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DESIGN OF AN INSTRUMENTED SANDPIT TO MONITOR SUBTERRANEAN TERMITE AND ANT ACTIVITY IN VIBRATION BIOASSAYS

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Termites are known to use vibrational communication in the form of alarm, walking and feeding signals, for the survival of the nest against predators and competitors, as well as unfavourable microclimate conditions. However, less is known about the mechanism of sensing and dispersion of this information as most termite species are cryptic, hiding their presence through quiet and remote interactions with their environment. To study how vibration communication is facilitated in subterranean termite species such as *Coptotermes acinaciformis*, we designed an instrumented sandpit to monitor their behaviour in making foraging decisions, in response to threats from a major predator such as the ant *Iridomyrmex purpureus*. The sandpit enclosure design simulates conditions typically found in and around termite nests – moist sand maintained at a constant temperature and relative humidity, and with dry/wet wood samples of different shapes and sizes. The enclosure has a modular design with transparent side walls to enhance visibility for video tracking of tunnelling activity in sand or termite soil and can be interchanged for mounting various sensors and wood pieces. The planned bioassays incorporate both passive and active control mechanisms to manipulate termite behaviour. To capture vibrations generated at the source and propagating through the substrate and sand (or soil) medium, we use vibration sensors such as accelerometers and geophones placed at defined distances around the termite nest. We also implement a continuous environmental monitoring system by embedding highly sensitive optical fibres measuring strain, temperature and humidity in the enclosure. We have validated the sandpit enclosure by vibration and modal tests, and finite element analysis after a model updating procedure, allowing the design of bioassays in a virtual environment before conducting controlled experiments in the laboratory. This system can also support the development of bio-informed sensing and actuation mechanisms for soft robotics and structural health monitoring applications.

Keywords: bioassays, biotremology, eusocial insects, sensors, vibrational communication

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1. Introduction

About 183 of all 3,100 extant termite (Isoptera) species are to some extent economically significant (20 in Australia), causing damage to timber structures, crops and other cellulose-based products [1,2], and 28 species worldwide are considered invasive [3]. Depending on the feeding habits and preferences, these species can have differing potential for causing damage. Subterranean termites are the most common type of termite that infest timber in buildings and are one of the most destructive pests worldwide [4]. In Australia, treatment and replacement services of timber-in-service due to termite damage were estimated to be at $910 million pa in 2006 [5], and their collective impact on critical infrastructure such as timber utility poles is much greater [6]. Subterranean termite *Coptotermes acinaciformis* (Heterotermitidae) [2], whose activities were recorded in all regions of Australia, is also a pest of trees and seasoned wood—they infest more than 85% of trees [7]. Their foraging is dependent on the weather conditions, with little activity in dry/winter season and high activity in summer after rainfall. In tropical areas, they can forage all year round [8], and their activities peak during warmer, wetter conditions [9]. They tunnel through soil to access moist soil or timber and in dry seasons, they tunnel down deeper into the soil to reach moisture, but they are also known to regulate the moisture content in timber and their nests [10]. Termites use soil as a material to construct shelter tubes and nests, and clay to build galleries and reinforce structures within their nests and excavation areas in living trees and buildings [11].

