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CETACEAN ACOUSTICS IN BUBBLY WATER

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Abstract: *Marine mammal signals often propagate through bubbly water, be they generated under breaking waves, wakes, or even by the mammals themselves. Two circumstances are of particular interest: the possible use of acoustic signals to trap prey in bubble nets; and the ability of dolphin sonar to operate in bubbly water (such as the surf zone) that would confound the best human sonar, despite the fact that the dolphins possess 'hardware' which is comparatively mediocre. This paper examines these circumstances.*

Keywords: *Bubble nets, bubble acoustics, fishing, humpback whales*

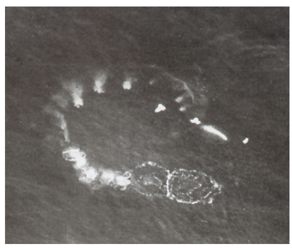
1. INTRODUCTION

Marine mammal calls often propagate through bubbly water, be they generated under breaking waves, wakes, or even by the mammals themselves. Two circumstances are of particular interest: the possible use of acoustic signals to trap prey in bubble nets; and the ability of dolphin sonar to operate in bubbly water (such as the surf zone) that would confound the best man-made sonar, despite the fact that the dolphins possess 'hardware' which is comparatively mediocre [1].

2. THE BUBBLE NETS OF HUMPBACK WHALES

For many years there has been speculation as to the mechanism by which humpback whales (*Megaptera novaeangliae*) exploit bubble nets to catch fish [2]. It has been known for decades that single whales, or groups, dive deep and then release bubbles to form the walls of a cylinder, the interior of which is relatively bubble-free (Fig. 1). The prey are trapped within this cylinder, for reasons previously unknown, before the whales lunge feed on them from below. It is usually assumed that prey are contained by the bubbles alone. However it is certainly known that when a proportion (as yet unquantified) of humpback whales form such nets, they emit very loud, 'trumpeting feeding calls', the available recordings containing energy up to at least 4 kHz. Leighton *et al.* [2] proposed that these whales may be using such calls to enhance the ability of their bubble nets to trap the fish, in the following manner. A suitable void fraction profile would cause the wall to act as a waveguide. Assume the scales permit the use of ray representation. Fig. 2 shows how, with a hypothetical tangential insonification, the mammals could generate a 'wall of sound' around the net, and a quiet region within it. The natural schooling response of fish to startling by the intense sound as they approach the walls would, in the bubble net, be transformed from a survival response into one that aids the predator in feeding [3]. The frequencies in the feeding call are indeed in the correct range to excite resonances in fish swim bladders and, given their sensitivities, presumably such excitation could discomfort the fish sufficiently for it to return to the interior of the net.

(a)

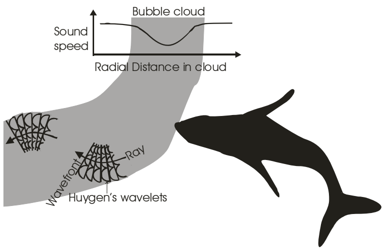


(b)

Fig. 1: (a) Schematic of a humpback whale creating a bubble net. A whale dives beneath a shoal of prey and slowly begins to spiral upwards, blowing bubbles as it does so, creating a hollow-cored cylindrical bubble net. The prey tend to congregate in the centre of the cylinder, which is relatively free of bubbles. Then the whale dives beneath the shoal, and swims up through the bubble-net with its mouth open to consume the prey ('lunge feeding'). Groups of whales may do this co-operatively (Image courtesy of Cetacea.org). (b) Aerial view of a humpback bubble net (photo graph by A. Brayton, reproduced from [4]).

Fig. 2(*b*) plots the raypaths from four whales whose beampatterns are represented by a 10° fan of 281 rays, for a bubble net in which the void fraction increases linearly from zero at the inner and outer walls, to 0.01% at the mid-line of the wall. The proposed 'wall of sound' and quiet interior are clearly visible. Even if the whales do not create sufficiently directional beams and insonify tangentially, the bubble net might still function through its acoustical effects. The 'wall of sound' effect in Fig. 2(*b*) is generated from those rays which impact the wall at low grazing angles. Those rays which never impact the wall do not contribute to the 'wall of sound'. If rays of higher grazing angle impact the net, they may cross into the net interior, though their amplitudes would be reduced by the bubble scattering, and attenuation alone would generate a quieter region in the centre of the net.

