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A Mechanical method of classifying the state of solid matter beneath a floating cover over an anaerobic lagoon

Dat Nha BUI[1,a*], Thomas KUEN[2,b], Benjamin Steven VIEN[1,c],
L.R. Francis ROSE[3,d], Wing Kong CHIU[1,e]

[1]Department of Mechanical & Aerospace Engineering, Monash University, Clayton, VIC 3008, Australia

[2]Melbourne Water Corporation, 990 La Trobe Street, Docklands, VIC 3008, Australia

[3]Defence Science and Technology Group, 506 Lorimer Street, Fishermans Bend, VIC 3207, Australia

[a]Dat.Bui1@monash.edu, [b]Thomas.Kuen@melbournewater.com.au, [c]Ben.Vien@monash.edu,
[d]Francis.Rose1@defence.gov.au, [e]Wing.Kong.Chiu@monash.edu

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Abstract. The formation and accumulation of scum—a layer formed from fats, oils and greases (FOG) and solid particles in the sewage—can occur under the geomembrane of a covered anaerobic wastewater treatment lagoon. Monitoring the state of scum is important for both operational reasons in the management of a wastewater treatment plant and for physical reasons related to the structural health assessment and monitoring of the covers. This task is challenging and currently involves an inspector physically assessing the scum through various sampling ports across the membrane. Another more subjective and less expensive method is where an experienced assessor classifies the state of the scum by walking on the cover and “feeling” its response to the impact of their footsteps. The development of a new objective, rather than the current subjective, approach to assessing the state and extent of the scum under the covers is proposed. In collaboration with Melbourne Water, we investigate an in-situ mechanical method to quantitatively assess the state of this scum. In this study, the frequency response functions of the membrane-scum system of different states of scum excited using a low-energy mechanical excitation were estimated. Our findings indicate that the high-gain frequency range of the cover-scum system is higher with the scum of a harder state ranging from 30-40 Hz for soft-to-fluffy scum up to 60-80 Hz for hard scum. Our findings also indicate that the response of the cover-scum system is highly damped. Differences between different states of scum have been observed in both the gain and the phase angle of the frequency response functions. Numerically, the area under the frequency response function curves decreases with the hardness of scum. This information paves the way for the next steps of this work, including improving the accuracy in modelling the scum and developing a mechanical means to quantitatively monitor the scum formation.

Introduction

Anaerobic lagoons have been widely adopted in wastewater secondary treatment processes as they are cost-effective [1,2]. To prevent the unpleasant odours and greenhouse gases from being released into the environment, uncovered lagoons rely on a naturally formed crust layer on top of them [3,4], which is not as effective as employing geomembranes as floating covers for the lagoons. Furthermore, in covered lagoons, the biogas generated during anaerobic digestion of the sewage, which is rich in methane, can be collected and utilised to generate electricity [1].

Scum—a layer formed from fats, oils and greases (FOG) and solid particles in the sewage—can form, and accumulate under the cover of a covered anaerobic lagoon. It has been observed in the dairy and meat processing industries that accumulated scum in the lagoons can have some undesireable impacts such as reducing the effective operation volume and clogging the gas collection system hence reducing the biogas yeild [5,6]. The scum layer can also consolidate and solidify over time forming the so-called scumbergs. In certain circumstances, their buoyance and movement can result in high-level stresses to the cover, or even cause irreversible damage to it [7-10].

The ability to monitor the state and extent of the scum, and predict the timing and extent of its future spread, is therefore important in helping to manage the operation of these anaerobic lagoons and mitigate any unwanted impacts on either the wastewater treatment processes or the structural integrity of the floating covers.

Melbourne Water's (MW) Western Treatment Plant (WTP) has two covered anaerobic lagoons, and they also experience the development of scum. Here, a cover-walk inspection is the current method to determine the extent and state of scum under the covers. In this method, an experienced operator qualitatively classifies the scum as "fluffy, soft, medium" or "hard" by walking on the cover and "feeling" its response to the impact of their footsteps [11]. A quantitative and objective method will provide a more useful, valuable, accurate, consistent, and automatable scum assessment procedure.