Termites communicate by using vibrations in the form of alarm, walking and feeding signals [12]. They can sense vibrations through subgenual organs in their legs [13] and generate vibrations by jerking and rapid/successive impact of their head and abdomen on the substrate [14]. While the use of substrate-borne vibrations is widespread in insects [15], this mode of communication allows termites to detect predators [16] and competitors [17] around their nest and to hide their presence. The cryptic behaviour also makes detecting them in infested timber more difficult. In most cases, their presence becomes known only at the complete failure of trees and timber structures due to their habit of hollowing the core region of the timber or parts that are rich in nutrients [18]. However, despite their appetite for predegraded and sound wood (but more so if the lignin layer has already some degradation from fungi activity [19]), termites appear to be selective in the food that they consume. The possibility that termites could use their chewing and alarm cues to evaluate the quality of the wood was first suggested by Lenz [20], who observed that drywood termite genus *Cryptotermes* responded to the volume of the food without measuring them physically. Subsequently, bioassays with pairs of wooden blocks of different sizes were used as treatment to test their food preference [17,21]: *Cryptotermes domesticus* preferred a smaller food resource [21], while *Cryptotermes secundus* preferred food of larger size [22]. By using food choice experiments and vibration recordings, Cr. secundus were shown to be able to distinguish its own species from their dominant competitor *Co. acinaciformis* [17]. Termites and ants, their major predators, are often found in close proximity, with tunnels only separated by a few millimetres, suggesting the hypothesis that termites could also eavesdrop on the ant walking signals to avoid detection [16]. Laboratory experiments measuring the walking activity of various ant and termite species on a substrate showed that ants are much louder than termites, about 100 times in vibration amplitude [16,23]. Termites' perception of ant activity was also reflected on their foraging [16]: wood eaten by *Co. acinaciformis* from wooden discs when exposed to live and synthetic walking signals [24] of the ant *Iridomyrmex purpureus* was less than the control and pink noise—revealing that they were making use of the information contained in vibration cues. However, the mechanism of sensing and processing of this information in the presence of environmental noise is still not known.

Numerous efforts to develop techniques for detecting hidden termite infestations have produced only a few successful alternatives to traditional visual inspection methods [25]. Notable alternatives include ground-based monitoring devices [26] and sensors that detect acoustic emissions of termites in wood [27,28]. Acoustic emission sensors are successful because they are non-destructive and operate at high frequencies (>40 kHz) where there is negligible background noise to interfere with the detection and interpretation of insect sounds [29]. The detection of subterranean termites in soil is more challenging with ultrasound-based devices due to stronger sound attenuation in soil than air or wood, which also increases with frequency. This attenuation reduces the detection range of acoustic emission to 2–5 cm in soil [30]. The spatial range of acoustic detection is much greater at frequencies <10 kHz. Low-frequency accelerometers with high signal-to-noise ratio (SNR) have been used to measure low-amplitude vibrations on timber [31]; and detect insect larvae over 1–2 m in grain [32], over 10–30 cm in soil [30], and termites feeding/excavation and alarm activities (2–5 kHz) near the base of infested trees [33]. Geophones, widely used to measure seismic activity, are highly sensitive to signals <500 Hz and have a wider spatial range than accelerometers [34]. They have been used to study communication and foraging behaviour of subterranean termites and ticking sounds of ants [35]. Distributed sensors are a promising alternative to the arrays of singular sensors for continuous remote monitoring of insect activity and integrated pest management [36]. The technology is based on scattering in an optical fibre—Rayleigh, Brillouin, and Raman, and the characteristics such as amplitude, frequency and polarization of the scattered radiation can depend on the physical action to be monitored [37]. To study ecologically important features of termites and small invertebrates in wet lab/*in situ* experiments, it is desirable to combine sensing and actuation technologies with signal processing [24,31,38]. In this paper, we demonstrate a proof-of-concept of an instrumented sandpit to monitor subterranean termite and ant activity. The sandpit design simulates conditions typically found in and around termite nests, and the enclosing box is mounted with various sensors and wood pieces to monitor and manipulate termite behaviour in the controlled experiments (bioassays).

2. Experimental Design

To study termite foraging, mating, construction behaviour, and colony defence against predation or competition among species and conspecifics, choice-test bioassays are commonly used. For pest control applications, passive attractors (e.g., insecticides [39]) and active signals [40] can be used to determine preferences for insects. Wood and cellulose-based products are commonly used to study termite diet preferences (typically in association with their gut microorganisms [41]), which can come in various quality and shape [42–45]. The bioassays are conducted in environmentally controlled chambers to promote activity at their naturally found conditions, e.g., chamber temperature and relative humidity are set as 28ºC and 80%, respectively, for *Co. acinaciformis* [16], 35ºC and 90% for *Cr. domesticus* [21]. To keep the ambient conditions similar across control and treatment batches, some form of noise/vibration insulation is recommended, e.g., damping/rubber mats, acoustic foams, anechoic or isolated test rooms [23].