The actual acoustics of the cloud will of course be complicated by 3D effects and the possibility of collective oscillations; and even, speculatively, bubble-enhanced parametric sonar effects [2] which might be utilized by whales, for example to reduce beamwidth or generate harmonics, sum- and difference-frequencies etc.. These effects are discussed elsewhere [2,3].



(a)

(b)

Fig. 2: (a) Schematic of a whale insonifying a bubble-net (plan view; sound speed is least at the mid-line of the net wall). (b) Four whales insonify bubble net (inner circle inner boundary of the net wall (outer one is obscured by rays)). See Leighton et al. [2] for details.

3. DOLPHIN ECHOLOCATION IN BUBBLY WATER

The previous section discussed how some humpback whales may have found acoustics techniques for enhancing the performance of their bubble nets. They are not alone in using bubble nets to catch prey. Dolphins have also been observed to feed using bubbles [3,5,6]. However *Odontoceti* regularly exploit frequencies in excess of 100 kHz for echolocation. At such frequencies the bubble nets influence the sound field in a very different manner to that shown in Fig. 2(*b*), most notably generating strong scattering and severe attenuation (>200 dB m^{-1} at 100 kHz, compared to only ~6 dB m^{-1} for the 4 kHz component used by humpback whales in bubble nets).

This creates a dilemma. In creating bubble nets, either the dolphins are blinding their sonar when they need it most (*i.e.* when hunting in a visually complex environment); or they have sonar systems which out-perform the best man-made sonar. Given that dolphin sonar hardware has only mediocre properties compared to the best man-made sonar [1], if their sonar is operational in bubble nets, it must be a result of the processing. Given the high amplitude pulses dolphins can generate, and the short ranges over which they are required to detect prey in bubble nets, it is conceivable that they are exploiting a nonlinearity. This will now be explored.

The above calculations indicated very high attenuations in bubbly water for frequencies associated with dolphin echolocation. However, as Leighton points out [3], such calculations assume that the bubbles undergo linear pulsations in the steady state, whereas dolphins can exploit short pulses of sufficiently high amplitude to drive bubbles into nonlinear oscillation (>50 kPa at 1 m, zero-to-peak [1]), which from Fig. 3(*b*) of reference [7] is sufficient to generate nonlinear effects. Furthermore, that paper has already shown that, without any special processing, the attenuation can be dramatically reduced. Indeed even very rudimentary processing, once nonlinearities have been generated, can enhance the contrast between the nonlinear bubbles and the linearly-scattering target. If the receiver is narrowband, then energy scattered in harmonics above the fundamental by a bubble will, of course be 'invisible' to such a detector. Furthermore, Fig. 3 of [7] showed how, if the bubble population falls within a certain range of power law distributions, even a wideband receiver could detect sonar enhancements resulting from the reduced absorption which the bubble nonlinearity provides. Additionally, there may be further gains if more sophisticated processing is considered.

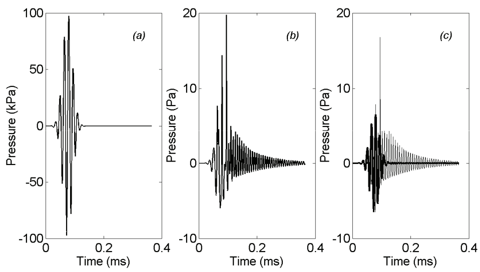


Fig. 3: (a) The driving pulse (centre frequency 65.7 kHz) used for Fig. 4. (b) Simulation of pressure detected at 1 m from target used in Fig. 4(a)-(c), and the bubble used in Fig. 4(d)-(f). (b) Superimposition of plot of Fig. 4(a) (thick black line) on plot of Fig. 3(b) (thin line).

