umerc + METS

# Investigation of Chaotic Behavior in an Irregular Sea State

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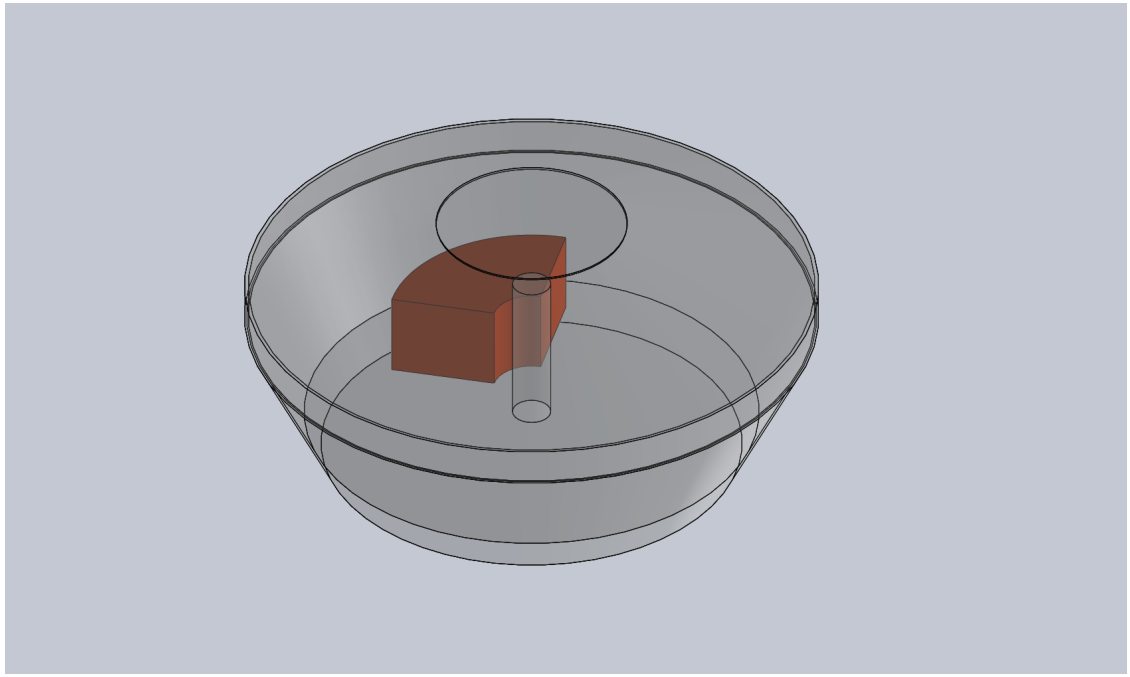
# Main Question

