The acoustic characteristics of marine archaeological wood

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Abstract

In response to the requirement for new techniques to undertake non-destructive surveys of submerged archaeological sites, adaptation of conventional acoustic characterisation techniques has been proposed. Identification of archaeological material (particularly wood) using such methods requires knowledge of their acoustic properties. Approaches for the calculation of p-wave velocity and density for waterlogged wooden artefacts are presented. Preliminary results suggest acoustic methods can be used to identify wooden artefacts and may be sufficiently sensitive to determine their degradation state. Such techniques could have a significant impact on the management and conservation of our submerged cultural heritage.

1. Introduction

Over the last fifteen years the underwater archaeological community has moved toward a strategy of *in situ* preservation of our submerged cultural resource. This trend has been politically galvanised in Article 1 of the ICOMOS Charter on the Protection and Management of Underwater Cultural Heritage [1] which states that the "..*in situ* preservation of our underwater cultural heritage should always be considered as the preferred management option". Further, this directive also emphasises that the choice of conservation strategies to be deployed should be achieved through non-destructive, non-intrusive survey rather than excavation. However, to date the majority of management decisions have been made on the basis of qualitative interpretation and site specific expertise. What is currently absent from the methodologies available to archaeologists and conservators is the ability to assess rapidly and non-destructively the state of deterioration of a range of archaeological materials *in situ* [2].

Adaptations of standard high-resolution geophysical techniques for what are generally small-scale archaeological sites provide a potential tool for the non-intrusive quantitative analysis of such sites. However, in order to progress the development of such methodologies, it is necessary to understand both the acoustic properties of archaeological wood and their variability with preservation state. This paper aims to present a methodology for extending our understanding of the acoustic properties of marine archaeological wood and thus providing a platform for future attempts to use acoustic sources to determine the preservation state of archaeological material.

Although it is anticipated that the methodologies discussed in this paper will be applicable to any submerged archaeological wooden materials, the initial work has been focused on the acoustic characteristics of oak. From the Mesolithic to the medieval period in NW Europe oak, ash, elm, hazel, alder, beech, yew, lime, birch, willow and pine have been used for boatbuilding [3]. However, in general oak seems to have been preferred for the main structural elements whenever it was available, from the mid-second millennium BC to the early nineteenth-century ships. Whilst the survival of boat finds is undoubtedly biased as oak has a greater chance of survival than most other species; nevertheless this apparent preference for oak is confirmed by documentary evidence [3].

2. Rationale

2.1 Acoustic characterisation of unconsolidated sediments

The remote determination of the physical properties of the seabed and the immediate sub-surface (<50 m) has been the subject of extensive research over the last two decades. This has resulted in the commercial development of a number of penetrative and non-penetrative sediment classification systems. Research has typically focused on either deriving impedance and attenuation estimates from reflected pulses [4-7] or the detailed shape-characterisation of reflected pulse form [8, 9]. Having identified from this literature that p-wave velocity, impedance and attenuation are the acoustic properties that have the strongest correlation with physical properties of the seabed (such as bulk density and porosity), it is proposed that such techniques could be used for the identification and characterisation of archaeological wooden material in the marine environment.

2.2 The propagation of sound through wood

Wood is an intrinsically anisotropic medium, a state induced by the specific deposition of anatomical elements during the life of a tree [10]. On a macroscopic level the dominant cell direction is oriented vertically in the tree stem, resulting in a pronounced grain direction and the characteristic growth ring structure when seen in section (Figure 1a). Approximately 10% by volume of the cells are oriented perpendicular to the stem, these cells forming the flattened ribbons of tissue known as rays, which radiate outward from the pith at the centre of the trunk and cross the growth rings (Figure 1a).

In order to enable a physical description of the direction of sound propagation within wood, three axes are defined that relate to this macroscopic structure [10]. They are a longitudinal axis oriented parallel to the tree stem (L), a radial axis perpendicular to the growth rings (R) and a tangential axis parallel to the growth rings (T) [10] (Figure 1b). These axes are located within the three planes of elastic symmetry, the L-T, L-R and R-T planes (Figure 1b). Wood elasticity theory assumes these planes to be mutually perpendicular and that wood is perfectly elastic and homogeneous [10]. In reality, wood only approximates to this ideal structure e.g. the L-T plane is actually roughly cylindrical. However, if a sample is taken far enough from the centre of the tree compared with the sample size, this surface is more truly planar [12].