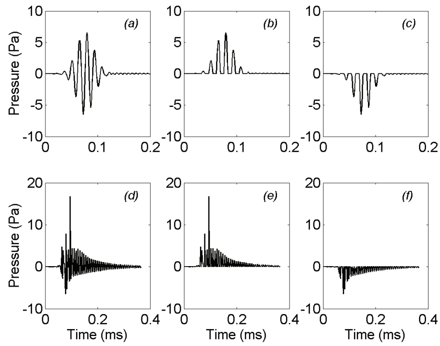


Fig. 4: (a) Pressure 1 m from linearly scattering target insonified by pulse of Fig. 3(a). Positive (b) and negative (c) half-wave rectification of (a) are shown. (d) Pressure at 1 m from air bubble (22.5 μm *radius water under 1 bar static pressure) insonified by pulse of Fig. 3(a). Positive (e) and negative (f) half-wave rectification of (d) are shown.*

It is very likely that, for dolphin sonar to operate effectively in bubbly water, the dolphins must mentally be undertaking signal processing which takes into account the nonlinearities they are generating [3]. This is because, although the best human sonar hardware is superior to that available to dolphins [1], the dolphins manage to echolocate in environments (bubbly water, sediments etc.) which confound the best man-made systems. The processing must therefore be making the difference. Given the severe scattering, attenuation and reverberation the dolphin must be counteracting, a nonlinear process would seem to be a strong possibility. Figs. 3 and 4 illustrate one such route.

The pulse of Fig. 3(*a*) is used to insonify a region of water containing both a linearly scattering target and an air bubble of radius 22.5 microns in water under 1 bar of static pressure. All of the scattered waveforms in Fig. 3(*b*),(*c*) and Fig. 4 are simulated at a distance of 1 m from the target and bubble. Fig. 3(*b*) shows the net scatter detected from the bubble and target. Whilst at first sight this may not seem to reveal much, when (in Fig. 3(*c*)) the scatter from the target alone (without the bubble, as calculated in Fig. 4(*a*)) is superimposed on the signal in Fig. 3(*b*), it is clear that the negative pressure component of the scattered signal more clearly shows the presence of the target than does the positive component. This is because the nonlinearity in the bubble response generates an asymmetry about the zero-pressure line, as will now be shown. Parts (*b*) and (*c*) of Fig. 4 show, respectively, the results when the signal in Fig. 4(*a*) is subjected to positive and negative half wave rectification. The signal from the linearly scattering target contributes equally to both, such that the energy in Figs. (*b*) and (*c*) are equal. The nonlinearities in the scatter from the bubble create a different picture (Fig. 4(*d*)). The pressure scattered from the bubble is clearly asymmetrical about the zero-pressure axis. Parts (*e*) and (*f*) of Fig. 4 show, respectively, the results when the signal in Fig. 4(*d*) is subjected to positive and negative half wave rectification. The energy in Fig. 4(*e*) is more than 2.1 times greater than that in Fig. 4(*f*). This asymmetry of course provides a method by which the signal from the linearly scattering target can be distinguished from the bubble, if both contribute to the scattered signal (Fig. 3(*b*),(*c*)). Hence when (in Fig. 3(*c*)) the signal from the linearly scattering target (Fig. 4(*a*)) is superimposed on the signal of Fig. 3(*b*), the potential of the nonlinearity is clear: whilst the temporal peak energy in the scattered signal of Fig. 3(*b*) comes from the bubble scatter, the temporal peak in the negative pressure comes from the linearly scattering target. Indeed Fig. 3(*c*) illustrates how much of the early stages of the return in Fig. 3(*a*) comes from the target. Of course, were the relative amplitudes of the scatter from target and bubble different, this simple result would not hold true, but the potential of the bubble nonlinearity to enhance the detection of targets and bubbles with respect to one another is clear.

Whilst illustrative, such examples should however be treated with care. There might, for example, be a temptation to quantify the enhancement in target detection by correlating the received signals with the driving pulse. However in Figs. 3 and 4 the bubble is being driven close to half of its pulsation resonance frequency. The response from the bubble is almost entirely at the bubble resonance, whereas the response from the linear scatterer is at the frequency of the transmitted pulse. Hence it would be very easy to separate the linear from the nonlinear responses, simply by filtering about the bandwidth of the transmitted pulse (which causes the bubble response to vanish almost completely). This is of course exactly what a correlation process does. The correlation output, with or without rectification, would be dominated by the linear response. Hence a correlator would not help indicate any improvement obtained by rectification. Indeed one might argue that you should look at the response at the output of a correlator, since this is the minimum that a standard sonar system would employ. At the output of such a correlator you would not see an asymmetry in the waveform. This is because the correlator acts as a band-pass filter, with a fairly narrow pass band. To get asymmetry, the signal must have a spectrum that occupies more than an octave, which the output of a correlator will not, in general, achieve.

