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VIBRATION BASED HARVESTER FOR WIND TURBINES

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Abstract. *Non-invasive Structural Health Monitoring (SHM) requires the deployment of sensors networks to continuously acquire acceleration signals from which modal analysis can be carried out. The need extends to the transportation and building phases of the structures, where damages may also happen. Whatever the case, it is desirable that such sensors be autonomous in terms of both energy and connectivity. To extend the battery life, or even avoid its use, harvesting energy from the environment is a solution.*

In the particular case of Wind Turbines (WT), alternatives for powering are scarce, but one source of energy available is the tower vibration itself. Such vibrations are of ultra-low frequency (less than 1 Hz), even lower than those found in other, more investigated, applications such as human movement or sea waves. Displacements, even at the tower tip, are also shorter. Moreover, and unlike those applications, vibrations in any direction on a plane need to be exploited to harvest the most energy.

In this paper we will present designs of vibration harvesters specifically designed for WT. Piezoelectricity, which is the basic principle used in low/medium-frequency vibrations, does not work here. Therefore, our harvesters are based on mechanical to electrical transduction through electromagnetic coupling between moving (rotating) parts comprised of magnets, and coils attached to the structure. The harvesters are modelled, characterized and experimentally tested under similar conditions to those found in an WT under operation. Powers in the range of few mW are obtained, which may suffice to supply low-power sensors.

1 INTRODUCTION

Structural Health Monitoring of structures such as buildings, bridges and wind turbines is more and more necessary to asses possible damages and to have information which may allow an extension of their useful operating life [1] [2]. This is particularly true in the case of wind turbines that were installed more than 20 years ago and are reaching their predicted life-time. Repowering a wind farm can be costly in terms of money and environmental impact and thus and extension of the operation is, when possible, preferable. To achieve this goal a continuous monitoring of the structure is mandatory, requiring the deployment of a network of sensors which measure accelerations at different points. Moving parts, such as blades, are more difficult to sensorize and thus only the tower is sensorized, which is anyway influenced by the dynamics of the blades. From such measurements, and making use of Operational Modal Analysis (OMA) techniques, the modal parameters are estimated and their evolution in time is expected to give information about possible failures, and accumulated damage in order to predict the remaining life-time. This is at least a topic of intense research, though well accepted solutions and comprehensive commercial products are still missing.

Whatever the solution be, a fundamental requirement is that sensor nodes must be cheap, easily deployable, autonomous and compatible with most wind farms and turbine models. These conditions point to IoT solutions where the nodes are wirelessly connected and, in most cases, autonomous in terms of energy supply. Energy autonomy greatly simplifies the installation procedures, and also allows using sensors in moving parts, and when the structure is transported and erected. Batteries cannot provide in many cases the required autonomy, and thus a harvesting mechanism becomes mandatory.

Since sensors have to be placed inside the structure, the only source of energy is the own vibration of the structure, which is obviously more intense at the tower tip and the nacelle. Anyway, such vibrations have a very low frequency content and the accelerations are also weak, with values of tenths of cm per squared second for strong winds. These are very difficult conditions for energy generation in a restrained size. A literature search shows that there is not much information about harvesters that operate under such conditions, and less particularly oriented to wind turbines [3][4]. Proof or that is that, in this context, the term “ultra-low” frequency is coined for operation under 10 Hz, whereas we are more interested in the range of 1 Hz. Solutions proposed in the ultra-low frequency range are mainly oriented to scavenge energy from human movement and sea waves, which have served as a reference for our designs.

In a recently published paper we proposed a first prototype of an energy harvester, specifically intended for wind turbines. We show in figure 1 a picture of the device, which basically consists of three wedge-shaped parts which may move around a common (vertical) axis, following horizontal vibrations on any direction of the plane. The moving parts are encased in a cylindrical case, whose round side incorporates 24 coils. The moving parts consist of Hallbach arrays of magnets, in such a way that their relative movement with respect to the coils generate, by the Faraday Law, an induced voltage and thus the power needed to feed the sensor node. Our harvester is thus based on the Electro Magnetic (EM) conversion which is the principle most ultra-low frequency harvesters are based on [5]. There are also examples where vibration is “up-converted” through, for instance, plucking mechanisms, increasing the frequency and thus allowing the use of piezoelectricity as the principle of energy conversion. One of the distinct features of our device, is its ability to extract energy from vibrations in any direction of a plane. This is required in wind towers because winds can blow in any direction. Taking this into account, the harvester we have proposed is the first one tailored to wind turbines [6]. In this paper we will not delve into the details of this device, that was described in detail in our previous publication, and has further been characterized by a novel measurement procedure described in a paper now under review [7].