Recently, in the collaboration between MW Corporation and the research team from Monash University Acoustic Laboratory, efforts have been made to deal with the problem of how to quantitatively determine the extent and state of the scum under the covers. Several non-contact scum assessment methods with different approaches including thermography [11,12] and photogrammetry [8,13] have already been developed. This paper on the other hand demonstrates the potential additional benefits of a technique using mechanical vibrations to characterise the state of scum underneath the cover.

Materials and Methods

In this study, the cover-scum system (the system) was considered a single-input single-output (SISO) system which was excited by tapping an impact hammer on a striking plate placed on the cover. The input force was recorded by the in-built force transducer of the hammer; and simultaneously, the output acceleration was measured using an accelerometer placed next to the excitation point (Figure 1a). This was done repeatedly at various locations on the cover to assess different states of scum across the lagoon (Figure 1b).

The recorded data length was maintained sufficiently long to ensure each tap is fully captured i.e., the input and output have decayed to near zero at the end of the recording. Assuming that all the taps are independent of each other, each recorded tap can then be considered an independent observation of the system's dynamic characteristic. By maintaining a consistent experiment setup for all the measurements across the lagoon, and since the size of the lagoon is significantly large (approximately 450 m × 175 m) that the energy from the excitation is expectedly dissipated before the boundary effect could take place, any change in the dynamic response, therefore, would imply a change in the state of the scum underneath the cover.

The states of scum reported in the latest cover-walk inspection provided by MW up to the experiment day at the related locations were assigned to the collected tap data (Figure 1c & d). The recorded time series data was transformed into the frequency domain. The frequency response function (FRF) was then evaluated in terms of gain and phase angle. Finally, the area under the FRF gain curves (AUC) across certain frequency bandwidths were calculated for every tap and statistically analysed to check if they are significantly different across different states of scum. Further details of the whole procedure are described below.

Experiment Setup

The striking plate used in the experiment is a 65×65×8 mm steel plate. The accelerometer mounting plate was sized 86×115×8 mm and placed next to the striking plate. The mounting plate was used as the sensor cannot be attached directly to the cover, while the striking plate was a safety precaution to avoid directly tapping the cover. The selection of the plates was to ensure that they maintain contact with the cover by their weights under the low-energy excitation from the hammer, yet they are light enough not to absorb all the energy. The edge-to-edge distance between the two plates was 10 mm. Both the hammer and the accelerometer were connected to a multi-channel data acquisition device so that their readings were recorded simultaneously.

For each state of scum (so-called "class") c, $L^{[c]}$ locations were tested. At each location $l \in \{1,2,\dots,L^{[c]}\}$, $S^{[c,l]}$ taps were performed repeatedly, and $S^{[c,l]}$ data blocks $\left(x^{[c,l,s]}, y^{[c,l,s]}\right)$ with $s \in \{1,2,\dots,S^{[c,l]}\}$ were recorded accordingly at Δf sampling frequency.

