Particle Motion, Fishes, & Invertebrates: What We Know and Don’t Know!

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Purpose

• Provide broad overview of issues needed to appreciate and understand PM

• Goals:
  • Introduce basic ideas about particle motion (PM)
  • Introduce the issue of substrate vibration (SV) and aquatic animals
  • Share my thoughts on gaps in understanding role(s) of PM, especially as related to tidal and wave energy

• While will primarily mention fishes, keep in mind that many aquatic invertebrates hear and even make sounds
Premise

• Issues focus on potential impacts on animals
• Thus, critical to consider potential effects of anthropogenic sound from animal's perspective!
  • If animal detects the signal, or affected by it in any way, we need to understand the potential effects and the signal itself
  • If animal not affected by the signal, much less need to measure or mitigate
  • Analogy: many animals hear ultrasound, but from the perspective of humans, there is no need to mitigate ultrasonic signals since we cannot detect them
• This approach (Popper et al. 2020) is different than most often done – tendency is to mitigate even without evidence that the signal is detectable by the animal or has any potential effect!
• (note, all references are given at the end of slides)
Why the Concern About Anthropogenic Sound?

• Vertebrae hearing was “invented” by earliest fishes!
• Provides information from all directions around the animal – soundscape
• Sound is a very important source of information for aquatic animals:
  • High speed
  • Directional
  • Detectable when vision not useable
  • Perceived in all directions around animals
  • Detect distant predators and prey
• Many invertebrates, including crab, lobster, octopus, can hear
• Moreover, many fishes and invertebrates make sound to communicate, find mates, etc.

Thus, anything that interferes with detection of sound can affect animals' lives
Some Potential Anthropogenic Sources
Briefly Consider Underwater Sound

- Underwater sound follows the same basic principles of sound in air.
- Due to the higher density of water, sound travels about 4.3 times faster than in air.
- This means wavelength in water is about 4.3 times greater in water.
- Speed of sound in air is about 330 m/sec.
  - Wavelength of 100 Hz signal about 3.3 m in air.
- Speed of sound in water is about 1,480 m/sec.
  - Wavelength of 100 Hz signal about 14.8 m in water.

www.dosits.org
Lay-level, scholarly reviewed, information about underwater sound, effects of anthropogenic sound, bioacoustics, and related topics.
• All sound has both sound pressure and particle motion
• In air, due to low density, PM is not consequential very far from the source – terrestrial vertebrates primarily use SP!
• In water, PM travels great distances and is used in hearing by all fishes and invertebrates
• This is because the ears in fishes and invertebrates evolved to detect particle motion and not sound pressure!
Sound Pressure vs. Particle Motion

- Sound pressure is scalar – does not have direction
- Particle motion is directional – it can be used to tell the position of a sound around an animal
- Fish (and invertebrate) ears are PM detectors!
- Thus, understanding PM is critical if we are to understand sound detection by fishes and invertebrates
  - Much data in the literature on hearing focused on SP
  - However, since fishes detect PM, most hearing studies were asking the wrong questions?
  - And getting wrong answers!
How is PM Detected?

- The ears in fishes and invertebrates are accelerometers!
- The ear evolved to detect PM and not SP
PM Detection

- PM is detected by all fishes and probably by all invertebrates that hear
- SP only detected by fishes that have a “discontinuity,” such as swim bladder or other air bubble
  - Walls vibrate in response to the impinging sound
  - “Re-radiates” signal as PM, which potentially stimulates ear
- SP only detectable by a sub-set of fishes, and probably not by any invertebrate
  - Fishes without a swim bladder (flatfish, sharks) only detect PM (fig. A)
  - Fishes like tuna, salmon, sturgeon, have a swim bladder, but its response not detected at the ear (fig. B) since they are far apart - PM attenuates due to body tissues
  - Fish with special adaptations like carp, catfish, cod, may detect SP (fig. C)
  - Even if a fish detects SP, it also detects PM, but not reverse!
- Thus, when considering sound detection, it is imperative to understand how and what animals do regarding PM, and not SP

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A Few Critical Points to Keep in Mind

• **In order to understand how fishes may react to anthropogenic sound, one must understand their responses to both PM and SP**

• BUT, even if a fish cannot detect SP, it may still have an effect by causing overstimulation of the swim bladder, and harm internal tissues

• Work in Popperlab showed this on several species that detect PM (salmon, sturgeon) ([www.ahukini.net](http://www.ahukini.net)) (e.g., Halvorsen et al. 2012; Casper et al. 2016)

• Ear may not even be involved, but still get injury, especially to intense impulsive signals
Substrate Vibration: A Critical New Issue

• To date, we think about sound traveling in water from source to animal
• Now understanding that sound from many sources may enter substrate
• Sound travels in substrate and comes out, and this has potential to be detected (called Biotremology)
  • Most work to date in terrestrial environments
  • But same issues underwater (Louise Roberts)
• Particularly an issue for sources that are near or contact substrate – pile driving, seismic airguns, etc. And likely tidal energy!
• A clear issue for animals living in, on, or near substrate: lobster, crab, flatfish, sturgeon, many others

Sources of Substrate Vibration

• Any source that puts energy into substrate
  • Pile driver, struck by a vertical hammer creates
  • Seismic airgun for geological exploration
  • Explosions

• These produce sound in water and vibrational waves within the substrate

• Energy can travel great distances in the substrate
  • Affect animals within the substrate
  • Also, animals living on or just above substrate
  • Energy leaving substrate travels through water as sound, and can affect animals at distances from source

• See Roberts and Howard (2021); Hawkins, A. D., et al. (2021)
Substrate Vibration from Driving Pile

- Recordings from pile strike
- Blue is accelerometer on pile, showing sharp acceleration
- Substrate vibration from accelerometers at 68 m mounted on substrate
  - Red – radial geophone
  - Green – vertical geophone
What is Known about Sound Detection by Fishes & Invertebrates?