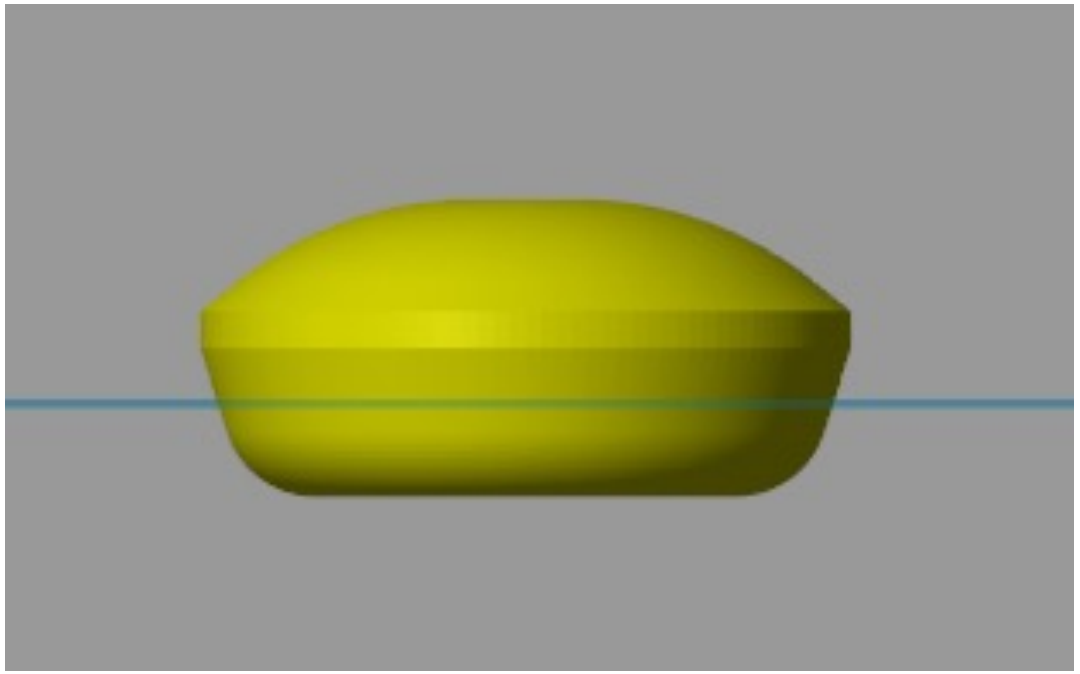
- Pendulum WECs exhibit chaotic behavior
- Previous study showed chaotic behavior suppressed power output, in regular sea conditions
- But what about irregular seas?

- “Does the pendulum PTO WEC continue to exhibit chaotic behavior when operating in an irregular sea state? How does this affect proposed ideas or applications?”

# Numerical Modelling

- In 6 DOF EOM contains hydrodynamics, mooring, PTO, multiple excitation frequency forces
