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Wake penetrating sonar

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ABSTRACT

This paper describes a sonar which can operate in bubbly water. It is here deployed to penetrate the wake of a ship of 3,953 gross register tonnage. Orthodox Cold War sonar technology is not optimized for the shallow coastal waters that typify many current operations. The United States use dolphins in such waters, and the Twin Inverted Pulse Sonar (TWIPS) described here arose as a demonstration that echolocation was possible in bubbly water in response to a video showing dolphins generating bubble nets when hunting: if echolocation were impossible in these nets, then during this hunt the dolphins would have compromised their sonar. In this paper TWIPS detects and classifies targets against clutter by distinguishing between linear and nonlinear scatterer. For other applications, it has the potential to distinguish those nonlinear targets which scatter energy at the even-powered harmonics from those which scatter in the odd-powered harmonics. TWIPS can also, in some manifestations, require no range correction (and therefore does not require the *a priori* environment knowledge necessary for many remote detection technologies). The method applies to a range of sensors, including the use of radar to distinguish between circuitry, metal and soil; the use of LIDAR to detect combustion products; and MRI.

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1. INTRODUCTION

This paper describes a wake-penetrating sonar, the design of which was stimulated by the observation of dolphins creating bubble nets in order to catch fish (Fig. 1): if the dolphins did not possess a sonar capable of penetrating such clouds, they would be ‘blinding’ their echolocation when hunting in this way. The hence this exercise was undertaken to see if it was possible to design a sonar that offered enhanced detection, and target discrimination between fish and bubbles, in the sort of bubble clouds found in bubble nets, ship wakes, and in coastal waters subject to breaking waves [1,2].