Another route for exploiting the nonlinearity to enhance target detection relies on the generation of even-powered terms in the expansion of the nonlinearity associated with the scatter from the bubble. Having identified a strong second harmonic, and noting that such even-powered harmonics would be insensitive to the sign of the driving field, Leighton [3,6] suggested that the use of closely-spaced pulses of opposite polarity could enhance the detection of prey with respect to bubbles. Fig. 5 illustrates just one of the ways in which the linear scatter from targets such as swim bladders driven off-resonance, or mines, might be enhanced compared to the scatter from oceanic bubble clouds. If the returned time series is split in half, then on subtraction of these two halves, the signal from the linearly scattering target doubles, whilst the energy invested in the even-powered harmonics of the scatter from the bubbles is suppressed (Fig. 5). Of course the linear and odd nonlinear terms will not be suppressed. This means that, when this technique is used to enhance the detection of linearly scattering targets compared to detection of bubbles, it will not be as effective as the converse. That is to say, it is not as effective as the enhancement of bubble scatter, compared to that from linearly scattering targets, which occurs when the two halves of the time series are added. This is a general feature of many of the possible nonlinear enhancement techniques, and may be exploited for contrast agents.

Let us say the problem is to detect a linearly scattering target (the 'target') which is difficult to detect because it is immersed in a cloud of bubbly water. Such a target might be a fish in a dolphin bubble net - even with a swim bladder, the fish would produce ostensibly linear scatter from dolphin echolocation because the gas is driven so far from resonance. Alternatively, it might consist of a military mine which is a hazard to landing craft because it is hidden from sonar by breaking waves. Consider if the emitted sonar signal were to consist of two high amplitude pulses, one having reverse polarity with respect to the other (Fig. 5, top line). Linear reflection from the solid body is shown in Fig. 5(*b*)*(i)*. The bubble generates nonlinear radial excursions (Fig. 5(*a*)*(i)*) and emits a corresponding pressure field (Fig. 5(*a*)*(ii)*). Whilst the pressure emitted by the bubble may contain linear and odd-powered nonlinearities, it is the even powered (e.g. quadratic) nonlinearities which will be insensitive to the sign or the driving pulse, and hence which can be used to enhance the scatter from the target over that from the bubbles. It is these quadratic (and high even-powered components) which will be discussed in Fig. 5, and below.

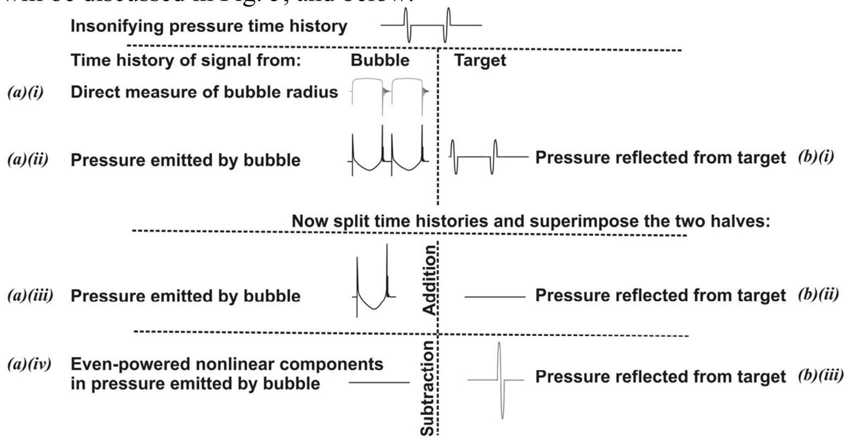


Fig. 5: Schematic of a proposed 'Twin Inverted Pulse Sonar', whereby the scattering from a linear scatterer (such as a fish or a mine), and scattering from nonlinear scatterers (such as bubbles) can be enhanced and suppressed relative to one another. After Leighton [3].