  - Leads to highly complex equation with many non-linearities
  - ∴ *WEC-Sim* with *MoorDyn* used to obtain dynamics of system





# Chaos Criteria

- Chaos occurs when systems that are deterministic display apparent randomness for certain operating conditions
- Criteria for this study
  - Positive Lyapunov exponent
  - Asymptotically periodic
  - Chaotic attractors

# Chaos Criteria

## *Positive Lyapunov Exponent (λ)*

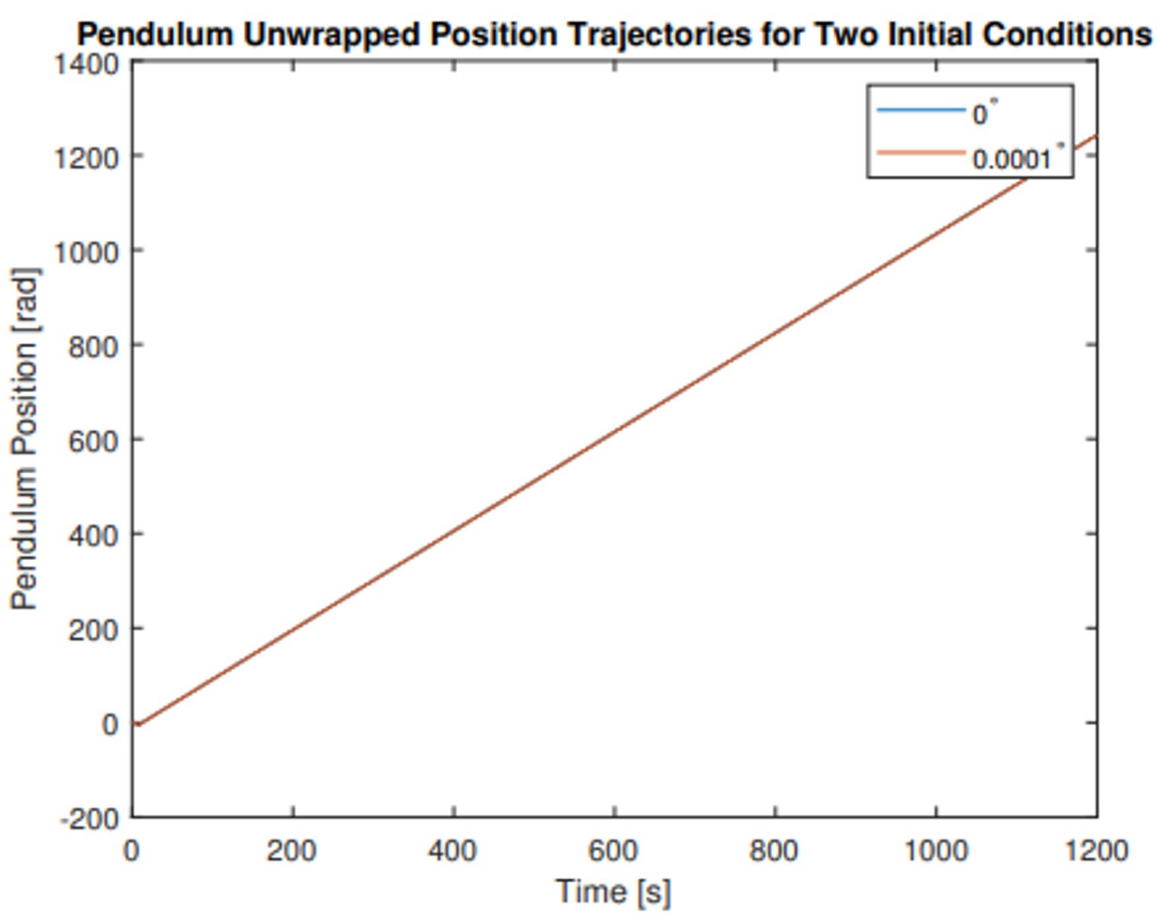
- Rate of separation of initially close trajectories