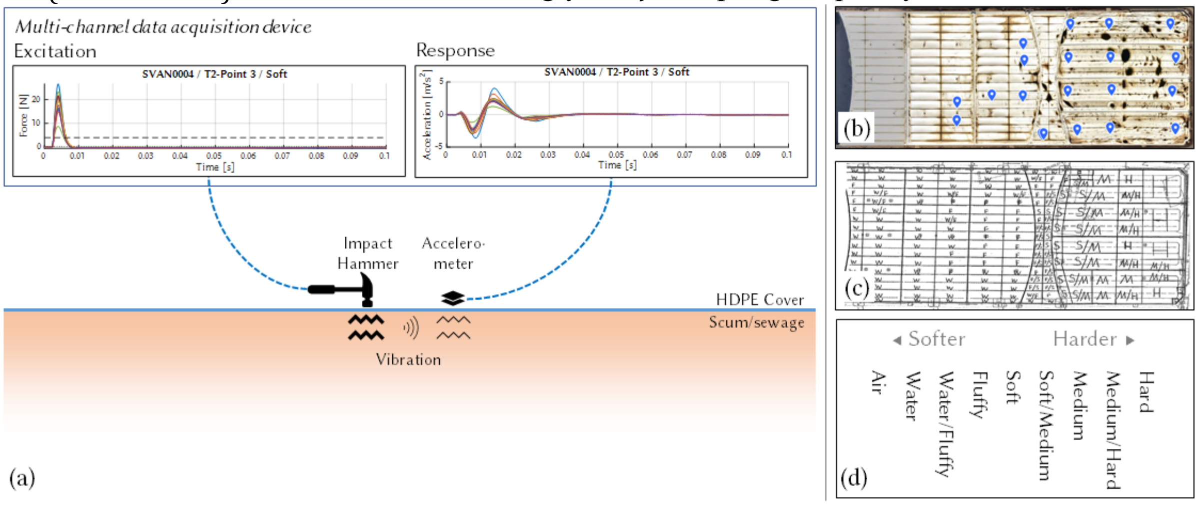

Figure 1. (a) Experiment setup, (b) tested locations (📍) across the lagoon, (c) the cover-walk inspection report provided by MW, and (d) the scum states used in the cover-walk assessment.

Data Processing

Each data block was verified automatically with an in-house developed tap qualification function followed by a visual inspection of the time series plots. After the verification process, any tap with a double-hit or too weak ("under range") input was discarded. The remaining valid taps were then truncated to the same length T and rearranged into $M^{[c,l]}$ truncated sub-records $\left(x^{[c,l,m]}[n], y^{[c,l,m]}[n]\right)$, where $n \in \{0,1,\dots,N-1\}$, $N = T\Delta f$, and $m \in \{1,2,\dots,M^{[c,l]}\}$, $M^{[c,l]} \le S^{[c,l]}$. To reduce leakage error, a 2% exponential window was applied to both $x^{[c,l,m]}$ and $y^{[c,l,m]}$.

For each valid tap $x^{[c,l,m]}$ and $y^{[c,l,m]}$, input and output power spectral density (PSD) G_{xx} and G_{yy}, cross power spectral density (CPSD) G_{xy}, and FRF H were calculated. For each location, squared coherence values γ_{xy}^2 were also evaluated.

The averaged AUC values over a bandwidth $[f_a, f_b]$ is defined as the integration of the FRF gain over that bandwidth. With discretized frequencies, the integration is approximated using a trapezoidal sum as below:

$$ {}_{f_a}^{f_b}E_H = E_H[a,b] = \frac{d_f}{2}\sum_{k=a}^{b-1}\left(|H[k]| + |H[k+1]|\right), \tag{1} $$

with $f_a = a d_f$, $f_b = b d_f$; $a, b \in \left\{0,1,\dots,\left\lfloor \frac{N}{2} \right\rfloor\right\}$ and $b > a$.

Results

Table 1 shows the classes of scum used in the cover-walk reports sorted by the level of hardness, and the number of valid locations and taps collected for each class. In total, 672 taps were collected on two anaerobic lagoons on days D+139, D+180 and D+188, where D was the day of the cover-walk report being used for scum class reference values. 462 of these taps were accepted and further processed. They were measured at 33 unique locations across 7 different states of scum. Figure 2a shows the waveforms of the input force and response acceleration of 18 taps collected at the same location, "25W.26", during the first 100 ms. To compare the shape of these waveforms, they are normalized by their local maximum value and plotted in Figure 2b. PSD, CPSD, FRF gain and phase angle of these 18 taps are shown together with the squared coherence values of the related location in Figure 3.