Figure 1: harvester views

Therefore, section 2 is devoted to describe a novel device which is an evolution of this first prototype. Its data driven, black box, model is outlined. In section 3 we show the experimental characterization of the harvester and section 4 is devoted to the conclusions.

2 HARVESTER DESCRIPTION AND MODELLING

As mentioned before, the first prototype consisted on three moving parts with a common vertical axis (with respect to the movement plane), surrounded by a cylindrical casing which contained 24 coils, not visible in the picture in figure 1. The magnets were embedded in the moving, plastic wedge-shaped parts, and thus the weight of such masses was mainly determined by the magnets' mass. So, an obvious way to increase the mass is by using a heavier material. We have now included brass, a diamagnetic material with a density close to 9 g/cm^3. In this way, the kinetic energy of the moving parts, which is the source of energy of the harvester, considerably increases.

The experiments with the first prototype showed that one of the moving parts tends to align with the movement direction, and thus does not contribute to energy generation. This happens in contradiction to the simulations and can be related to several modelling simplifications. This effect is particularly relevant for low-frequency, low-acceleration vibrations when angular movements are reduced. At higher frequencies, when moving parts may even hit each other, this effect is not so relevant. In the prototype presented here we have included four moving parts which, as we will see, tend to move symmetrically in pairs. Figure 2.a shows a 3D model of the device where the holes to insert the magnets can be appreciated, together with those for the brass parts (in gold), which are shown in figure 2.b.

Moreover, the number of coils is reduced to twelve by a more careful design of the windings. In this way the electronics for the power conversion can be simplified. We note that coils cannot be directly connected in series because the signals they produce are not in phase, and thus may cancel each other reducing the generated energy. A picture of the actual prototype is shown in figure 2.c

Figure 2: 3D model of the harvester (a), brass parts (b), and actual harvester (c)

The final dimensions for the prototype are 100 mm diameter, 78 mm height and a total mass of 1,7 kg. Each proof mass accounts for 298 grams and its moment of inertia is I_{zz}=108·10^{-6} kg·mm^2.

The device has been modelled as we did with the previous prototype. Actually, the model is very similar with the obvious modifications due to the increased number of moving parts (three to four), the reduction in coils (24 to 12) and the value of some parameters (mass and moment of inertia). Therefore, the reader is addressed to [6] for more details about the model.

Suffice to say here that we have obtained the four equations for the movement of the masses by differentiating a Lagrangian composed of a conservative part and the Raleigh dissipation function [8]. The conservative part can be expressed by:

$$L = \sum_{i=1}^{4} E_{k_i} - E_p \tag{1}$$

where E_{k_i}correspond to the kinetic energy of each one of the masses expressed in terms of the movement of its centre of masses and moment of inertia. E_p is the magnetic potential energy resulting from the interaction, i.e. repulsion, of adjacent masses (magnets), which works as a non-linear stiffness. Modelling such forces (fields) can be accomplished by a physical model which is based on the magnetic dipoles generated by each pair of moving parts (actually their internal edges). Such model however does not provide as good results as a parametric one, simply based on a trigonometric dependence (Fourier series) of angles between masses. Thus, the black box model proposed for the potential magnetic energy is as follows:

$$E_p = \sum_{j=21,32,43,14} \sum_{k=1}^{N} a_{j,k} \sin(k\theta_j) + b_{j,k} \cos k\theta_j \tag{2}$$