• Very little!
• Several issues (Popper & Hawkins, 2021):
  • Sound fields calibrated in SP, even when the fishes only detect PM – this means that we have no idea of signal levels to which fish were responding
  • Work done in tanks where sound fields are very complex and cannot easily even measure PM
  • Most recent studies done using physiological measures (ABR, AEP) that measures ear responses – but that is not hearing!!!!
  • Very variable, even for same species, from different labs
• Only a very small amount of usable data on detection of PM
• Minimal data on detection of sounds on or near substrate
Hearing by Different Fishes – PM Data Done in the Field

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Consider What We Don’t Know, and Need to Know (Data Gaps!)

• Most knowledge gaps re PM (and SV) are similar to those identified in general for fishes and invertebrates and anthropogenic sound (Hawkins et al. 2015)

• Moreover, the gaps associated with Tidal and Wave projects are likely to be similar to those for other sources such as seismic, pile driving, shipping, etc.

• Quite similar issues to Offshore Wind (Popper et al. 2022)

• Thus, following suggestions may seem familiar, but they provide good guidance
Data Gaps: Broader Issues to Consider

- There are 34,000 fish species & many more aquatic invertebrates
  - All fishes likely can hear, but data on perhaps 100, and most data not good!
  - There is extensive diversity in morphology of the auditory system
  - Thus, very hard to extrapolate data on hearing or effects of sound between species in many cases
  - Issue: Need to decide “representative” species to study as done for fish criteria analysis (Popper et al. 2014)

- Need data on PM as well as SP, and possibly also SV for select species

- Lack of tools to easily measure PM – far more complex and expensive than tools for SP
Possibly Most Important Data Gap!

- BEHAVIORAL RESPONSE to anthropogenic sources
  - Mortality/physical damage is measurable, but most fishes do not die from sound exposure, just as humans do not die from most sound exposure
  - Far bigger issue is how animals respond behaviorally to the sound, no matter if PM or SP!
  - These can happen on a far larger distance from source than physical effects

- Very few good data on behavioral effects
  - Most studies done in lab where behavior not easily extrapolatable to wild animals
  - Very hard to do in field – but see Hawkins et al. (2014)

- Some behavioral effects of anthropogenic sound:
  - None – but even then, could affect stress levels
  - Small responses (e.g., startle) that does not really alter fitness
  - Temporarily leaving feeding or breeding site – but return quickly
  - Permanently leaving sites
  - Changes in migration routes
  - Not hearing sounds of potential mates or predators or food
Hearing Data Gaps

• Masking – lessening likelihood of detection of biologically important sounds
  • Sounds from potential mates
  • Sounds of nearby predators
• Temporary decrease in hearing sensitivity (TTS – Temporary Threshold Shift)
  • Similar effects to masking
  • Decreases fitness
  • No evidence of permanent hearing loss in fishes
• Impact on PM detection has never been studied
• VERY CRITICALLY: Hearing is not just threshold or bandwidth
  • Much more important issues are discrimination, localization, detection of signals in noise
  • Sensitivity and bandwidth are not very informative of how an animal uses sound, or how use of sound can be impaired
Other Critical PM Data Gaps (and for SV)

- Hearing (need improved methods such as experimental tanks, etc.)
  - Comparative (decide on appropriate species)
  - Age, size, season
  - Thresholds, bandwidth
  - Detection in presence of masker
- Potential effects of PM on development (e.g., of eggs an larvae; growth)
- Behavioral responses to PM to determine the levels that will have an impact on the animals
- Dose/response data and before/during/after data! Cumulative effects
- Physiological effects such as stress, endocrine levels, etc.
- Many more
Data Gaps for Sound-Producing Devices

• Also need:
  • More acoustic data (SP, PM, SV) for devices
  • Ambient sound levels in device locations with and without operations
  • Data on preconstruction, construction, and post construction sounds (levels, frequencies, etc.)

• Need common approaches to measures, measurement approaches, and terminology so data can be compared between sites and devices (same as for OSW)
Potential Sound Issues with Tidal Generation

• Sits on bottom
• Need data on acoustic energy in form of:
  • Sound Pressure
  • Particle Motion
  • Substrate Vibration
• Also, data on:
  • Signal levels including in water, on, and in substrate
  • Sounds during construction and operation
  • Ambient levels
• How fishes and invertebrates react behaviorally to the signals
  • (Distinguish between responses to “sound” and other stimuli, such as vision)

https://www.reinforcedplastics.com/content/other/hall-spars-rigging-manufactures-composite-components-for-orpc-s-tidgen-tidal-turbine
Potential Issues with Wave Generation

- Same types of information as for tidal generator
- Needs substrate signals if any bottom contact
- Since variety of different approaches in different devices, need characterization of each
- First “guess” is that fewer sound issues than for tidal, but this could vary by device
Mitigate: But First Ask Animal What Needed!

• To develop mitigation, first need to know what the animals can detect, and how they respond to the sounds
• If there is no response, do we need to mitigate?
• If the response is minimal and the animal goes back to doing “it’s thing,” do we need to mitigate
• Developing “criteria” for when one needs mitigation to PM is critical
• Also need ways to mitigate PM and substrate vibration!
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  - Brandon Casper
  - Richard Fay (collaborator of >50 years!)
  - Michael Smith
  - Frank Thomsen
The Effects of Noise on Aquatic Life
Berlin, Germany, 10-15 July 2022

- AN2022.org
- >180 papers
- Focus on networking across species, techniques, regulatory issues, mitigation, etc.
- Sixth in series since 2007
- All papers published in a book (online) by Springer Nature
Some Suggested Readings