The FRF gain and phase angle calculated for each of all 462 valid taps at all locations are plotted in Figure 4a&b; the corresponding coherence values of 33 related locations are shown in Figure 4c. The colour of a line on these plots represents its related scum class. Note that in Figure 4a&b, FRF curves of taps that belong to the same location tend to stay very close to each other forming a "bundle" of lines that visually appears as a thick line.

Standard notched box charts described in [14] were used to visualize the AUC values calculated over two different frequency bandwidths [10, 20] Hz and [20, 50] Hz (Figure 5, left and right respectively). Each box represents the data of one scum class.

Table 1. Scum classes used in cover-walk reports.

Abbreviation	Scum Class	Total Locations with Valid Taps	Total Valid Taps
A	Air	4	43
W	Water	4	59
W/F	Water/Fluffy	-	-
F	Fluffy	8	99
F/S	Fluffy/Soft	-	-
S	Soft	6	120
S/M	Soft/Medium	5	42
M	Medium	1	17
M/H	Medium/Hard	-	-
H	Hard	5	82

Discussion

Waveform Reproducibility and System Linearity

In the time domain, it can be seen from Figure 2a that the peak of the impact force ranges from 4.16 N to 26.21 N. Accordingly, the maximum absolute response acceleration recorded in the lightest tap is 0.71 m/s^2 while the value is 3.35 m/s^2 for the hardest tap. Figure 2b further shows that all the taps share the same waveform. In addition, the width of the impulse is about 5 to 6 ms.

In the frequency domain, the input PSD curves (Figure 3a) of all taps gradually decrease with frequency and reach -20 dB attenuation from their maximum at above 300 Hz. In other words, with such excitations, the frequency characteristics of the system can be effectively analyzed up to 300 Hz. As mentioned previously, the level of excitation is different for each tap, hence the magnitudes of both input and output PSD are also different; however, the PSD and CPSD curves of all taps have a similar shape (Figure 3a,b&e). This similarity can be seen more clearly in the FRF gain and phase angle plots (Figure 3c,d) in which the curves of all taps stay very close to each other over the frequency range of 15 up to 150 Hz. This is an indication of good linearity of the system over this bandwidth which is further confirmed by very high (> 0.95) squared coherence values (Figure 3f). Beyond 150 Hz, the output PSD curves of most of the taps start to degrade resulting in a degradation of the CPSD and FRF.

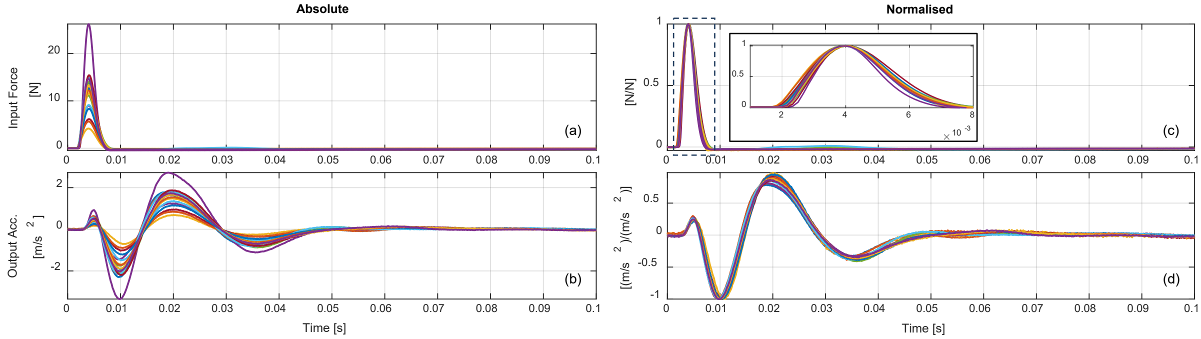

Figure 2. Recorded time series of all the taps collected at location "25W.26" of soft scum plotted in absolute values (a, b) and normalised-to-maximum values (c, d).