The model is linear in the parameters to be determined, $a_{j,k}$ and $b_{j,k}$, which is important to simplify the identification procedures. The angles between the moving parts are denoted as θ_j, and can be expressed in terms of differences between the absolute angles of each one of the parts. *N* is obviously the model order, which in practice is limited to 2. Regarding the non-conservative part of the model, we have the contribution of friction that does not contribute to the generation of energy and is dissipated. The useful part corresponds to the damping introduced by the coils-magnets interaction. While in our previous work we considered a damping proportional to the (angular) velocity, we have improved the model by introducing a dependence on the angles, considering the geometry of the harvester (twelve coils evenly spaced). In this way we are able to model the dynamics of the harvester at a lower temporal scale. Therefore, the resulting Rayleigh dissipation function is expressed, for each mas, as:

$$R_i = R_i^e + R_i^e = \frac{1}{2}\dot{\theta}_i^2 sin^2(12\theta_i) b_g + \frac{1}{2}\dot{\theta}_i^2 b_0, \qquad for\ i = 1,2,3,4 \tag{3}$$

where b_g and b_0 are the energy generation and mechanical damping coefficients, respectively, and θ_i are the angular positions, relative to a fixed axis on the casing, of each moving part. The four equations of motion are then calculated as:

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{\theta}_i}\right) - \frac{\partial L}{\partial \theta_i} + \frac{\partial R_i}{\partial \dot{\theta}_i} = 0, \qquad for\ i = 1,2,3,4 \tag{4}$$

Last, the power generated by the harvester is straightforwardly obtained from the Rayleigh dissipation function, already introduced in (3).

$$P_G = \sum_{i=1}^{4} R_i^e = b_g \sum_{i=1}^{4} \dot{\theta}_i^2 sin^2(12\theta_i) \tag{5}$$

In order to solve and extract information from all these equations, once the excitation is known, some parameters' values need to be known. Some of them such as mass and moment of inertia can be directly measured or estimated. Others such as b_g, b_0, $a_{j,k}$ and $b_{j,k}$ have to be estimated from indirect measurements. The procedure will be described in the next section. The reason to pay so much attention to the model is that, once properly identified, it allows a prediction of the energy generation capability of the harvester, without resorting to detailed measurements. The operation condition of a harvester can be so diverse in both frequency and acceleration that measuring each and one of the possible situations is not feasible. Having a precise and well-characterized model makes it possible to avoid this type of measurements on a case-by-case basis.

3 MODEL IDENTIFICATION AND EXPERIMENTAL MESUREMENTS

In order to determine the model parameters an ad hoc experimental setup has to be designed. The difficulty comes from the fact that not only the input(acceleration)-output(power) has to be measured, but also the very movement of each mass. The basic setup used for the first harvester prototype is described in [7] and has been adapted to this harvester, as shown in figure 3:

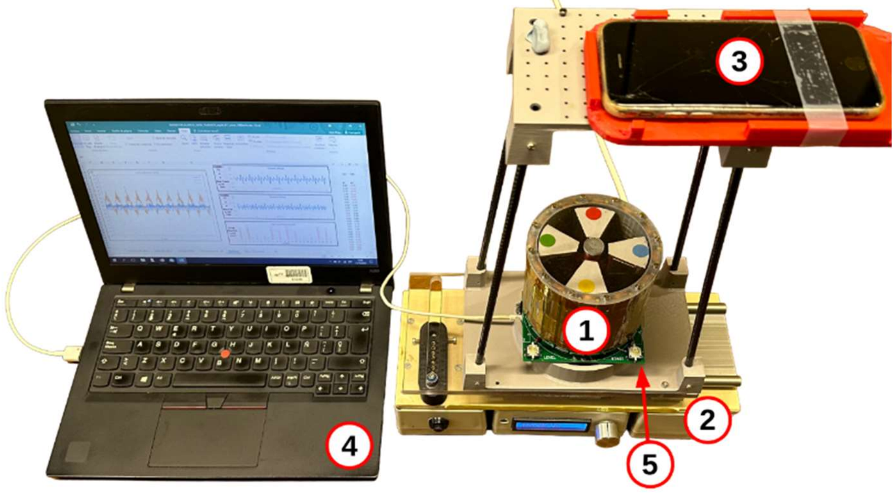

Figure 3: Experimental setup for the harvester characterization

The picture shows the five basic elements of the measurement bench. The device to be identified ① is mounted on a specifically designed moving platform ② that acts as a low-frequency sinusoidal shaker and is the element which provides the kinetic energy that the device harvests. On the upper part of the platform, mounted on a structure there is a phone ③ with a high speed and resolution camera (240 fps). In order to measure the accelerations of the moving platform with respect to the inertial frame, a triaxial accelerometer (ADXL345) is installed in the electronics of the harvester and it is measured together with the power generated by the 12 coils of the harvester. All data are collected using a UART communication protocol through a cabled USB connection, and are written to a data table automatically.

