Killer Whales with Killer Tails:

Can killer whales slap their tails on the ocean surface and stun a fish down below?

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Phys 438

Abstract

Killer whale pods sometimes hunt herring by corralling the fish into a tight ball near the ocean surface and stunning them with underwater tail slaps before eating them. I asked if this was possible with an above-water tail slap at the ocean surface, without any physical contact between fluke and fish. Basic physics concepts used were conservation of momentum ($m_{Fluke}u_{Fluke,i} = m_{Water}u_{Water,f}$) and pressure waves ($I = \frac{1}{2} \rho v u_o^2 = \Delta p^2/2\rho v$). When a whale's fluke collides with the ocean surface, the fluke's momentum is transferred to the water directly underneath. A pressure wave with intensity, I, is created that exerts a pressure on anything in its path, including fish. The sound pressure level fatal to fishes (using guppies as a representative species) is 230dB//1μPa, corresponding to an intensity of 3.252×10^4 Watt/m^2. Major assumptions were that all of the fluke's momentum is transferred to the water through a collision without any losses, and that decreases in pressure wave intensity are negligible because the ball of fish is near the water surface, close to the collision. Results for a 7m long (average length) whale were that with a collision time of 0.00455 seconds or less, which corresponds to the fluke going into the water a maximum depth of 3.28 cm, a pressure wave with an intensity of 3.252×10^4 Watt/m^2 or higher could be generated. It was concluded that given the assumptions, it is possible for killer whales to use above-water tail slaps to stun or kill fish in the water below, if the collision time between fluke and water is sufficiently short.

Introduction

I asked if it was possible for killer whales to slap their tails on the ocean surface and stun a fish in the water below without any physical contact. Killer whale pods are known to hunt herring using a "carousel" method, in which the whales encircle a school of herring creating a dense ball of fish. A few whales will perform underwater tail slaps, using the undersides of their flukes to slap at the edges of the ball in an effort to stun some of the fish (figure 1). The whales then eat the stunned fish one by one. I asked this question because what causes the stunning is not quite clear: a loud "bang" is heard when a whale performs a tail-slap, but it is not known if the fish is stunned by a sound wave, or by physical contact between the fluke and fish.

Controversy over which mechanism is at work exists among researchers, and both hypotheses have been tested with the results published in scientific literature.

It appears that killer whales use this “carousel” method of hunting particularly for herring, as herring have excellent vision and hearing, and are fast and agile swimmers capable of escaping predation by whales (Simila and Ugarte 1993). Tail slaps therefore would appear to be an effective solution for whales that are not as agile as their prey: whales do not necessarily need to be fast swimmers, so long as they possess a hard tail slap.

Sound (or pressure) waves of 230 dB//1μPa are capable of stunning or even killing fish (value for guppies, Zagaeski 1987). Fish posses a lateral line system that is sensitive to vibrations in water, as well as ears that act as organs of equilibrium; both systems may be affected when a fish is stunned by a large pressure wave. Herring (average length 35 cm) are considerably larger than guppies (average 5 cm), but it is assumed that their internal organs have similar tolerance thresholds for pressure wave intensities.

Methods

An analysis of an above-water tail slap occurring on the surface of the ocean was done to make the model as simple as possible. This way, I could assess whether a tail slap possessing the maximum possible momentum could create a pressure wave capable of stunning a fish.

Overview of physics concepts

Conservation of momentum

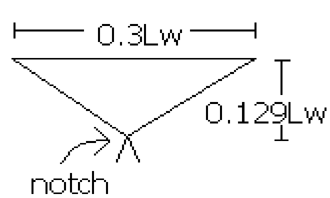
The killer whale's fluke (the portion of the tail that includes only the broad flat flaps) has a mass, and when the whale performs a tail slap, the fluke moves at a certain velocity. Therefore, the fluke has momentum. When the fluke collides with the ocean surface, momentum is transferred to a mass of water beneath the fluke, and momentum in the fluke-water system is conserved.