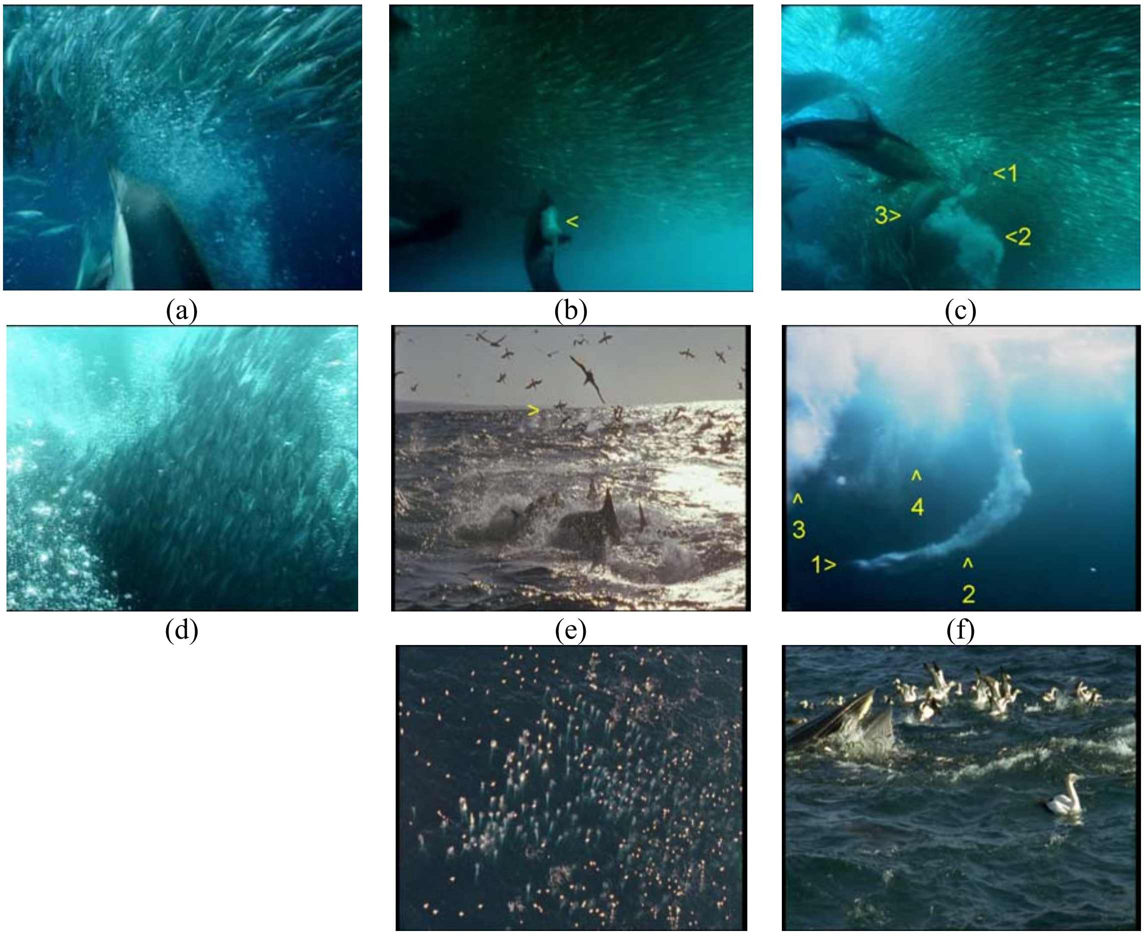


Figure 1. (a) Common dolphins herd sardines with bubble nets. (b) Swimming beneath a school of sardines, a dolphin starts to release a cloud of bubbles (arrowed) from its blowhole. A moment later (c) the dolphin (1) swims on, leaving behind the expanding cloud (2). Other dolphins (incl. 3) enter the frame. (d) The sardines school within a surrounding wall of bubbles that they are reluctant to cross, whilst (e) gannets dive into the sardine shoal to feed, folding their wings just before entry (arrowed). Dolphins are visible in the foreground. (f) On diving, a gannet (1) entrains a bubble plume (2). Plumes a few seconds old (3, with an older 4) have spread. (g) An aerial view shows hundreds of tight bubble plumes beneath airborne gannets. Imagine a torpedo trying to negotiate a field of gannet countermeasures! (h) A Bryde's Whale joins the feed. It surfaces with open mouth, which it then closes, sardines spilling from it. Images courtesy The Blue Planet (BBC). See Byatt *et al.* [3].

The limitations of active sonar in shallow water, primarily due to the presence of natural or anthropogenically induced bubble clouds and the seabed, have become of paramount importance in the last decade [4]. Military operations (e.g. mine detection, landings, and the protection of harbours and shipping lanes for military, commercial and aid craft) cannot rely on the decades of sonar experience built up for deep water applications during the Cold War because of these effects [5]. Similarly, a wide range of commercial industries (e.g. fisheries, coastal and offshore engineering and hydrographic surveying) would benefit from the ability to acquire reliable sonar data in both the swash and wave breaking zones, as well as busy shipping lanes.

In such waters manual searches by divers and military-trained dolphins represent the only viable option for detecting targets. Rear Admiral W.E. Landay (Chief of Naval Research, Marine Corps for Science and Technology) is quoted as saying *'The explosive ordnance disposal divers and the marine mammals run counter to the drive to get people out of the minefields, ... but they provide "so much flexible capability" that they are likely to remain. The divers and the mammals work mainly in very shallow water and the surf zone, which "continues to be the most challenging environment" for mine warfare'* [6]. Therefore, sonar which could work effectively in bubble clouds would have significant implications for safety, cost and tactics.

The suggested approach to this problem through the use of a Twin Inverted Pulse Sonar (TWIPS), use of which should result in the suppression of non-linear scatterers (bubbles) and the enhancement of linear scatterers (solid targets). Following the initial suggestion [1, 2], this approach was tested through simulation [7- 11] and tank experiments [10- 15], before eventual deployment at sea in the wakes of large vessels [16]. The object was to test the extent to which TWIPS improved classification of the seabed, distinguishing this linear target from the bubble clouds in the vessel wake. Some of the implications of the technology (for radar, MRI, LIDAR and dolphin echolocation) are discussed.

