]	[s]		
Main and auxiliary machinery	ABS	15	22.5	–	5	7.5	–	Yes	–
	BV	15	22.5	10	5	7.5	5	Yes	–
	DNV	15	22.5	–	5	7.5	–	Yes	–
	LR	22.5	22.5	10	22.5	22.5	10	No	15
	KR	15	22.5	–	5	7.5	–	Yes	–
Safety or emergency equipment	ABS	22.5	22.5	–	10	10	–	Yes	–
	BV	22.5	22.5	10	10	10	5	Yes	–
	DNV	22.5	22.5	–	10	10	–	Yes	–
	LR	22.5	22.5	10	22.5	22.5	10	No	15
	KR	22.5	22.5	–	10	10	–	Yes	–

The Society may consider deviations from these angles of inclination taking into consideration the type, size and service condition of the ship.
On ships for the carriage of liquefied gases and chemicals, the emergency power supply is to remain operational with the ship flooded up to a maximum inclination of 30°.

Maximum deviation determination

In order to ensure accurate comparisons between the deviations in operational parameters during normal operation and during the experiment, it is necessary to account for high-frequency noise in the operational data and gradual changes over time. Therefore, a maximum deviation is calculated, which takes into account the variability in the data over a certain time period:

$$\Delta x_{max} = \max(|x_i - x_{i+\frac{1}{2}T}|) \tag{B.2}$$

where $x_{i+\frac{1}{2}T}$ is the value of the dedicated variable at half oscillation period after the current time. To prevent the possibility of overlapping different test conditions, Eq. (B.2) is used for each different combination of inclination setting, rotation direction, and oscillation period.

References

[1] IMO, Fourth IMO GHG study, 2020.
[2] European Environmental Agency, Emissions of air pollutants from transport, 2020, URL: https://www.eea.europa.eu/data-and-maps/indicators/transport-emissions-of-air-pollutants-8/transport-emissions-of-air-pollutants-8.
[3] IMO, Rules on ship carbon intensity and rating system enter into force, 2022, URL: https://www.imo.org/en/MediaCentre/PressBriefings/pages/CII-and-EEXI-entry-into-force.aspx.
[4] IMO, Nitrogen oxides (NOx) – regulation 13, 2020, URL: http://www.imo.org/en/OurWork/Environment/PollutionPrevention/AirPollution/Pages/Nitrogen-oxides-(NOx)----Regulation-13.aspx.
[5] L. van Biert, M. Godjevac, K. Visser, P.V. Aravind, A review of fuel cell systems for maritime applications, J. Power Sources 327 (February 2018) (2016) 345–364, http://dx.doi.org/10.1016/j.jpowsour.2016.07.007.
[6] F. Baldi, S. Moret, K. Tammi, F. Maréchal, The role of solid oxide fuel cells in future ship energy systems, Energy 194 (2020) 116811, http://dx.doi.org/10.1016/j.energy.2019.116811.
[7] L. Kistner, A. Bensmann, R. Hanke-Rauschenbach, Optimal design of a distributed ship power system with solid oxide fuel cells under the consideration of component malfunctions, Appl. Energy 316 (2022) 119052, http://dx.doi.org/10.1016/J.APENERGY.2022.119052, URL: https://linkinghub.elsevier.com/retrieve/pii/S0306261922004500.
[8] A. Haseltalab, L. van Biert, H. Sapra, B. Mestemaker, R.R. Negenborn, Component sizing and energy management for SOFC-based ship power systems, Energy Convers. Manage. 245 (2021) 114625, http://dx.doi.org/10.1016/J.ENCONMAN.2021.114625.
[9] M. Rivarolo, D. Rattazzi, L. Magistri, Best operative strategy for energy management of a cruise ship employing different distributed generation technologies, Int. J. Hydrogen Energy 43 (52) (2018) 23500–23510, http://dx.doi.org/10.1016/j.ijhydene.2018.10.217.
[10] A. Choudhury, H. Chandra, A. Arora, Application of solid oxide fuel cell technology for power generation - A review, 2013, http://dx.doi.org/10.1016/j.rser.2012.11.031.
[11] B. Veldhuizen, E. Zera, L. van Biert, S. Modena, P. Aravind, K. Visser, H. Hopman, Experimental evaluation of SOFC system exposed to marine inclination conditions, ECS Trans. 111 (6) (2023) 687–698, http://dx.doi.org/10.1149/11106.0687ecst.
[12] R.S. Gemmen, C.D. Johnson, Evaluation of fuel cell system efficiency and degradation at development and during commercialization, J. Power Sources 159 (1) (2006) 646–655, http://dx.doi.org/10.1016/J.JPOWSOUR.2005.10.109.
[13] R.S. Gemmen, M.C. Williams, K. Gerdes, Degradation measurement and analysis for cells and stacks, J. Power Sources 184 (1) (2008) 251–259, http://dx.doi.org/10.1016/J.JPOWSOUR.2008.06.047.
[14] L. Zhu, J. Chen, Prognostics of PEM fuel cells based on Gaussian process state space models, Energy 149 (2018) 63–73, http://dx.doi.org/10.1016/j.energy.2018.02.016.
[15] H. Deng, W. Hu, D. Cao, W. Chen, Q. Huang, Z. Chen, F. Blaabjerg, Degradation trajectories prognosis for PEM fuel cell systems based on Gaussian process regression, Energy 244 (2022) 122569, http://dx.doi.org/10.1016/j.energy.2021.122569.
[16] Tameson, Proportional solenoid valve - how they work, 2023, URL: https://tameson.com/pages/proportional-solenoid-control-valve.
[17] S. Zarabi Golkhatmi, M.I. Asghar, P.D. Lund, A review on solid oxide fuel cell durability: Latest progress, mechanisms, and study tools, Renew. Sustain. Energy Rev. 161 (2022) 112339, http://dx.doi.org/10.1016/J.RSER.2022.112339.
[18] S. Futamura, A. Muramoto, Y. Tachikawa, J. Matsuda, S.M. Lyth, Y. Shiratori, S. Taniguchi, K. Sasaki, SOFC anodes impregnated with noble metal catalyst nanoparticles for high fuel utilization, Int. J. Hydrogen Energy 44 (16) (2019) 8502–8518, http://dx.doi.org/10.1016/J.IJHYDENE.2019.01.223.
[19] L. Lu, C. Ni, M. Cassidy, J.T. Irvine, Demonstration of high performance in a perovskite oxide supported solid oxide fuel cell based on la and Ca co-doped SrTiO3, J. Mater. Chem. A 4 (30) (2016) 11708–11718, http://dx.doi.org/10.1039/c6ta04074h.
[20] C. Comminges, Q.X. Fu, M. Zahid, N.Y. Steiner, O. Bucheli, Monitoring the degradation of a solid oxide fuel cell stack during 10,000 h via electrochemical impedance spectroscopy, Electrochim. Acta 59 (2012) 367–375, http://dx.doi.org/10.1016/J.ELECTACTA.2011.10.080.
[21] Q. Fang, L. Blum, R. Peters, M. Peksen, P. Batfalsky, D. Stolten, SOFC stack performance under high fuel utilization, Int. J. Hydrogen Energy 40 (2) (2015) 1128–1136, http://dx.doi.org/10.1016/J.IJHYDENE.2014.11.094.
[22] Lloyds Register, Type Approval System Test Specificaton Fuel Cell Modules, Technical Report, 2023.