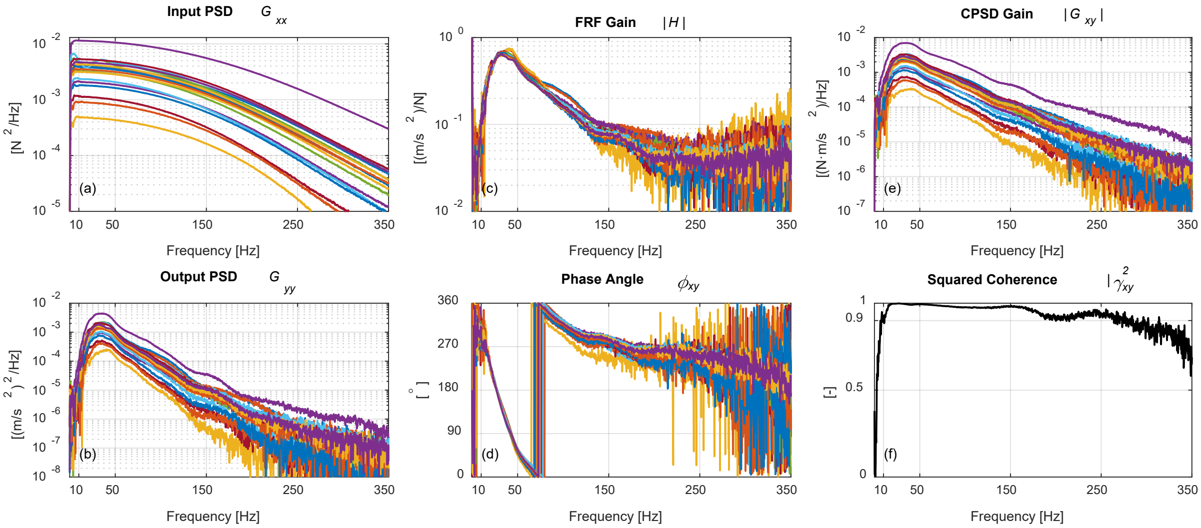

Figure 3. PSD, FRF and CPSD of all taps at location "25W.26" and squared coherence value of the location. PSD, FRF and CPSD are plotted on logarithmic scale.

Frequency Response Function

Relatively flat gain curves with slow, steady change in phase angles of the FRFs of all tested classes (Figure 4) indicate that the scum-cover system is highly damped.

A change in the gain curves can be seen when the state of scum changes. For instance, an attenuation in the gain with a slope of about 10 dB per 10 Hz started to appear with the locations of fluffy scum and appeared more obvious with harder scum classes. The gain levelled out over the 30-40 Hz frequency band for "Fluffy" scum before slowly decreasing again. This high-gain frequency band slightly shifted to the right for harder scum, which was about 40-80 Hz for Soft/Medium scum and 60-80 Hz for "Medium" and "Hard" scum.