2. METHOD

Theory

The technique is described fully in Leighton *et al.* [16]. Figure 2 schematically shows the operation of a Twin Inverted Pulse Sonar (TWIPS). Consider the following problem scenario: Sonar fails to detect a linearly-scattering body (the 'target', e.g. mine or seabed), because the returned sonar signal is dominated by the scatter from wave-generated bubble clouds in the vicinity of the target. If the insonifying field had sufficient amplitude to generate a nonlinear response, it might be possible to enhance scatter from the target whilst simultaneously suppressing it from the bubbles. Consider if the insonifying field $p(t)$ consisted of two high amplitude pulses, one having reverse polarity with respect to the other (Fig. 2(a)). The scattering from the linear scatterer (in the figure, represented by the solid) is portrayed to resemble the outgoing pulse (Fig. 2(b)(i), noting that in principle this echo could include other linear characteristics such as linear resonances and surface waves, multipaths etc.). Scatter from the bubble however contains nonlinear components (Fig. 2(b)(ii)). When the time series of the echo from the solid is split in half, suppression occurs if the two halves are added together to form p_+ (Fig. 2(c)(i)) but enhancement occurs if one is subtracted from the other to form p_- (Fig. 2(d)(i)). However when the same operations are performed on the echo from the bubble, whilst odd fractionals are suppressed by subtraction and enhanced by addition (following the same trend as the linear scatter), the even fractionals are enhanced by addition and suppressed by subtraction (Fig. 2(c)(ii) and 2(d)(ii)). This opposite behaviour is used to distinguish nonlinear scatterers from linear ones. Details can be found in reference [16].

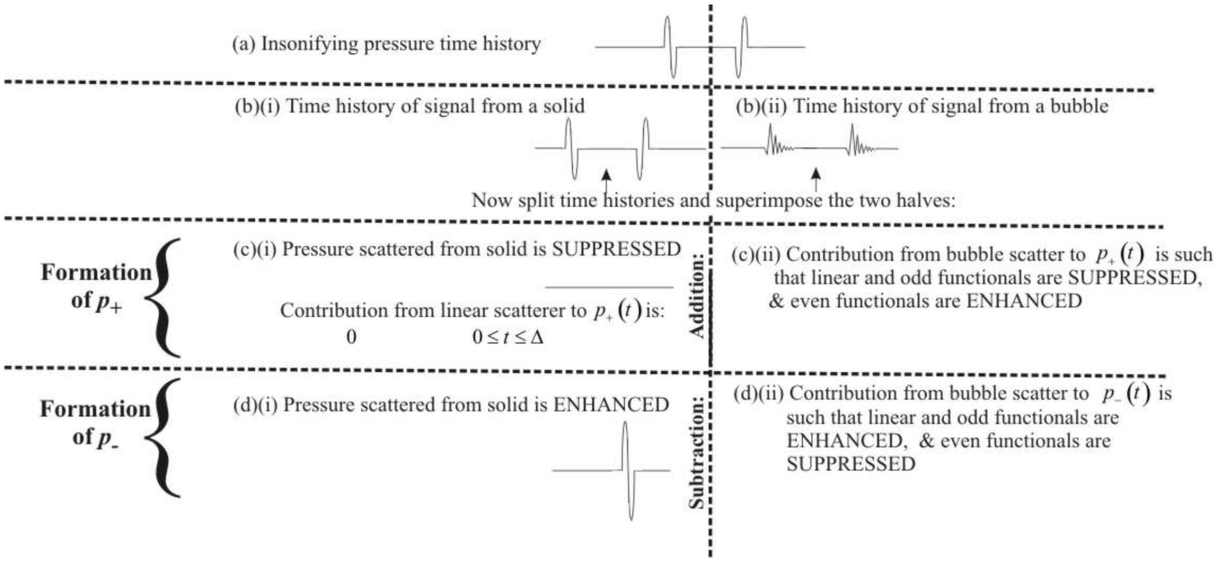
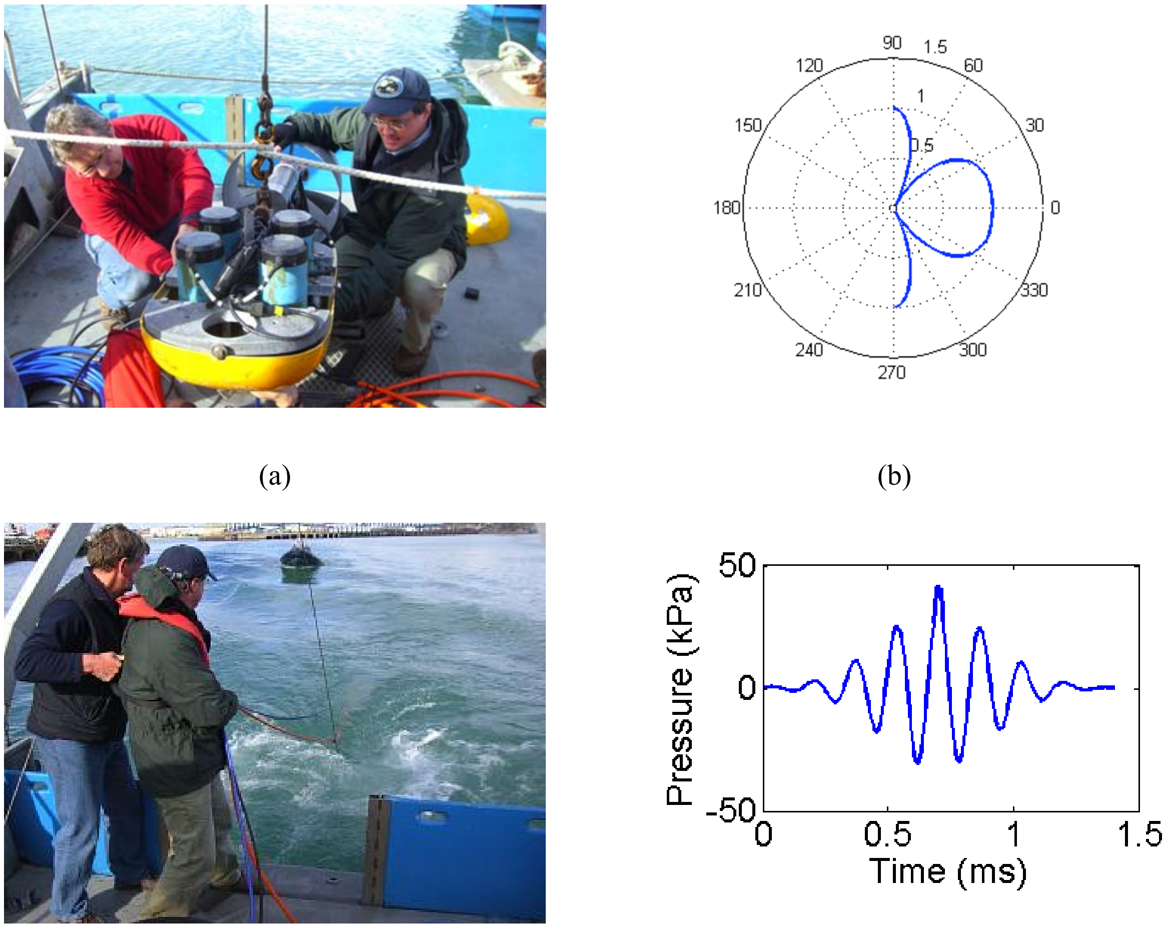