Pressure waves

The collision between the fluke and ocean surface causes water particles to oscillate with a certain velocity as the water gains the fluke's momentum. A pressure wave is generated with a particular intensity and pressure, and as the wave propagates downward in the water, it exerts a pressure on fishes in its path. For a successful stunning, the intensity of the wave created by the fluke must be greater than or equal to the intensity fatal to fishes.

Detailed analysis (see figure 2 for illustrations)

Whale body lengths of 6m, 7m, and 8m were considered, with 7m being the average length of a male whale. The whale fluke was modeled as a triangle with uniform thickness:



Using an image of a killer whale as a reference, I assumed that fluke width is approximately 1/3 the body length (Lw), fluke height is approximately 1/8 Lw, and thickness is 9cm for a 6m whale, 10cm for a 7m whale, and 11cm for an 8m whale.

Volume of the fluke = surface area x thickness

$$= \tfrac{1}{2} (0.3Lw) (0.129Lw) \times \text{thickness}$$

For a 7m whale:

$$Vol_{Fluke} = 0.5 (0.3 \times 7) (0.129 \times 7) \times 0.10m = 0.0945\ m^3$$

Assuming that fluke density = 1000 kg m^{-3}

Fluke mass = $\rho_{Fluke} Vol_{Fluke}$ = 1000 kg m^{-3} x 0.0945 m^3

= 94.5 kg

The maximum velocity of the fluke during a tail slap (measured at the notch in m/s) is given by

$$u_{fluke} = 1.7Lw + 2.5$$ (Domenici *et al*. 2000)

This equation calculates velocity for underwater tail slaps, so fluke velocity at the surface in air will likely be larger. However, the equation calculates a maximum velocity, so I assumed that the calculated values could still be representative of probable velocities in air as well.

For a 7m whale:

$$u_{fluke} = 1.7(7) + 2.5 = 14.4\ m/s$$

∴Momentum of the fluke = $m_{Fluke} u_{Fluke}$ = (94.5 kg)(14.4 ms^{-1})

= 1361.8 kg ms^{-1}

Assumptions

1) Before the collision, u_{Water}=0 m/s, and after the collision, u_{Fluke}=0 m/s; all of the fluke's momentum is transferred to the water.
2) The fluke is completely flat when it collides with the ocean surface.
3) No deformations of the fluke occur during the collision.

4) Momentum is transferred only to the water directly beneath the fluke, that is, to a mass of water shaped like a prism (see figure 2).
5) The water surface is smooth.

By assumption 1), the conservation of momentum equation

$$m_{Fluke}u_{Fluke,i} + m_{Water}u_{Water,i} = m_{Fluke}u_{Fluke,f} + m_{Water}u_{Water,f}$$

reduces to

$$m_{Fluke}u_{Fluke,i} = m_{Water}u_{Water,f}$$

To determine the mass of water that gains the fluke's momentum, the time it takes for the collision to occur was considered. Collision time, Δt, is related to the water depth the fluke reaches before coming to rest, Δy, by the equation

$$\Delta t = \frac{\Delta y}{\frac{1}{2}u_{Fluke}}$$

This assumes that the average velocity of the fluke is $\frac{1}{2}u_{Fluke}$ as the fluke decelerates from u_{Fluke} to 0 m/s. A range of Δy values was arbitrarily chosen, with consideration that tail slaps on the surface of the water often do not penetrate very deeply, as observed on video.

The range of Δy considered was 0.01m to 0.15m

For a 7m whale with Δy=0.03m:

$$\Delta t = \frac{0.03\text{m}}{0.5(14.4\text{m/s})} = 0.00417 \text{ seconds}$$

In 0.00417 seconds, the pressure wave created at the start of the collision travels to a depth

$$d = v\,\Delta t = (1500\text{m/s})(0.00417\text{s}) = 6.25\text{m}$$

where v is the phase velocity of a pressure wave traveling in water.