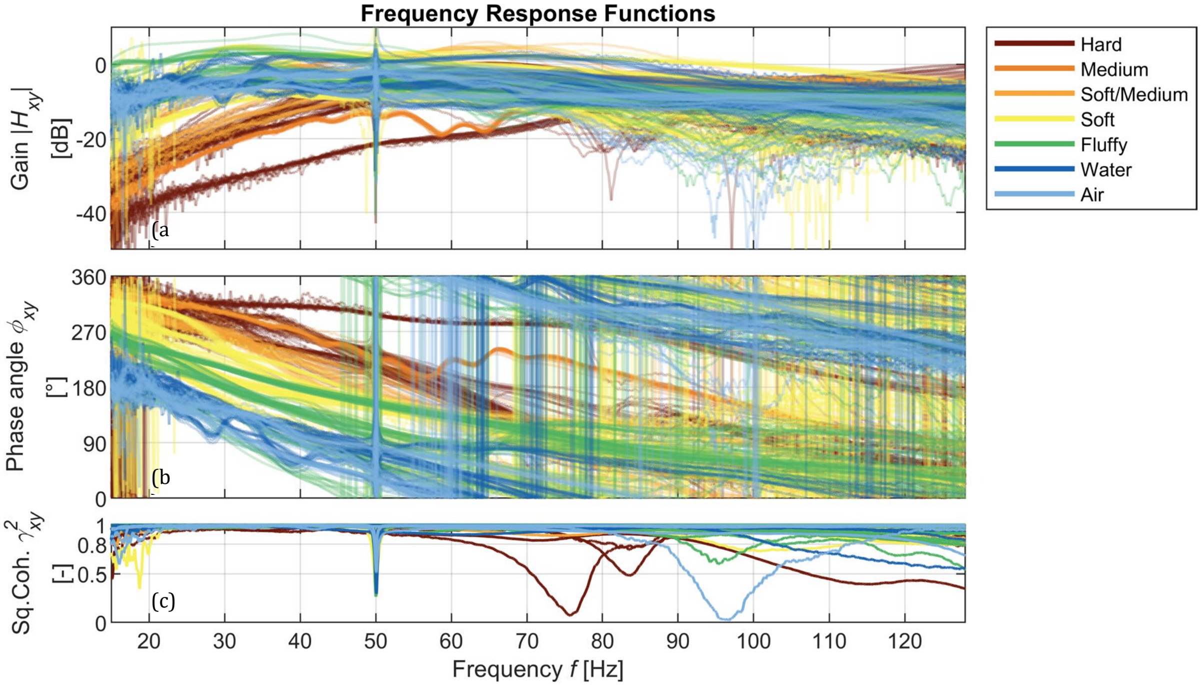

Figure 4. FRF gain (top) and phase angle (middle) of all valid taps and squared coherence values of each location (bottom). FRF gain is plotted in dB magnitude with reference value of 1 (m/s²)/N.