The acquisition system is based on a 32-bit Teensy microcontroller at 180 MHz. Its 12 analogue inputs of 12 bits resolution with a full scale of +/- 1.65 Volts are connected to the 12 EM generators of the harvester. Simultaneously, the interface board collects data from the triaxial accelerometer via I2C. It also contains sockets to plug in resistors arrays acting as dummy loads for the generators. Voltages are acquired at a rate of 100 samples per second.

Moreover, a video of the masses moving with respect to the case is recorded while the acquisition system ④ is running and in order to synchronize the video and the acquisition system, a LED (Light-Emitting Diode) ⑤ lights-up and is recorded by the camera. Post-processing the video, the acquired signals are synchronized to the video frames using the LED as a trigger. After the video is recorded it has yet to be processed in order to estimate the positions, velocities and acceleration of the masses.

The procedure used to measure the positions of the four masses is based on image processing. Movements are very slow and the number of frames per second acquired (240) allows for an off-line processing of the images which determines with enough accuracy their positions. To this end, a colored sticker is placed on each one of the masses, as can be seen in figure 4 and is also appreciated if figure 3. Using built in functions of MATLAB©, the central point of each sticker is determined (also indicated in figure 4) and thus its position. Assuming that each of these four points move around a common center, their positions are fitted to a circumference for a better accuracy.

The position as a function of time, together with the instantaneous power generated, is the basic information for identification purposes. We have carried out acquisitions of 10 seconds for sinusoidal excitations of different frequencies (from 0.2 to 1.2Hz), amplitudes (1 to 5 cm), and loads (nominal 150, 670 and 1000Ω). In order to solve the identification problem, not only the angular positions are needed but also velocities and accelerations. This latter two parameters are calculated by numerical differentiation in time. It is well known that differentiation is usually, for noisy signals as it is now the case, an ill posed problem. Thus, regularization mechanisms, in this case Tikhonov method, has been used for those calculations.

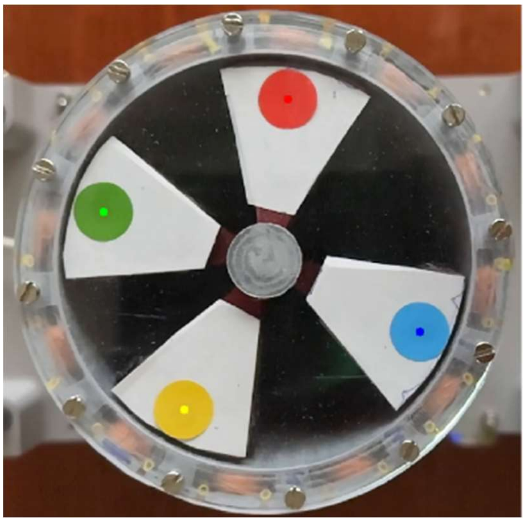

Figure 4: Upper view of the harvester with stickers on the masses

The details of the identification problem are out of the scope of this paper and will not be described here. Suffice to say that we have used concatenated records of several measurements, resulting in sequences of 250 seconds to build the observation matrix. Figure 5 is an example of such sequences for the angular displacements of the four masses, which clearly show segments of 10 seconds with evident differences in frequency and amplitude. A procedure based on the Maximum Likelihood estimator is used to obtain the desired parameters. A number of experiments (25%) have been left out of the identification process, in order to be used for model validation purposes.