By assumption 4), the volume of water that gains the fluke's momentum is given by

$$Vol_{water} = 6.25\text{m x fluke surface area}$$
$$= (6.25\text{m})(0.945\text{m}^2) = 5.910 \text{ m}^3$$

Since the density of sea water ρ_{sea} = 1025 kg m^{-3}, the mass of water gaining the fluke's momentum is

$$m_{Water} = \rho_{sea} \times Vol_{water} = (1025 \text{ kg m}^{-3})(5.910 \text{ m}^3)$$
$$= 6058 \text{ kg.}$$

$$\therefore u_{water,\,f} = \frac{m_{Fluke} u_{Fluke,\,i}}{m_{Water}} = \frac{1361.8 \text{ kg m/s}}{6058 \text{ kg}} = 0.2248 \text{ m/s}$$

This is the particle velocity of the pressure wave.

The intensity of this pressure wave is given by

$$I_{wave} = \tfrac{1}{2} \rho_{sea} v u_{water}^2$$
$$= 0.5(1025 \text{ kg m}^{-3})(1500\text{m/s})(0.2248\text{m/s})^2$$
$$= 3.88 \times 10^4 \text{ Watt/m}^2$$

The minimum wave intensity required to kill or stun a fish was calculated using the value of 230dB//1μPa as the sound pressure level fatal to fish, where 1μPa is the reference pressure (value for guppies, Zagaeski 1987).

$$\text{sound pressure level} = 20 \log_{10}\left(\frac{p}{p_{ref}}\right)$$
$$230 \text{ dB} = 20 \log_{10}\left(\frac{p}{10^{-6} \text{ N/m}^2}\right)$$

$$p = 3.162 \times 10^5 \text{ N/m}^2$$

This is the wave pressure that is fatal to fishes.

The corresponding fatal intensity is given by

$$I_{fatal} = \frac{\Delta p^2}{2\rho v} = \frac{(3.162 \times 10^{-5} \text{ N/m}^2)^2}{2(1025 \text{kg/m}^3)(1500 \text{m/s})} = 3.25 \times 10^4 \text{ Watt/m}^2$$

Assumptions

6) Spreading of wave intensity and losses of intensity to heat are ignored, since the ball of fish is close to the surface where the collision occurs.
7) The volume of water displaced by the fluke is ignored since it is small compared to the volume of water that gains the momentum (less than 0.5%).
8) Guppies and herring have similar thresholds for maximum tolerable pressure.
9) Only one fish needs to be stunned or killed per tail slap.

By assumption 6), I_{fatal} can be compared directly to I_{wave}, with the requirement that $I_{wave} \geq I_{fatal}$.

By requiring that the intensity of the wave generated by a tail slap must be at least equal to the intensity that will kill or stun a fish, values of Δy and Δt that allow this requirement to be met can be calculated. That is, constraints have been put on the conditions under which it is possible to stun a fish with an above-water tail slap.

Note: although it is possible to compare pressures only and not include any calculations for intensity, I personally preferred to work with intensities, as they were easier to deal with conceptually.

Results

Whale length (m)	Fluke momentum (kg m/s)	Fluke depth Δy (m)	Collision time Δt (sec)	Wave intensity (Watt/m^2)	Fatal intensity (Watt/m^2)	I_{wave} - I_{fatal} (Watt/m^2)
6	794.2	0.010	0.001575	171314.76	32520.325	138794.4
6	794.2	0.020	0.003150	42828.69	32520.325	10308.4
6	794.2	0.023	0.003614	32520.33	32520.325	0.0
6	794.2	0.050	0.007874	6852.59	32520.325	-25667.7
6	794.2	0.100	0.015748	1713.15	32520.325	-30807.2
6	794.2	0.150	0.023622	761.40	32520.325	-31758.9
7	1361.8	0.0100	0.001389	349578.62	32520.325	317058.3
7	1361.8	0.0315	0.004375	35230.90	32520.325	2710.6
7	1361.8	0.0328	0.004554	32520.32	32520.325	0.0
7	1361.8	0.0330	0.004583	32100.88	32520.325	-419.4
7	1361.8	0.0370	0.005139	25535.33	32520.325	-6985.0
7	1361.8	0.1500	0.020833	1553.68	32520.325	-30966.6
8	2187.5	0.010	0.001242	660973.07	32520.325	628452.7
8	2187.5	0.020	0.002484	165243.27	32520.325	132722.9
8	2187.5	0.045	0.005600	32520.32	32520.325	0.0
8	2187.5	0.050	0.006211	26438.92	32520.325	-6081.4
8	2187.5	0.100	0.012422	6609.73	32520.325	-25910.6
8	2187.5	0.150	0.018634	2937.66	32520.325	-29582.7