Figure 2. Schematic of the formation of p_+ and p_-

Experiment

The sonar source consisted of four transducers (GeoAcoustics T135D) mounted on a towfish (Fig. 3(a)) in a downwards-looking 2×2 configuration (the approximate directionality of which is shown in Fig. 3(b)). The system emits pairs of pulses with Gaussian envelopes and with a centre frequency of 6 kHz. Each pulse had ~1.5 ms duration and the interpulse time was 50 ms. The zero-to-peak acoustic pressure amplitude at range 1 m was as shown in Fig. 3(d). The hydrophone was a Blacknor Technology D140 (serial number 18938 with built-in preamplifier, calibrated by the National Physical Laboratory). Hydrophone data were acquired onto a PC using a 4-channel National Instruments sound card acquiring data at 200 kHz on each channel. One channel acquired a trigger signal from a trigger box, and second channel acquired the acoustic data. Acoustic signals were passed through a pair of Krohn-Hite model 3203 filter banks. The high-pass was set at 0.2 kHz to eliminate mains contamination, and the low-pass was set at 100 kHz to avoid any frequency-folding effects.

On 27 February 2008, the sonar was towed 2-4 m behind the stern of the *RV Bill Conway* at ~1.5m depth through the wakes of various vessels. A time varying gain (proportional to $r^2(t)$ where $r(t)$ is the penetration depth at time t) was applied to all the echoes before processing to allow fair comparison between the conventional sonar and TWIPS results (noting that any such corrections cancel out in the TWIPS functions P_+/P_- and P_-/P_+). The test was to judge the ability of TWIPS to discriminate between the wakes and the seabed (without using the prior knowledge of what features occurred in the sonar display at what range) as the source was towed through the combined wakes of the *RV Bill Conway* and vessels of opportunity. The route was from the National Oceanography Centre (Southampton) (50°53'33"N 1°23'38"W) to Calshot Castle (50° 49′ 11.53″ N, 1° 18′ 23.17″ W), and hence took place in the very busy shipping lanes of Southampton Water (which handles 7% of the UK's entire seaborne trade), where the seabed varies between 10-20 m depth. Results are presented for when the *RV Bill Conway* tows the source into the wake wake of the Southampton to East Cowes *Raptor* Class Red Funnel car ferry *MV Red Osprey* (3953 gross register tonnage; 93.22m in length and 17.5m beam; with a capacity for 895 passengers plus 220 cars) (Fig. 4).



(a) (b)

(c) (d)

Figure 3. (a) The towfish is shown upside down, its front facing the reader, as the four transducers (blue cylinders with black caps) are fitted into it The hydrophone tip is mounted between the blue transducers and the horizontal aluminium hardware bottle at the rear of the picture. The upper half of the streamlined yellow casing has been fitted (the lower half, yet to be fitted, is visible in the lower right of the picture). (b) One-sided directivity pattern of a 2 × 2 array of monopole-like pistons having a spacing of 250 mm and an operating wavelength of 250 mm. In this plot, 0 deg corresponds to the direction the pistons face. (c) The towfish deployed from the stern of the *RV Bill Conway*. The dark, nearly vertical cable takes the tension to tow the towfish from the *Bill Conway's* stern A-frame. The coloured cables supply power and the control/data acquisition signals, and need to be held out of the propellers. A wave from the wake from one of the many larger vessels in the area can be seen approaching the stern of the *RV Bill Conway*. (d) The hydrophone record of one of the pulses at range 1 m from the source in a 'bubble-free' test tank. This pulse was followed 50 ms later by its inverse. The pair are then repeated every second.

3. RESULTS

Figure 5 show the sonar output when the source was in the wakes of both the *RV Bill Conway* and the *MV Red Osprey*. The echoes from consecutive sweeps are stacked to form an image (one sweep is emitted each second). The figure plots smoothed envelopes derived from the basic signals $p(t)$, $p_{+}(t)$ and $p_{-}(t)$. These envelopes are evaluated by band-pass filtering the signals, then computing their envelope (exploiting the Hilbert transform) and finally smoothing the result by averaging over the duration of the outgoing pulse. These smoothed envelopes are denoted here using capital P notation, so that the envelopes of $p(t)$, $p_{+}(t)$ and

$p_{-}(t)$ are denoted by P, P_{2+} and P_{1-}, respectively (the '2' subscript indicating that band-pass filters used in the initial stage of this processing has been undertaken about the second harmonic; and the subscript '1' indicating that the band-pass filtering is done about the fundamental).

(a) (b)

Figure 4. Approaching the wake of the Red Funnel ferry just prior to taking sonar records of Fig. 5. The commercial depth sounder (Wheel house unit: Simrad CR50 with Transducer: Simrad combi C50/200 dual 50 kHz / 200 kHz operating at 200 kHz) fitted to the *RV Bill Conway* could not function in this wake.

Figure 5(a) shows what we have termed 'standard sonar processing', which is achieved as follows. First, the returned signal is band-pass filtered about the centre frequency of the outgoing pulse. Second, the energy of the return is computed by temporally averaging the envelope using a period that corresponds to the duration of the original pulse. The final step is to average the results from both TWIPS pulses; both pulses are exploited so that the standard technique is not inherently disadvantaged relative to TWIPS processing. Figure 5(a) shows two returns, a stronger and more compact one at an echo time of around 3 ms, and a weaker and more diffuse one beyond around 12 ms. There is no inherent information to enable classification. However the near, compact target disappears in the TWIPS function P_{1-}/P_{2+} (Fig. 5(b)), but reappears in the function P_{2+} (Fig. 5(c)), indicating that the scatterers are nonlinear (bubbles). The opposite trend is seen in the ~12 ms target (which is present in the TWIPS function P_{1-}/P_{2+} (Fig. 5(b)), but absent in the function P_{2+} (Fig. 5(c)), indicating that it is a linear scatterer (the seabed).