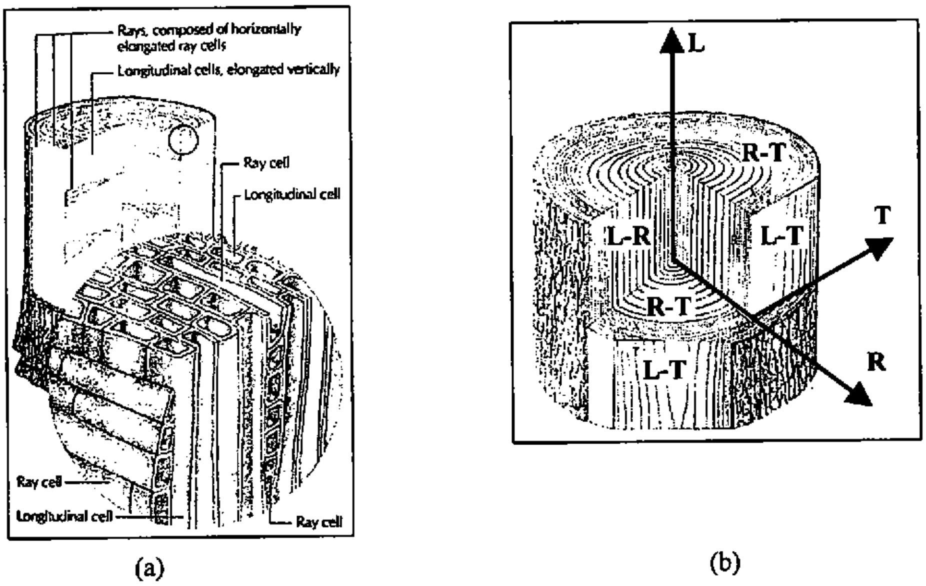

Figure 1. (a) Major structural components of wood and (b) the three mutually perpendicular planes of elastic symmetry and their principal axes (Modified from [11]).

2.3 Measurement of the acoustic properties of wood

To date ultrasonic velocity measurements have been made in wood for three main purposes. The first of these was to establish values for the elastic constants of wood, for use in the construction industry and for the manufacture of musical instruments [13, 14]. Secondly, research for the forestry industry has focused on the use of velocity measurements for the detection of decay in standing trees [15, 16], albeit this work has focused on identifying internal decay pockets. Such large internal decay features are not present in degraded cut timbers, although submerged timbers can be extensively attacked by marine borers (e.g. *Teredo navalis*) which can create a network of individual (c. 3 cm length) chambers. Finally, velocity measurements have been made through drying timber to try and establish a non-destructive technique of measuring moisture contents in order to control the kiln drying of lumber and prevent warping [17].

These experiments on *in situ* or cut timbers typically use a simple direct transmission technique, using frequencies in the range of 0.25 - 1.0 MHz. There are two key issues related to these direct transmission experiments: coupling of transducers to the sample and the moisture content of the sample. The majority of investigations use silicon grease to assist coupling. However, it is probable that such a medium will penetrate the sample and affect its elastic and acoustic properties [14]. Alternatively, solid couplants have been used, with each specimen being bonded to PVC buffer blocks [18]. However, this is a time intensive operation. Finally, some experiments have been performed in a water bath [15] Whilst this technique creates an excellent transmission medium, it cannot be used for samples with low moisture contents, as the process of saturation creates surface bubbles which cause extensive scatter of input signal.

The hygroscopic nature of wood results in a constant change in the water content of a sample as it attempts to maintain equilibrium with the ambient hygrometric conditions. Water is contained in wood in two ways, with free water being present in the cell cavities and bound water being present within the cell walls. In the timber industry the water content of wood is expressed in terms of an equilibrium moisture content (EMC), which can be expressed as the weight of water in a sample, at a known relative humidity, as a percentage of its oven-dry weight [19, 20]. The age and species of the timber affect the EMC, with freshly cut green timbers recording values in the range 35-300% [21], whilst typical oak boat timbers (which have been seasoned and then equilibrated with the marine environment) have EMC values of c. 25% [3]. Early work [22] on p-wave velocity measurements through timber samples show a 25% reduction in velocity values between 0 and 50% moisture content. This decrease in p-wave velocity is a result of a decrease in the modulus of elasticity and an increase in density with increasing EMC [20]. Consequently, the majority of velocity measurements in the literature are quoted with reference to a known EMC (typically 10-12%).