Subcolonies of subterranean termites collected from the field are pre-processed such that only mature soldiers and workers (1:10) are used in the bioassays [42,46]. For storage and testing, polyethylene terephthalate (PET) containers are filled with a mixture of vermiculite, sawdust, water and their own nest material in a 2:2:1:1 ratio adjusted according to the size of the container and the number of termites inside (measured by their mass, e.g., 2,000 termites ≈ 10 g in *Co. acinaciformis* [42]). As the termites consume the initial food matrix in the container, they build fortifications in the nest using moist clay sands, faecal pellets and saliva [10,11,47,48]—lasting typically 1–2 week(s) depending on their overall activity. As initial food resources run out, foraging activities intensify—they build foraging trails on the exploration sites that are determined safe by the soldiers [47,48].

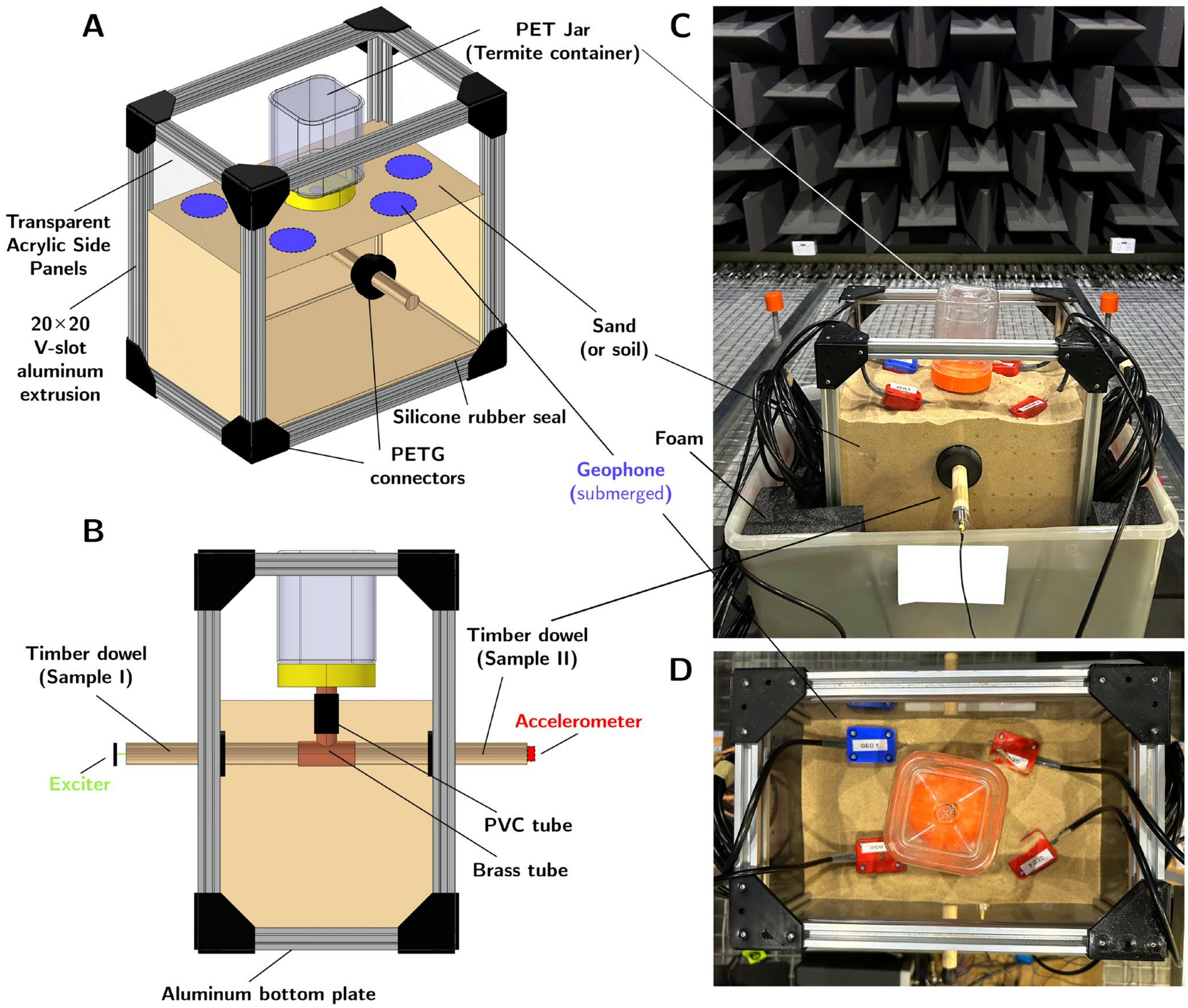

Figure 1: Schematics of the instrumented sandpit (350 × 227 × 350 mm^3) for vibration bioassays of subterranean termites and ants. A) isometric view showing individual parts and materials used in the sandpit setup, B) side view showing the arrangement of food choice samples and instrumentation in connection with the termite container (food matrix and termites are not shown), C) physical setup of the instrumented sandpit shown here in an anechoic chamber at UTS Tech Lab, D) top view of the setup showing the locations of geophones concerning the termite container.

Based on previous studies [16,23,42], proposed bioassay protocol includes an enclosure sandpit setup that allows easy access for instrumentation, intervention and tuning. Figure 1 depicts schematics of the enclosure (350 × 227 × 350 mm^3) with individual parts and materials