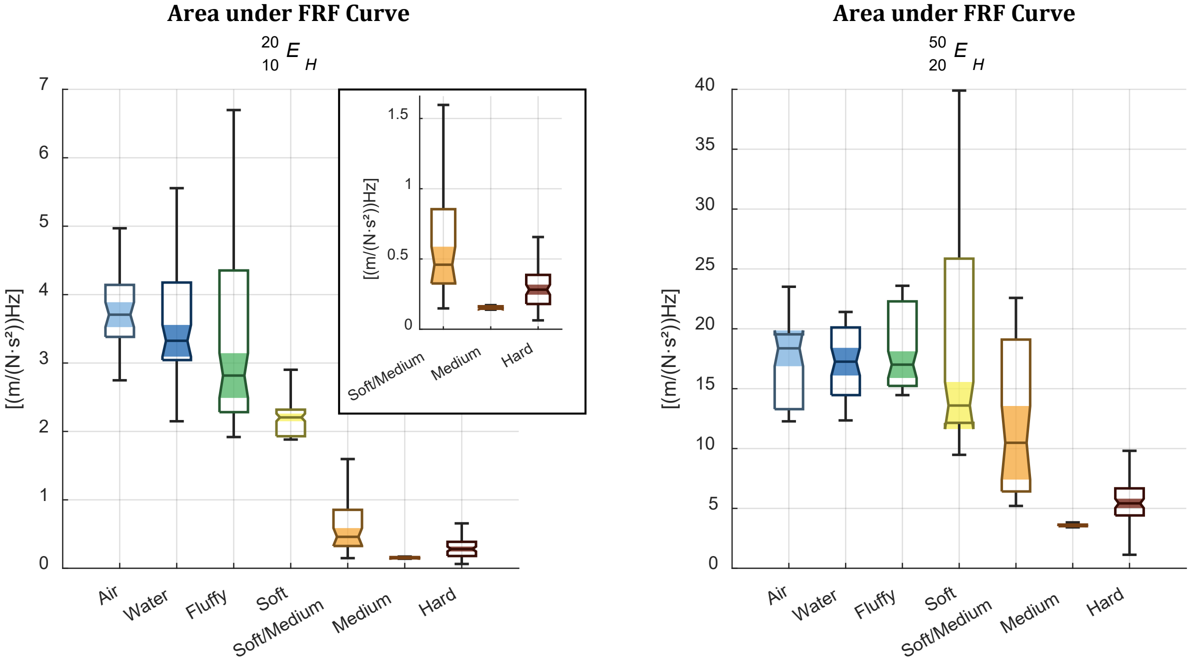

Figure 5. AUC calculated over frequency bandwidths [10, 20] Hz and [20, 50] Hz.

Similarly, a change in the phase plot can be seen in Figure 4. Although the rate of change of the phase angle appeared to be similar across all the tested states of scum, the phase plots of harder scum appeared to the right of those of softer scum. Specifically, for locations of “Air” and “Water”, the phase angle crossed 90° at around 30-50 Hz, while the observed range for “Fluffy” scum is 30-80 Hz. The ranges for “Soft, Soft/Medium” and “Hard” are 40-80 Hz, 60-100 Hz and 70-120 Hz respectively.

These observations demonstrate the potential of FRF to classify the states of scum and are further confirmed by the statistical results regarding the extracted AUC values (Figure 5). Specifically, over both [10, 20] Hz and [20, 50] Hz frequency bandwidths, the median (shown as the horizontal line within the box) of the AUC values calculated for the locations of “Air” is the highest, followed by that of “Water” and further decreased when the scum was harder.

Over the [10, 20] Hz bandwidth, the median of “Soft” scum is significantly lower than those of “Air, Water” and “Fluffy” and significantly higher than those of “Soft/Medium, Medium” and “Hard”, indicated by non-overlapping notches of the boxes. However, large variations in the results indicated by longer boxes and whiskers can be seen for “Air, Water” and “Fluffy”.

The [20, 50] Hz bandwidth shares a similar trend with the [10, 20] Hz bandwidth providing slightly better differentiation among “Soft/Medium, Medium” and “Hard” but is poorer in distinguishing other states of scum. AUC calculated for “Air, Water” and “Fluffy” groups have smaller variation with [20, 50] Hz bandwidth compared to [10, 20] Hz while it was the opposite for “Soft” and “Soft/Medium”.

Errors and Sources of Errors

The squared coherence values of most tested locations were higher than 0.8 from 20 Hz to over 80 Hz confirming good linearity of the collected data over this frequency range. However, sharp dips can be seen in coherence at 50 Hz which correspond to furious peaks/dips in the FRFs. It was later confirmed that these dips were due to electrical interference caused by the 50 Hz AC power grid used to power the data acquisition device and did not happen after the device was replaced with a battery-powered one.

Bias errors in the scum class reference values also contributed to the uncertainty of the current results. First, these reference values (“ground truths”) were taken from a cover-walk report which as discussed above are subjective. Second, the data was aggregated from measurements done on three different days (which are 41, 8, and 49 days apart); additionally, these days are more than 130 days later than the day the cover-walk inspection was performed. During these long periods of time, the state of scum may have changed.

Summary

This paper demonstrated the potential to differentiate the states of scum underneath the floating cover of an anaerobic lagoon using FRFs calculated from the force and acceleration data collected when the cover is excited using an impact hammer. Some differences can be seen in both the gain and the phase angle plots of the FRFs. AUC values extracted from the FRF gain further confirmed this observation numerically as they decreased with harder scum. Nevertheless, further studies are yet to be done to improve the capability of using FRFs to classify the state of scum by (1) optimising the frequency range in the AUC value calculations, (2) incorporating more features extracted from FRFs including the phase angles and the coherence values into the statistical classification model, (3) improving the instrumentation setup including optimising the selection of striking and sensor mounting plates, and (4) reducing the bias errors.

Acknowledgments

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