4. CONCLUSIONS

The ability of TWIPS to provide target classification has been demonstrated at sea, distinguishing between linear scatterer (the seabed) and nonlinear scatterers (the bubbles in the wake). This demonstration of classification is part of a larger study which also demonstrates detection enhancement of targets in test tanks, and confirms both these results with simulations [16]. TWIPS could in principle be applied to a range of radiations (including RADAR, LIDAR and MRI) where the distinction between linear and nonlinear targets is important [16].

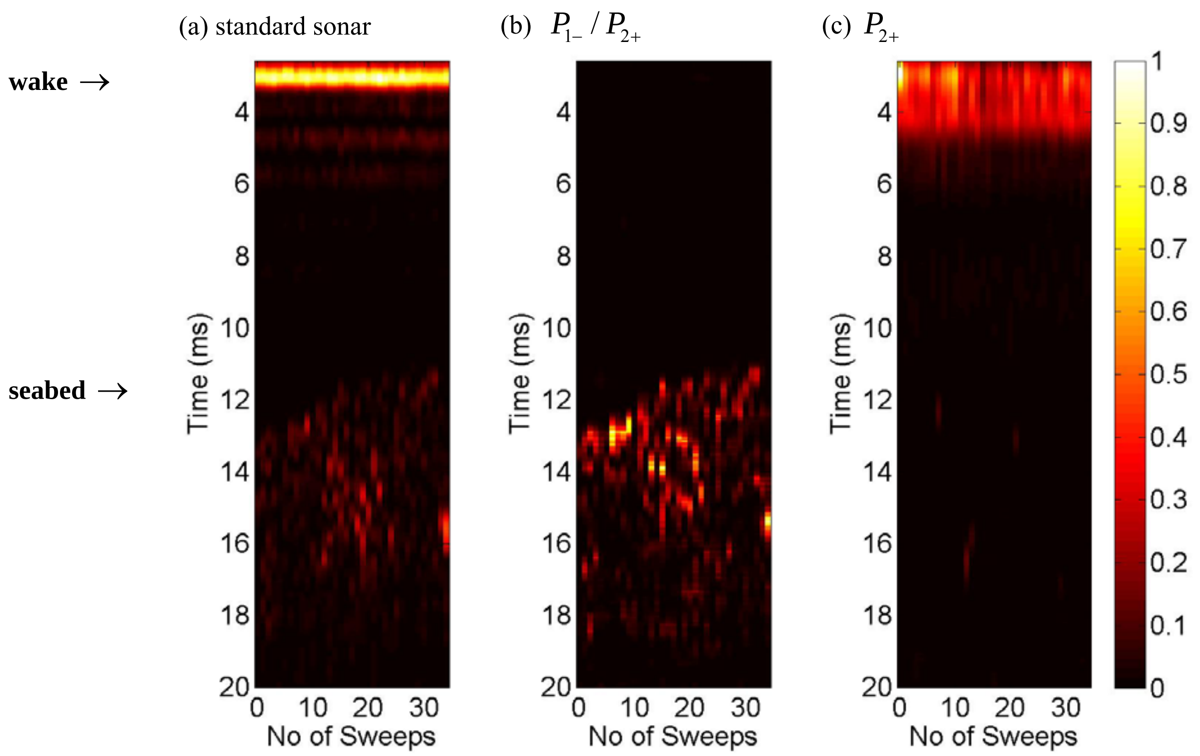


Figure 5. Data taken in the wake of the *MV Red Osprey* (Fig. 4). Comparison of three processing types for the same set of raw data (taken with an interpulse time of 50 ms and presented using linear colour scale having a maximum value shown in {} brackets). The sweeps (i.e. time from the emission of one pulse pair to the next) was 1 s. The plots show: (a) Standard sonar {maximum value =260}; (b) P_{1-}/P_{2+} {maximum value = 7.9×10^5}; and (c) P_{2+} {maximum value = 0.24}. For all three representations, noise level thresholding was set at 1% of maximum value and geometric averaging was carried out for each ten lines in the denominator of (b).

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