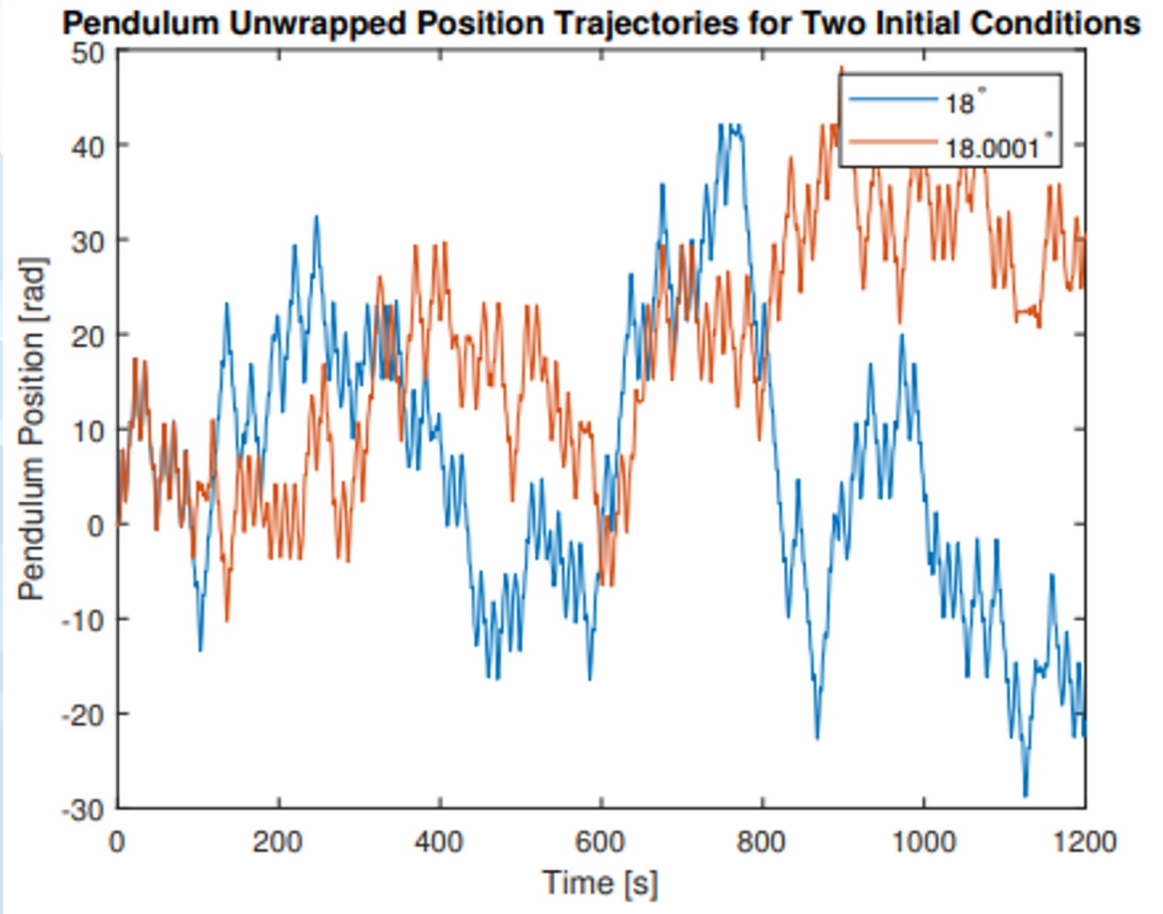
$$\lambda t = ln\left(\frac{|\delta Z(t)|}{|\delta Z(0)|}\right) \qquad (1)$$