used in its construction. The enclosure frame uses 20×20 v-slot aluminium extrusion that is joined by bolts and thermoplastic (e.g., PETG, ASA) connectors for enhanced durability. Transparent acrylic sheets of 3 mm-thickness (h) are cut into size to slide in the grooves of the aluminium extrusion. The bottom section of the enclosure is a metal plate with h = 3 mm, e.g., aluminium or stainless steel, to withstand the weight of the sand/soil. All sides are sealed with silicone rubber strips of h = 0.4 mm. Acrylic panels can be modified with cylindrical or rectangular cut-outs for food choice tests or mounting sensors/exciters, as shown in Figure 1B. Food choice tests typically include veneer discs [42] or solid wood blocks [21]. In our current demonstration, we use two 160 mm-long *Pinus radiata* (Monterrey pine) dowels with a diameter of 19 mm, whose ends are connected with a "T-maze" brass/PVC tube that allows access for termites.

3. Instrumentation

To manipulate termite behaviour in bioassays, the instrumentation of the timber samples can be done by passive and active vibration control mechanisms, e.g., by a piezo microactuator device to play back signals mimicking ant vibrations based on a mathematical model of ant walking [23,24,48]. The microactuator device can also play other termite-attracting/repellent signals to test different treatment scenarios [49]. Accelerometers with high sensitivity and low-noise are mounted on the termite container and timber samples, and geophones are inserted in the sand/soil to measure low-amplitude vibrations (see Fig. 1). Mechanical strain along the axial or helical axis of the timber sample is measured through a fibre-optic sensing system using sub-millimetre distributed strain gauges based on the Rayleigh back-scatterer.