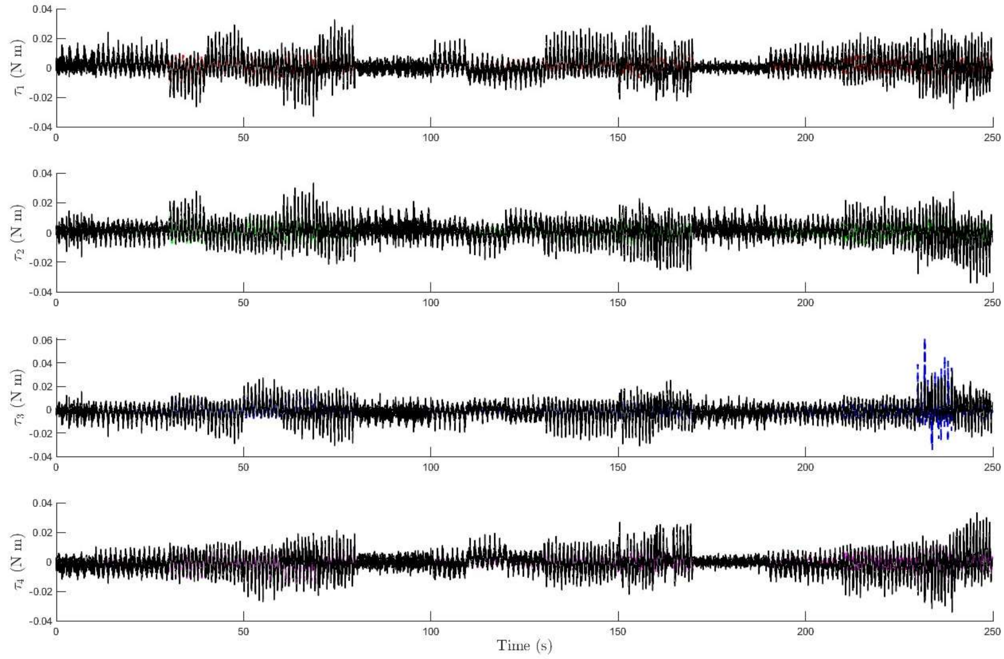

Figure 5: Concatenated measurements (250 seconds in total) of the moving masses

As a representative example to demonstrate the performance of our harvester, and also the capabilities of the model, we show in Figure 6 two curves representing the instantaneous power generated by the harvester under a sinusoidal excitation of 1 Hz, and with 1KΩ load. The black line corresponds to actual measurements whereas the blue line corresponds to the power predicted by the model, making use of the parameter's values identified. It goes without saying that these measurements were not used for the identification. It is really noteworthy how the simulated response given by the model is very close to the actual measurement.

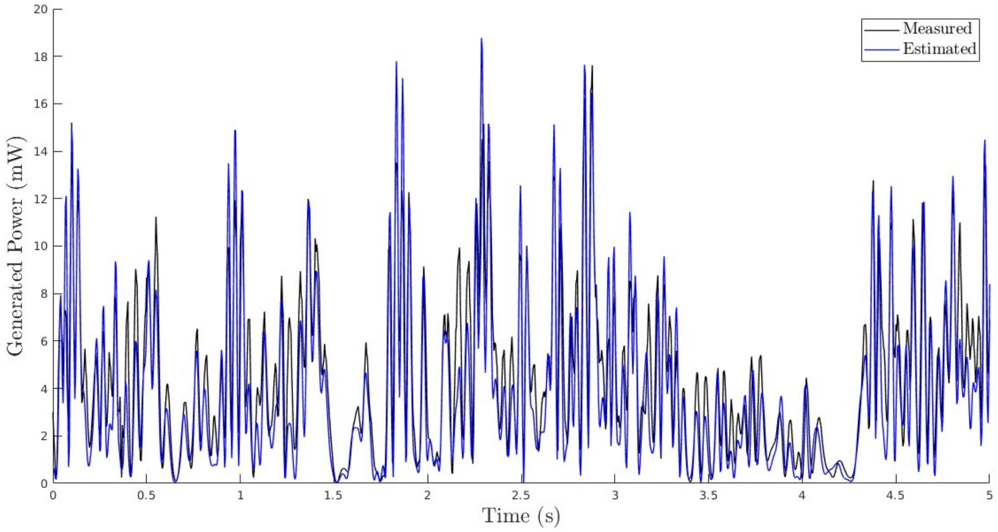

Figure 6: Generated power (measured and estimated) by the harvester proposed in this paper

We can observe peak generation powers between 16 and 18 mW (1KΩ load) similar for those obtained by the previous harvester at 100Ω. Above results can be compared with those obtained under similar conditions with the first harvester prototype, and shown in figure 7. Voltage levels are clearly higher for the harvester described in this paper, and is the energy generated. The measured energy generated by the four masses harvester in the five seconds shown in the figures is 22.4 mJ (19.6 mJ estimated), against the 16.2 mJ (11.4 mJ estimated) given by the three masses harvester. This is around a 40% increase.