All velocity measurements quoted within the referenced literature are for the three possible end-member cases V_L, V_R and V_T representing incident propagation along the three principal axes. The empirical data identify that the longitudinal velocity (V_L) is found to be much higher than those along the other two axes, probably because 90% of cells are oriented parallel to this direction [20]. The radial velocity (V_R) is slightly higher than the tangential (V_T) because the rays are oriented in this direction and there is no corresponding alignment of cells in the tangential direction [20]. This structural difference is enhanced as the longitudinal cells tend to be aligned in the radial direction but randomly distributed in the tangential direction [13]. Typical values for end-member p-wave velocity for European White Oak are given in Table 1 [13].

	Longitudinal Velocity (V_L) – ms^{-1}	Radial Velocity (V_R) – ms^{-1}	Tangential Velocity (V_T) – ms^{-1}
European White Oak	5071	2148	1538

Table 1. The p-wave velocities for European White Oak samples [13]. Measurements acquired by the direct transmission technique with a 1 MHz source and at an equilibrium moisture content of 12%.

2.4 Density of wood

In addition to the literature available on the propagation of sound through modern timbers, there is also a significant corpus on density variation within and between wood types. There are four different measurements of density, which again relate to the hygrometric conditions. Oven-dry density, is derived from both mass and volume of oven-dry wood but problems in volume calculation can be encountered as a result of shrinkage on drying. Air-dry density, is that found under a controlled environment with an EMC of 12% but again may have inherent inaccuracies due to shrinkage. Conventional or basic density, is calculated from oven-dry weight and water-saturated volume. However, this does require the permanent destruction of the artefact. Finally, apparent density is a simple measure of mass and volume at an unknown moisture content [19, 20, 23].

Moisture content (MC) and structure principally affect the density of wood. Wood mass increases with increasing moisture content up to the fully saturated condition. The volume of wood, however, only increases at first (up to the maximum swelling capacity c. 30% MC) and then remains constant; however much more moisture is retained. Dinwoodie [20] gives the approximate relationship that for each 1% increase in moisture content, up to a maximum of 30%, density increases by around 0.5%. As the volume remains constant above 30% MC, above this level the density is predicted to increase rapidly, albeit there are very few directly recorded measurements of density for high moisture contents.

Structural controls on wood density for an individual species result from a number of spatial variants. These include changes in ring width, the development of reaction wood (formed when a wood grows under tension), and the relative proportion of latewood (formed later in the growing season) to earlywood. In addition, the density tends to reduce with height and distance from the pith [19]. Finally, variation between trees of the same species is influenced by heredity and environmental conditions (climate, soil, spacing). Consequently, because of density variations both within and between trees, there is considerable variation in densities of trees of the same species, with European white oak having quoted densities of 600 - 770 kgm^{-3} [13, 19], although in many papers it is unclear what type of density value is being recorded.

2.5 Reflection Coefficient Calculation

As outlined in Section 2.1 the key acoustic parameters used to infer the *in situ* physical properties of the sea bed are p-wave velocity, impedance and attenuation. Previous work by Quinn *et al.* [24] attempted to demonstrate that acoustic impedance in the form of pressure amplitude reflection coefficients (K) could be used to identify wood on or immediately beneath the seabed. For normal incidence, amplitude reflection coefficients for pressure waves were simply estimated from the Zoeppritz' equation. As is well known, a reflection will occur at the boundary between these two mediums if a contrast exists between their respective acoustic impedances (ρV_p). The polarity of this reflection coefficient is, of course, dependent on whether there is an increase or decrease in impedance across the interface. The compressional velocities used for this work were calculated from basic elastic theory for modern timbers, whilst conventional densities were extracted from the literature. This work suggested that wood (and in particular the key boat building material - oak), buried within unconsolidated marine sediments, should provide a characteristic large and negative normal incidence pressure amplitude reflection coefficient (K_{wood} -0.03 to -0.64). These values were generally outside the range typically found in normal geological situations (K_{geo} ± 0.1 [25]) and hence the calculation of reflection coefficients from high-resolution seismic data could provide a method of remotely identifying buried wood. *In situ* reflection coefficients were extracted from swept frequency Chirp data [6] acquired over an 18th Century oak vessel, which was buried in the fine sands of the East Solent, UK. This data confirmed the above theoretical calculation, as the wreck recorded an average K_{wood} of -0.27 [6, 24].