Normal sonar would not be able to detect the signal from the solid (Fig. 5(*b*)*(i)*), as it is swamped by that from the bubbles (Fig. 5(*a*)*(ii)*). If however the returned time histories are split in the middle and combined to make a time history half as long, enhancement and suppression occurs. If the two halves of the returned signals are added, the even-powered nonlinear components of the scattering from the bubble are enhanced (Fig. 5(*a*)*(iii)*), whilst the signal from linearly scattering target is suppressed (Fig. 5(*b*)*(ii)*). This can be used to enhance the scatter from biomedical contrast agents. If however the two halves of each returned signal are subtracted from one another, the even-powered nonlinear components of the scattering from the bubbles is suppressed (Fig. 5(*a*)*(iv)*) whilst the reflections from the solid body are enhanced (with the usual constraints imposed by increased signal-to-noise ratio) (Fig. 5(*b*)*(iii)*).

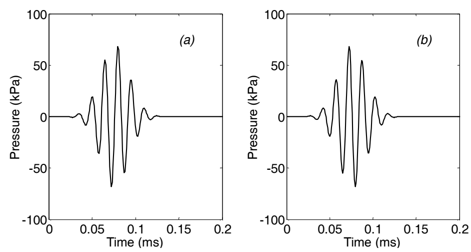


Fig. 6: The two driving pulses (centre frequency 65.7 kHz) used to insonify a bubble: the (a) 'positive' pulse has negative polarity with respect to (b) the 'negative' pulse.

If echolocation is the equivalent of vision underwater, then switching from linear to nonlinear sonar in bubble clouds might find analogy with driving through fog. 'Linear headlamps' would provide the familiar backscatter from the fog, making detection of targets difficult (analogous to the intense sonar backscatter from bubbles). However switching to nonlinear sonar might be equivalent to turning on 'nonlinear headlamps' in a car, which backscatter far less from the fog and so make driving easier. A preliminary calculation suggests that this technique may have potential to enhance the detection of linearly scattering targets in bubble clouds. Fig. 6 shows two driving pulses which are used to insonify a bubble: one has negative polarity with respect to the other. Fig. 7 shows the linear scatter from the target (above the dashed line, in (*a*) and (*b*)), and the scatter from a bubble (below the dashed line, in (*c*) and (*d*)). The graph on the left in each case (i.e. (*a*) for the target; (*c*) for the bubble) shows the scatter from the pulses from Fig. 6: the upper plot (*i*) shows the scatter when excited by the 'positive' pulse of Fig. 6(*a*); the lower plot (*ii*) shows the scatter when excited by the 'negative' pulse of Fig. 6(*b*).