Table I. The effect of varying the fluke depth (how far the fluke penetrates the surface of the water before coming to rest) on the intensity of the pressure wave generated by a tail slap. Negative and zero values in the I_{wave} - I_{fatal} column correspond to a wave capable of killing or stunning a fish. See the appendix for an extended version of the table.

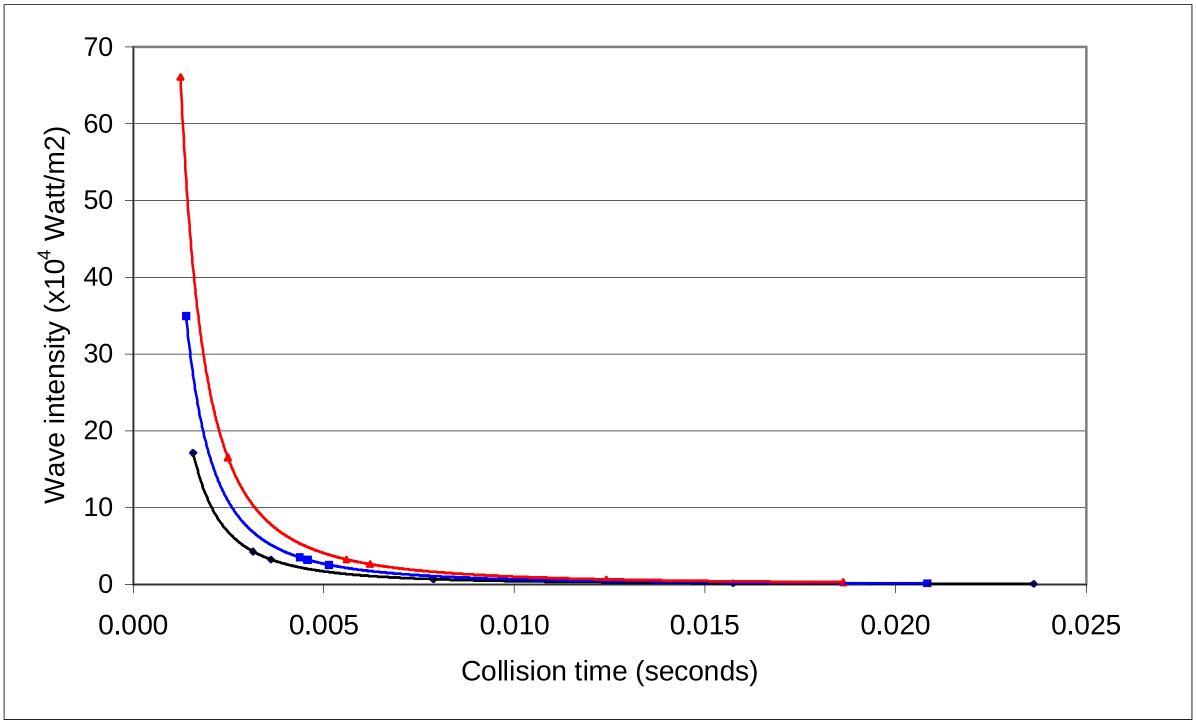


Figure 3. The effect of varying the length of the collision between the fluke and the water surface on the intensity of the pressure wave generated by whales of different body lengths.