However, the research presented here suggests that velocity and density measurements obtained from modern air-dried timbers, are poor analogues for the physical and acoustic properties of archaeological wood.

3. Experimental Method

Marine archaeological wood has physical characteristics that are distinct to the seasoned or air-dried material that have been the subject of previous studies (See Sections 2.2 – 2.4). The major difference is the equilibrium moisture content of archaeological wood from the marine environment, which rarely has a moisture content less than 90% and values in excess of 800% have been recorded [26]. This is significantly higher than the EMC values of between 10% and 25% that are typical of previous wood measurements [13, 14, 18]. As outlined in Sections 2.2 – 2.4 these higher EMC values are predicted to have a major effect on both the p-wave velocity and density of the waterlogged material. In order to assess the impact of such high moisture contents on the physical properties of the major wood building material, a series of experiments were constructed. The principal set of experiments were undertaken on sapwood oak specimens measuring 10 cm x 10 cm x 1 cm and cut parallel to the L-T, L-R and R-T planes, thus enabling the direct measurement of V_R, V_T and V_L respectively. These samples were saturated under pressure to achieve 100% saturation and thus to replicate EMC values of marine archaeological wood as recorded by Hoffmann [27] for a series of marine artefacts dated from the 1st to the 17th Century. The maximum water content is that which would occur if the wood were fully waterlogged compared to the actual water content (or EMC), with the % saturation being the actual water content represented as a percentage of the maximum value. This work shows that the majority of the marine artefacts tested were between 85 and 100% saturated.

3.1 P-wave velocity measurements

A direct transmission method [28], with the samples placed within a water bath, has been used for the p-wave velocity measurements. The fully saturated nature of the marine material enabled the use of water as the coupling medium without any of the problems of air bubble scattering experienced when seasoned samples were placed in water tanks. The measurements were conducted using a modular system, consisting of; a TG1010 Programmable 10 MHz DDS function generator; a TERA Mk1 transducer and receiver amplification unit; and a set of Panametric V301 p-wave transducers with a resonant frequency of 0.5 MHz (Figure 2). The system was configured to produce a single frequency tone burst, 3 cycles in length. Data was logged using a LeCroy 9314 AM Quad 400 MHz oscilloscope, with an average of 50 stacks being taken for each measurement. Compressional phase velocity was calculated by picking the first positive peak value through water and the same peak through a water/wood/water travel path and using, the simple, Equation 1. The dimensions of the wood samples were chosen to reduce the problems of edge effects and significant attenuation loss following the methodology of Best [28]. The transmission times were recorded to an accuracy of 10 ns and the dimensions of the samples were measured with a precision of ± 0.1mm.

$$V_P = \frac{a}{\left(\Delta t + \dfrac{a}{V_W}\right)} \tag{1}$$

where V_P is the velocity through the wood sample, a is sample thickness, V_w is the velocity through the water and Δt is the time through the water and the sample minus the time through the water only. Calibration of the system was undertaken on an aluminium block standard [29] with an error of ± 0.1% being recorded. Further, an initial series of experiments were undertaken to determine the frequency dependency of measurements taken on saturated oak samples. Velocity measurements calculated for pulses between 200 kHz and 800 kHz at 100 kHz increments showed a variance in V_P of only ± 0.6%. All subsequent experiments were taken at 500 kHz, the resonant frequency of the transducers.

Multiple readings were taken for the three principal transmission directions (V_L, V_R and V_T) and for comparative purposes three oriented sections were cut from a well preserved 17th Century (1640-1644) timber taken from "Wreck 5" of the B&W Christianshavn excavation, Copenhagen.

3.2 Density measurements

As the principal aim of these experiments is to derive a method by which archaeological material can be interrogated without disturbance, density measurements that required the oven- or air-drying of the saturated samples (See Section 2.4) were considered inappropriate. Consequently, apparent densities were calculated at the known saturation values of 100%. Dimensions were measured with a precision of ± 0.1 mm and mass with a precision of ± 0.01 g.