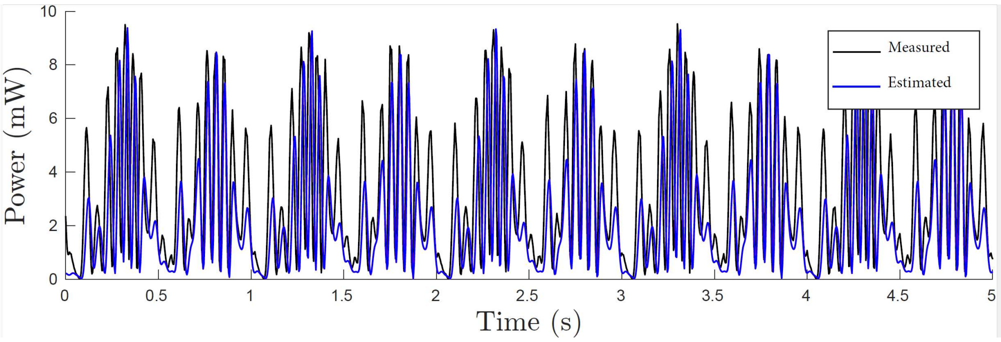

Figure 7: Generated power (measured and estimated) by the harvester first prototype

4 CONCLUSIONS

In this paper we have described and practically demonstrated a harvester prototype specifically designed to power up sensor nodes operating in a wind turbine, for SHM purposes. The harvester transforms the ultra-low frequency vibrations present in a wind turbine into usable energy by means to the EM conversion. The device, which is an evolution of a previous prototype, has been modelled in such a way that its performance can be predicted under any possible excitation conditions. Experimental measurements are shown, demonstrating the capability of the harvester to provide energy to low-power nodes.

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REFERENCES

[1] G. Oliveira, F. Magalhães, Á. Cunha, and E. Caetano, “Continuous dynamic monitoring of an onshore wind turbine,” *Eng. Struct*, vol. 164, no. January, pp. 22–39, 2018, doi: 10.1016/j.engstruct.2018.02.030.

[2] E. H. Fort *et al.*, “Wireless and Low-Power System for Synchronous and Real-Time Structural-Damage Assessment,” *IEEE Sens J*, vol. XX, no. Xx, 2023, doi: 10.1109/JSEN.2023.3270961.

[3] B. S. Joyce, J. Farmer, and Inman D.J., “Electromagnetic energy harvester for monitoring wind turbine blades,” *Wind Energy*, vol. 17, no. February 2013, pp. 869–876, 2014, doi: 10.1002/we.1602.

[4] H. Fu, J. Jiang, S. Hu, J. Rao, and S. Theodossiades, “A multi-stable ultra-low frequency energy harvester using a nonlinear pendulum and piezoelectric transduction for self-powered sensing,” *Mech Syst Signal Process*, vol. 189, no. August 2022, p. 110034, 2023, doi: 10.1016/j.ymssp.2022.110034.

[5] R. Sun, S. Zhou, and L. Cheng, “Ultra-low frequency vibration energy harvesting: Mechanisms, enhancement techniques, and scaling laws,” *Energy Convers Manag*, vol. 276, no. September 2022, p. 116585, 2023, doi: 10.1016/j.enconman.2022.116585.

[6] C. Castellano-Aldave, A. Carlosena, X. Iriarte, and A. Plaza, “Ultra-low frequency multidirectional harvester for wind turbines,” *Appl Energy*, vol. 334, no. March 2023, p. 120715, 2023, doi: 10.1016/j.apenergy.2023.120715.

[7] A. Plaza, X. Iriarte, C. Castellano-Aldave, and A. Carlosena, “Comprehensive Characterization of a Low-Frequency Vibration Energy Harvester,” *Mesurement*, 2023.

[8] A. M. Bersani and P. Caressa, “Lagrangian descriptions of dissipative systems: a review,” *Mathematics and Mechanics of Solids*, vol. 26, no. 6, pp. 785–803, 2021, doi: 10.1177/1081286520971834.