Legend: 6m whale ■ 7m whale ■ 8m whale ■

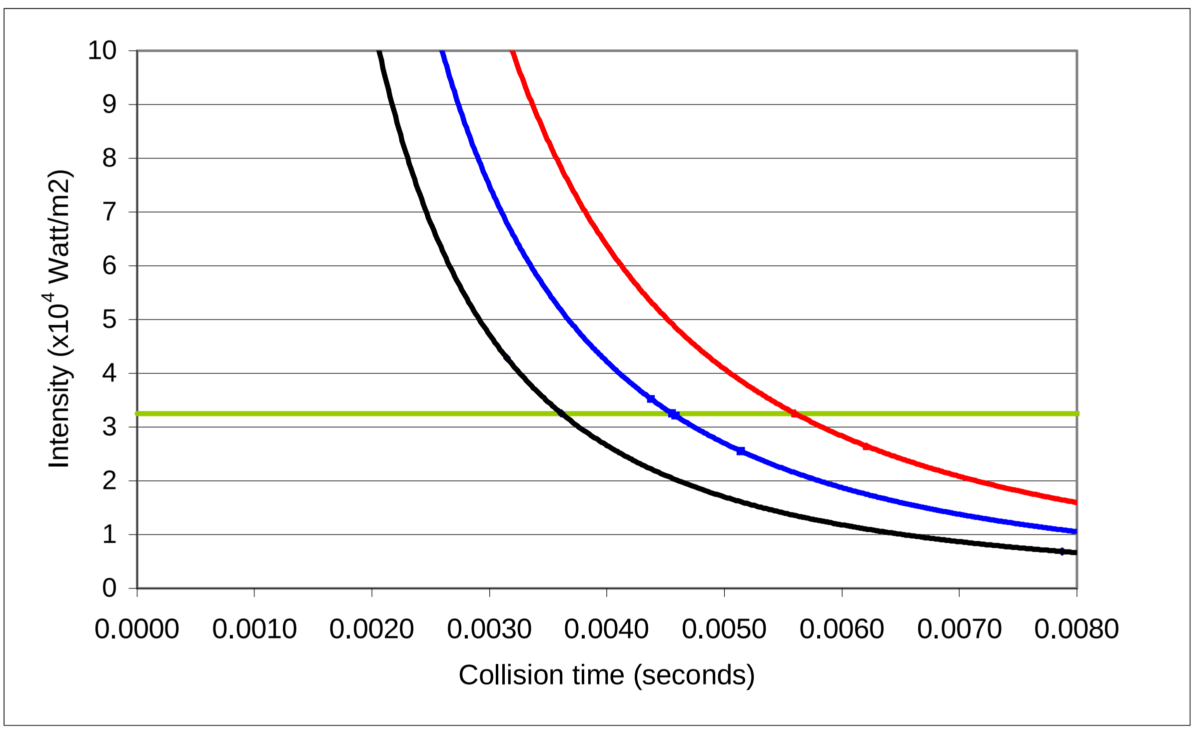


Figure 4. Intensities of waves generated by tail slaps from whales of different body length, and the varying collision times at which wave intensity is equal to the fatal intensity.

Legend: fatal intensity ■

As shown by table I, the momentum of the fluke increased as whale length increased, as both fluke velocity and fluke mass increased. Fluke momentum was calculated to be 794.2 kg m/s for a 6m whale, 1361.8 kg m/s for a 7m whale, and 2187.5 kg m/s for an 8m whale. This translated into larger whales being able to generate pressure waves with greater intensity for a given fluke depth: a 6m whale could create a wave with an intensity of 17.1 $\times 10^4$ Watt/m^2 if its fluke transferred its momentum to the water before coming to rest a depth of 1 cm. For the same fluke depth, a 7m whale could create a 35.0 $\times 10^4$ Watt/m^2 wave, while an 8m whale could generate a 66.1 $\times 10^4$ Watt/m^2 wave.