Figure 1C,D show the physical setup of the instrumented sandpit enclosure in the fully anechoic chamber at UTS Tech Lab. In this representation, two accelerometers (Sinocera Piezotronics Inc. CA-YD-127 with 1.62 V/m/s^2 sensitivity factor, including Dytran 4705 inline charge amplifier) and four geophones (Geospace Technologies GS-32CT with a sensitivity of 0.218 V/cm/s) are used for instrumentation. Using beeswax, one accelerometer is attached to the outer end of the timber dowel shown Fig. 1C, and the other accelerometer is attached to the base of the dowel at the opposite end. For characterisation of the vibration level in the system, we played pure tone and sweep signals through a compact vibration exciter (Qsources Qlws electromagnetic shaker with a force transducer sensitivity of 39 mV/N coupled with Qsources QMA amplifier) mounted at the outer end of the timber dowel (see Fig. 2d). Time signals and frequency response functions (FRFs) are measured using Siemens Simcenter Testlab 2206 with SCADAS Mobile with a sampling frequency of 20,480 Hz. To ensure accuracy, 50-100 runs are taken and averaged for each configuration using a Hanning window with an overlap of 50%. Experimental resonances and mode shapes of individual components are obtained through modal testing using NV-Tech scalable automatic modal hammer (SAM1) and laser scanning Doppler vibrometry using Polytec PSV-500.

4. Results and Discussion

We use the Solid Mechanics and Acoustics modules of the commercial software COMSOL Multiphysics (version 6.2) to validate and visualise the vibration characteristics of the sandpit setup. We model the geometry, as seen in Fig. 1, using tetrahedral quadratic elements. The mechanical properties of the *P. radiata* dowels and construction materials are extracted from a model updated using experimental data and FEMTools [50]. We analysed the response of the system for three excitation scenarios: ① the outer end of Sample I — to simulate attraction or deterrence (see Fig 1B); ② the termite-accessible end of Sample I — to simulate initial termite attack on one sample; ③ the termite-accessible ends of Sample I and II — to simulate more advanced infestation situation. Figure 2A and 2B compare the experimentally and numerically obtained frequency spectra at geophone locations for the scenario ①, and simulated wave propagation in the sand coinciding with neutral axis of dowels for all three scenarios, respectively. For simplicity, a unit pressure load was applied on the surface of the dowel (black arrows in Fig. 2B). The velocity response in the sand measured at geophone locations (see Fig. 1D) show a slight variation in frequency and amplitude (in Fig. 2A with a grey band). There are a few dominant peaks at the low-frequency end of the spectrum, namely 123 Hz, 320 Hz, 406 Hz and 480 Hz. From experimental modal analysis, we find that these frequencies correspond to bending deformation of the acrylic panels and aluminum extrusion, and below the first mode (bending) of the *P. radiata* dowel (2.9 kHz). In the numerical simulations (Fig. 2A), the dominant frequency peak occurs at 350 Hz. The velocity response in the sand shown at the neutral axis of the dowel represents a uniform distribution, higher in amplitude adjacent to larger acrylic panels, and similar in amplitude as the bulk response of the Sample I. This frequency also corresponds to global bending mode of the sandpit enclosure—with highest deformation occurring at the smaller side panels with a (2,1) plate modal pattern. The kinetic energy distribution, visualised at t = 100μs, demonstrate reflections from the boundaries and an accumulation of the energy around excitation locations. This visualisation technique can be extended to the experimental test scenario to optimise the location of the geophones with respect to the position and orientation of the dowels and the termite container to maximise the SNR and increase measurement accuracy.