[23] J.M.J. Journée, W.W. Massie, Offshore Hydromechanics, Technical Report, second ed., TU Delft, 2008.

[24] B. Buchner, B. Abeil, L. Kaydihan, J. Koning, R.V. Veer, Research into container loss above the Dutch Wadden Islands after the MSC ZOE incident, in: PRADS, 2022, pp. 1–22.

[25] Jamal, A. Sulisetyono, W.D. Aryawan, Review of the seakeeping criteria for the study of a passenger ship criteria in Indonesian water, in: IOP Conference Series: Materials Science and Engineering, 2020, 012041, http://dx.doi.org/10.1088/1757-899X/982/1/012041.

[26] A. Lawther, M.J. Griffin, The motion of a ship at sea and the consequent motion sickness amongst passengers, Ergonomics 29 (4) (1986) 535–552, http://dx.doi.org/10.1080/00140138608968289, URL: https://www.tandfonline.com/doi/abs/10.1080/00140138608968289.

[27] F. Cakici, Vertical acceleration control using LQG approach for a passenger ship, Ocean Eng. 241 (2021) 110040, http://dx.doi.org/10.1016/J.OCEANENG.2021.110040.

[28] I.B. Kucukdemiral, F. Cakici, H. Yazici, A model predictive vertical motion control of a passenger ship, Ocean Eng. 186 (2019) 106100, http://dx.doi.org/10.1016/J.OCEANENG.2019.06.005.

[29] J. Kim, Y. Kim, Time-domain analysis of passenger comfort on cruise ships under motion responses in waves, Proc. Inst. Mech. Eng. M 228 (4) (2014) 331–347, http://dx.doi.org/10.1177/1475090213486890.

[30] R. Shigehiro, T. Kuroda, Y. Arita, Evaluation method of passenger comfort for training ships in irregular seas, in: Proceedings of the International Offshore and Polar Engineering Conference, Vol. 4, 2001, pp. 562–569.

[31] ABS, Fuel Cell Power Systems for Marine and Offshore Applications, Technical Report, 2019.

[32] ABS, Rules for Building and classing Marine Vessels - Part4, Vessel Systems and Machinery, Technical Report, 2023.

[33] Bureau Veritas, Part C - machinery, electricity, automation and fire protection, in: Rules for the Classification of Steel Ships, 2021, URL: https://marine-offshore.bureauveritas.com/bv-rules.

[34] DNV, Ship Rules Pt.4 Ch.1 - Machinery Systems - General, Technical Report, 2022, http://dx.doi.org/10.4233/uuid.

[35] Lloyds Register, Type Approval System Test Specification Number 1, Technical Report, 2022.

[36] Korean Register, Rules for the Classification of Steel Ships Part - Part 5 Machinery Installations, Technical Report, 2011.