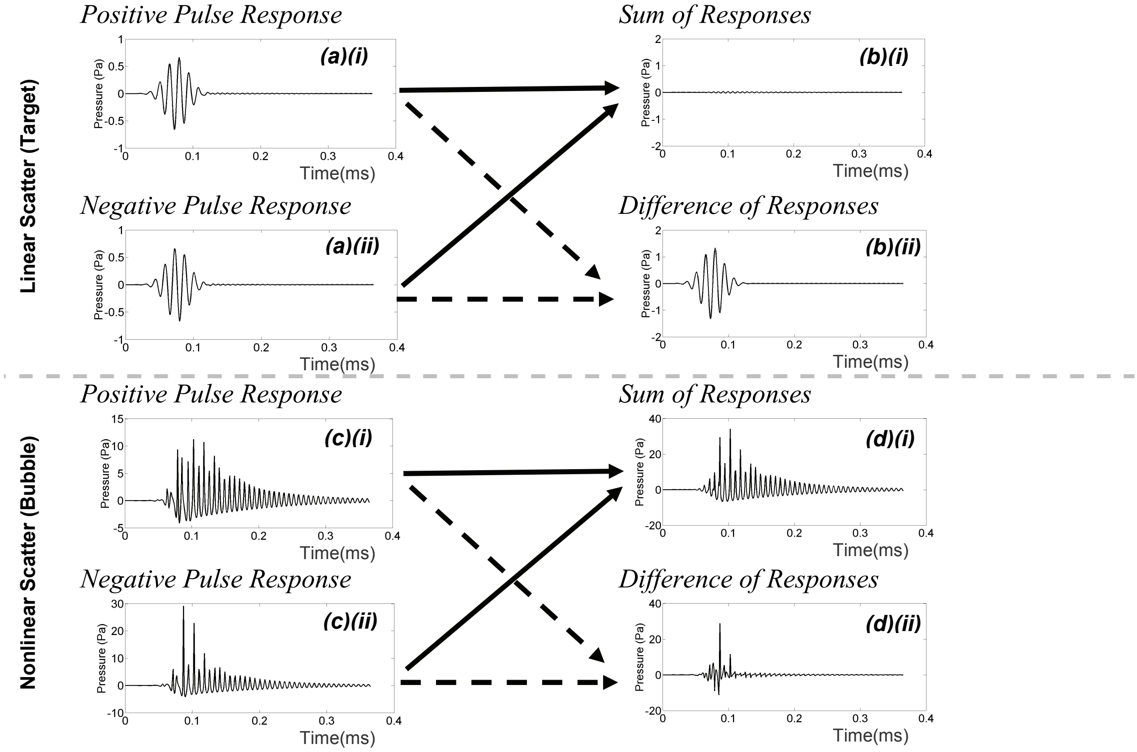


Fig. 7. Scatter after insonification by pulses of Fig. 7, with linear scatter from the target (above the horizontal dashed line, in (a) and (b)), and the scatter from the bubble used in Fig. 4 (below the horizontal dashed line, in (c) and (d)). The graph on the left in each case ((a) target; (c) bubble) shows scatter from the pulses from Fig. 6: the upper plot (i) shows scatter when excited by the 'positive' pulse of Fig. 6(a); the lower plot (ii) shows the scatter when excited by the 'negative' pulse of Fig. 6(b). Solid arrows indicate addition, dashed arrows indicate subtraction.

The linear scatter of the positive pulse (Fig. 7(*a*)*(i)*) is in antiphase with that from the negative pulse (Fig. 7(*a*)*(ii)*), so that they add (the process indicated by the upper pair of solid arrows lines in Fig. 7) they produce zero signal (the time history in Fig. 7(*b*)*(i)* is not precisely zero because of numerical errors). When they are subtracted from each other (the process indicated by the upper pair of dashed arrows in Fig. 7), the amplitude of the signal is doubled, which is of course equivalent to a 6 dB increase over the energy in either of the original signals in (*a*). However the nonlinear scatter by the bubble of the positive pulse (Fig. 7(*c*)*(i)*) is not in antiphase with that from the negative pulse (Fig. 7(*c*)*(ii)*). Indeed, when they add (the process indicated by the lower pair of solid lines in Fig. 7) they produce a signal (the time history in Fig. 7(*d*)*(i)*) which is 5 dB greater than the average energy of the original signals in (*c*). When they are subtracted from each other (the process indicated by the lower pair of dashed lines in Fig. 7), the amplitude of the signal is 1 dB less than the average energy of the original signals in (*c*). The key point to note here is that addition of signals in Fig. 7 enhances the scatter of the bubbles compared to the linear scatter from the target; whilst subtraction does the opposite, enhancing the signal from the linearly scattering target compared to that of the bubbles. That it is easier to enhance the detection of bubbles compared to the linearly scattering target, than to do the converse, is of course expected, given that the bubble signal does not consist of purely even-powered nonlinearities. There are very many ways in which the nonlinearity generated by the bubbles may be exploited to enhance sonar detection of a linearly scattering target. If the receiver is narrowband, that proportion of energy which is at harmonics that are outside of its bandwidth will become 'invisible'. Even if the bandwidth of the receiver is sufficiently great to detect these harmonics, their higher frequencies may well be preferentially absorbed compared to the linear scatter from the fundamental (although an increase in attenuation with frequency should not be taken for granted in bubble clouds, as it will tend to peak around the main resonance of the population). The two examples shown above (asymmetry (Figs. 3,4) and pulse inversion (Figs. 6,7) have been demonstrated by using the scatter from a single bubble, and comparing it with a target which linearly scatters a similar amount of energy to that bubble. Bubble populations at sea tend to have a wide size distribution. Elsewhere in this volume [7] population-dependent techniques for enhancing sonar detection via bubble nonlinearities were discussed.

4. CONCLUSIONS

This paper has outlined some possible interactions between the acoustic emissions of marine mammals, and the bubbly environment. In specific circumstances the physics would allow the bubble nonlinearity to be exploited to enhance sonar operation.

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