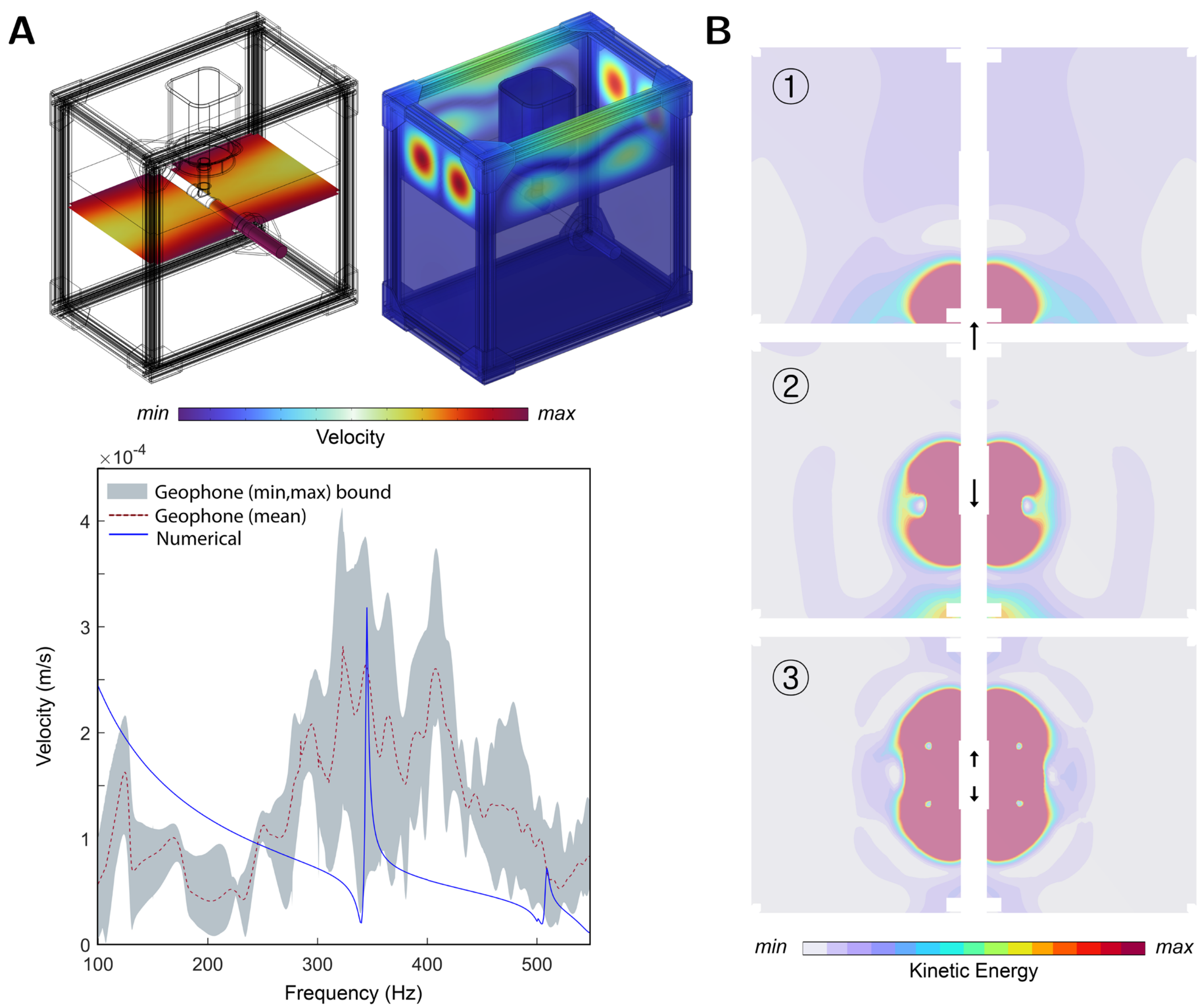

Figure 2: Experimental and numerical analysis of the sandpit setup. A) Velocity response in the sand measured at geophone locations (Fig. 1D) shown as (min, max) bound and mean value. The blue curve corresponds to the numerically measured response at measurement locations. The top visualisations show the velocity response and eigenmode of the system at 350 Hz, coinciding with the frequency peak in the numerical analysis (bottom). B) Kinetic energy distribution in the sand shown at t = 100μs for three test scenarios, where a unit pressure load is applied at the end of the timber dowel, shown with black arrows.

5. Conclusions and Future Work

This paper has presented a proof-of-concept study of an instrumented sandpit setup for measurement of low-amplitude vibrations produced by termites and ants in bioassays. The results have shown that the resonances and deformation originating from the finite size of the enclosure might be important to identify before conducting bioassays for reliable analysis of insect signals. The geophones, with their high accuracy in the low-frequency region, can be a substitute for accelerometers to capture the frequency- and time-domain characteristics. The instrumented sandpit system can also support the development of various sensors and actuators through a bio-informed program of soft robotics and structural health monitoring applications.

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