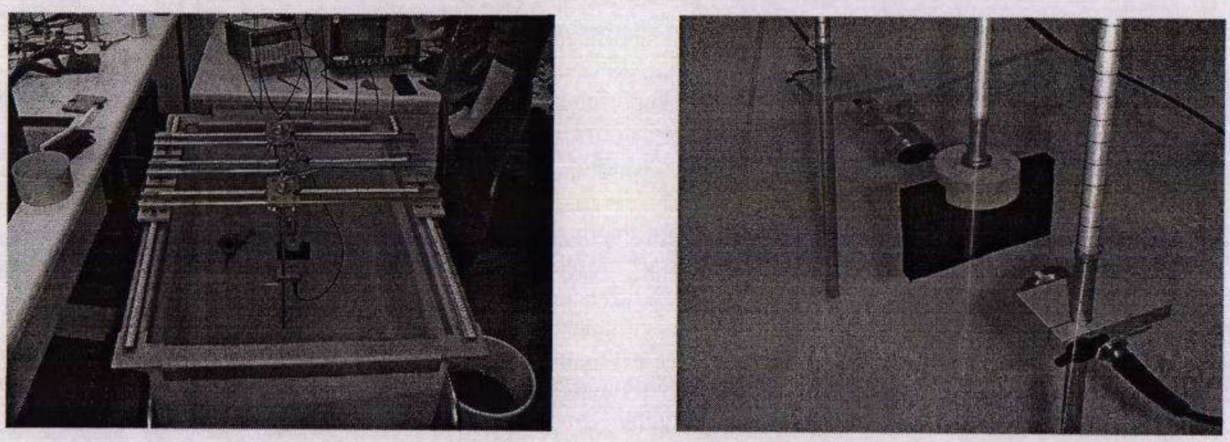

Figure 2. Images of water bath experiments on both fully saturated samples of oak and marine archaeological material

4. Results

Table 2 shows the results for p-wave velocity, density and normal incidence pressure amplitude reflection coefficient measurements obtained for fully saturated oak samples and the 17th Century oak artefact for the longitudinal, radial and tangential axes. The normal incidence pressure amplitude reflection coefficients have been calculated for three different sedimentary environments, burial in sand, sand-silt-clay and clay. The p-wave velocity and density values for these sediments are taken from Orsi and Dunn [30]. Table 2 also shows similar calculations but for the wood velocities and densities of both Bucur [13] and Quinn *et al.* [24] for comparison.

Source	Density (kgm^{-3})	V_L (ms^{-1})	V_R (ms^{-1})	V_T (ms^{-1})	K_{VL} Sand	K_{VR} Sand	K_{VT} Sand	K_{VL} S-S-C	K_{VR} S-S-C	K_{VT} S-S-C	K_{VL} Clay	K_{VR} Clay	K_{VT} Clay
100% Sat.	1161 ± 28	2882 ± 110	1668 ± 10	1528 ± 15	-0.04	-0.306	-0.345	0.099	-0.172	-0.214	0.213	-0.057	-0.100
Arch. Wood	1172 ± 6	3564	1527	1383	0.069	-0.341	-0.348	0.207	-0.210	-0.257	0.316	-0.096	-0.145
[13]	600	5071	2148	1538	-0.09	-0.477	-0.596	0.052	-0.360	-0.496	0.168	-0.255	-0.403
[24]	660	3120	1960	1230	-0.278	-0.476	-0.635	-0.142	-0.359	-0.543	-0.026	-0.253	-0.455

Table 2. Summary table showing the p-wave velocity, density and reflection coefficient values for 100% saturated oak and a 17th Century timber. Values for oak, taken from Bucur [13] and Quinn et al. [24] are shown for comparison, but these experimentally and theoretically derived values respectively were taken at 12% EMC.

The results demonstrate that the anisotropy exhibited by seasoned timbers is maintained when fresh oak samples are fully saturated. The absolute p-wave velocity values are significantly reduced for the longitudinal and radial axes measurements from waterlogged wood. However, the tangential axis shows only a small reduction in velocity (within measurement error of the Bucur value [13]). Conversely, as would be anticipated the fully saturated apparent densities have increased significantly. Re-calculation of reflection coefficient values for the three principal axes for a sand/sand-silt-clay/clay substrate exhibit an overall reduction of K_R values for the radial and tangential orientations, whilst the longitudinal K_R values are significantly increased. Furthermore the velocity (particularly V_R and V_T), density and hence reflection coefficient values for the archaeological material correspond well with those recorded for the 100% saturated material.