Larger whales also generated higher intensity pressure waves for a given collision time (figure 3). Differences in wave intensity among whales of varying body length were greatest at shorter collision times. When Δt was 10 msec or longer, wave intensities for the different sized whales differed by a relatively small margin as intensity decreased exponentially with increased collision time.

For a 6m whale, a collision time of 0.00361 seconds, corresponding to a fluke depth of 2.3cm, could create a pressure wave with just enough intensity (3.252 $\times 10^4$ Watt/m^2) to kill or stun a fish (figure 4 and table I). A 7m whale could generate a wave with fatal intensity in a collision time of 0.00455 seconds and fluke depth of 3.28cm, while an 8m whale could do so with a collision time of 0.00560 seconds and fluke depth of 4.5cm. The increasing collision times and fluke depths reflected the fact that larger whales generated more momentum with faster tail slaps. These results suggest that given the assumptions, it is possible for a killer whale to use an above-water tail slap to stun herring in the ocean below. However, the length of time over which the collision occurs must be sufficiently short: only a few milliseconds longer, and wave intensity may not be high enough to stun a fish.

Conclusions

A 6m whale that transfers its fluke's momentum to the water in 0.00361 seconds or less can stun its prey with the pressure wave that the tail slap generates. For 7m and 8m whales, the upper limits on collision time are 0.00455 seconds and 0.00560 seconds, respectively. Therefore the answer to the question, "Can killer whales stun prey with above-water tail slaps?" is yes, but only if all of the fluke's momentum is transferred to the water within a limited number of milliseconds. In effect, I have produced values on what is required for tail slaps to be successful in stunning prey, but whether these requirements are actually met in the wild, I have not tested.

Assumptions were made generally to disregard incomplete transfer of momentum from fluke to water, and reductions in wave intensity due to energy losses to the environment. As a result, the calculated wave intensities are probably an overestimate of what would actually be produced in the real ocean, as energy is lost in the form of water splashes, heat, and tail deformations, to name a few. The assumptions regarding smooth water surfaces and flat flukes served to simplify the model, and probably also contributed to the overestimates of wave intensity. For instance, a choppy water surface—which is likely in the ocean, especially with herring and whales swimming close to the surface—would increase actual collision time. A fluke that is not completely flat as it slaps the water would also increase collision time, as not all parts of the fluke's surface would hit the water at the same time. As figures 3 and 4 show, an increased collision time of only a few milliseconds may drastically reduce wave intensity, and result in an unsuccessful stunning attempt. Ultimately, the required collision time in the real ocean may be so short that stunning prey is not possible.

If stunning prey with pressure waves is a feasible option for killer whales hunting herring, this implies that flukes have more functions than simply locomotion. Flukes may also be used as hunting tools or weapons in conjunction with cooperative hunting techniques such as the "carousel" method, which brings whales and fast moving herring within close range. Killer whales that are limited in maneuverability because of large size may be able to compensate with a hard tail slap.

Tail slaps on the ocean surface are in fact behaviours used for communication and signaling purposes; whether above-water tail slaps are actually used for hunting is a question that can be answered with field observations. Other questions that arise include: do larger whales that generate more momentum have a higher success rate in stunning prey with tail slaps? Regardless of whether the tail slap is above or below water, I would predict that males would perform this behaviour more often as they are on average larger than females. Also, how do the results change for an underwater tail slap? I would expect that the force of drag in water would significantly reduce the momentum a fluke could generate. An analysis of the net force produced by an underwater tail slap could be done to help answer this question. Finally, is collision time and therefore fluke depth a consequence of water density? For a less dense medium, is the fluke effectively cushioned during the collision, therefore extending the collision time and fluke depth? If so, then the density of seawater would ultimately determine whether stunning prey with an above-water tail slap is possible.

References

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