5. Discussion

The direct transmission measurements taken along the three principal axes of fully saturated oak samples demonstrates that at these high saturation states (>85% saturation) the p-wave velocity values have been significantly affected in the longitudinal and radial directions when compared to measurements on seasoned wood. At 100% recorded saturation V_L and V_R values have been reduced by 43% and 22% respectively, when compared to measurements taken at EMC's of 12%. By comparison, the tangential velocities exhibit no significant variation between the air-equilibrium condition and the fully saturated condition, thus emphasising the importance of cell structure on sound propagation in wood.

The use of apparent density measurements has resulted in significantly greater values than the conventional densities commonly recorded in the literature, and more significantly, than those used by Quinn *et al.* [24]. The authors consider that apparent density measurements at 100% saturation are more representative of the material *in situ*, and consequently are more indicative of the bulk density values required for the impedance/reflection calculations.

Re-calculated reflection coefficients, based on the actual measured p-wave velocities and apparent densities predict that wood buried in the marine environment should still have characteristically large and, in most cases, negative normal incidence pressure amplitude reflection coefficients, thus supporting the original assertions of Quinn *et al.* [24]. Indeed the K_{VR} *and* K_{VT} values for oak in sand calculated with these values are closer to the *in situ* values recorded from the East Solent wreck. There are though several issues raised from these new measurements. Firstly, K_{VL} values are actually large and positive for sand-silt-clay and clay substrates, albeit their magnitude (between 1 and 3 times greater than typical K_R's recorded from marine sediments) should still make them easily distinguishable from the sediment stratigraphy. Conversely, the K_{VL} values for sand are significantly reduced, suggesting that longitudinally oriented artefacts buried in such sands may be difficult to image. It should be noted that the dominant timber components found on wreck sites are planking which from the early pre-historic period to the middle ages was produced by radially splitting the trunk [3]. Even with the introduction of saws to boat building in the early 14th Century, the typical planking cuts were radial and tangential. Consequently, it is more likely that the radial and tangential orientations will be insonified in a moderately undisturbed wreck. Finally, the K_{VR} and K_{VT} values of wood buried in clay are closer to the $\pm$ 0.1 K_{geo} values recorded from 'normal' sedimentary environments, suggesting that acoustic characterisation of wooden artifact material in very fine grained stratigraphies should be undertaken with care.

The saturated measurements, and the comparable set made on actual waterlogged archaeological material, suggest that the use of a direct acoustic transmission technique in a water bath provides accurate and reproducible measurements of p-wave velocity. It is suggested that the use of these more realistic velocities, in tandem with apparent density measurements, should be used for the calculation of impedance and hence normal incidence pressure amplitude reflection coefficients. This would significantly improve upon the simplistic concept of using values calculated or measured from seasoned timbers.

This first set of recorded measurements of p-wave velocity and density for waterlogged material will provide the basis for extending this experimental work into the analysis of degraded archaeological material. Current research by the authors is attempting to establish if the structural changes to wood caused by macro- and micro-faunas are reflected in their acoustic signature.

6. Conclusions

This paper presents a method for accurately obtaining p-wave velocity measurements for waterlogged archaeological material from the marine environment. It has been demonstrated that measurements of both p-wave velocity and apparent density of fully saturated oak samples are more representative of marine archaeological wood than the seasoned wood values previously used. These recorded values have enabled the calculation of realistic normal incidence pressure amplitude reflection coefficients for archaeological wood buried in a range of marine sediments. Further, these results suggest that radially and tangentially cut timbers (typical of planking) will have characteristic large and negative reflection coefficients (-0.057 to –0.348), albeit within a range lower than previously expected (-0.253 to –0.635 [24]). This work provides a technological platform for future research in to the variation of acoustic properties with changing degradation state. The ability not only to identify buried archaeological material, but also to assess its state of preservation, will represent a major advance in our ability to manage our submerged cultural heritage.

7. Acknowledgements

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