- (1) yields separation versus time plot, where λ is the slope
  - λ < 0 = stable
  - λ = 0 steady-state
  - λ > 0 = chaotic

# Chaos Criteria

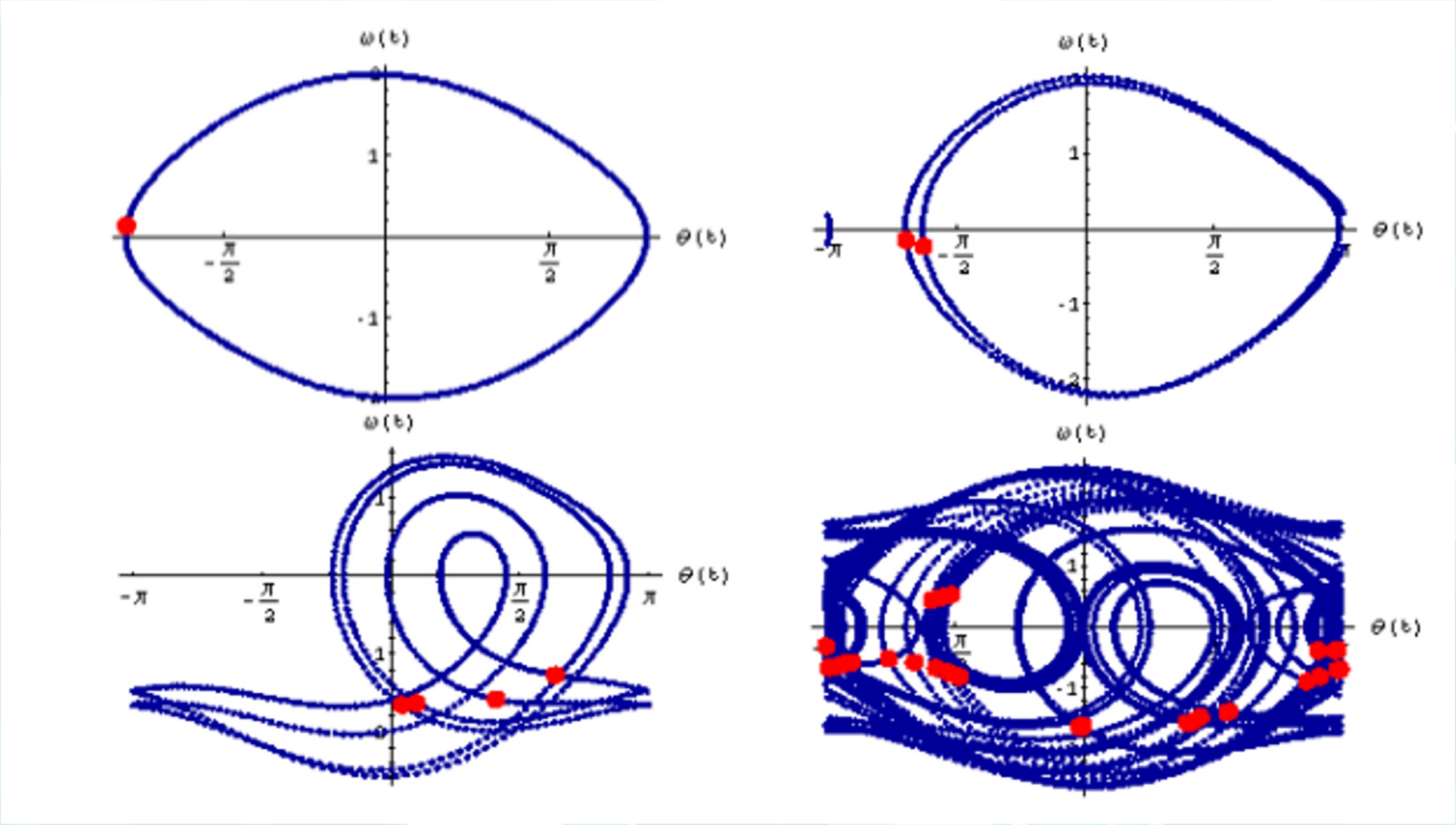
## *Lyapunov Exponent (λ)*




Positive Lyapunov Exponent | Asymptotically Periodic| Chaotic Attractor

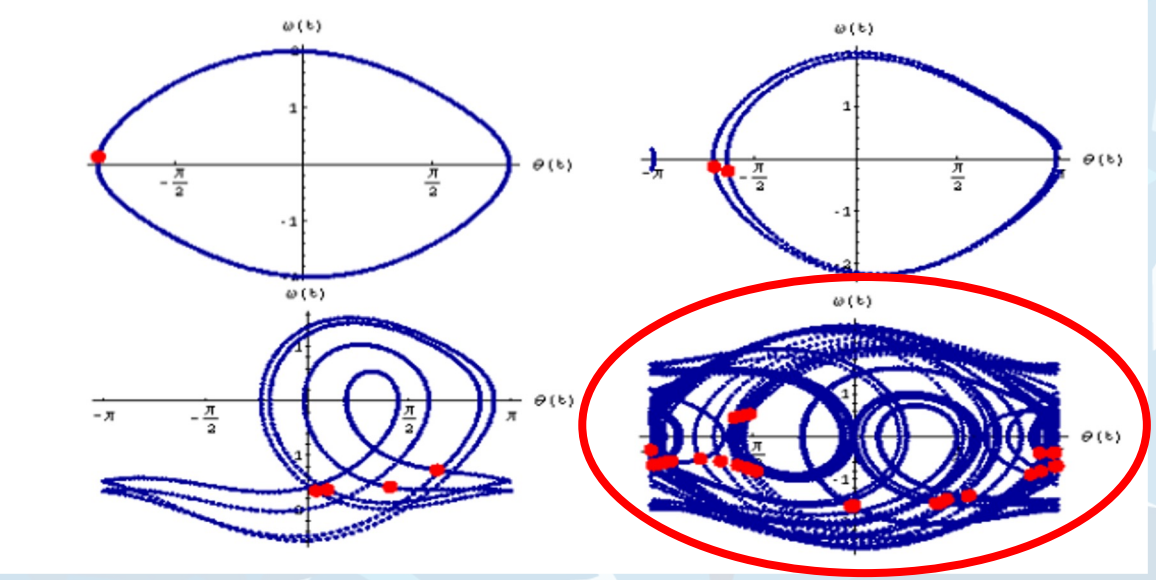
# Chaos Criteria
## *Asymptotically Periodic*

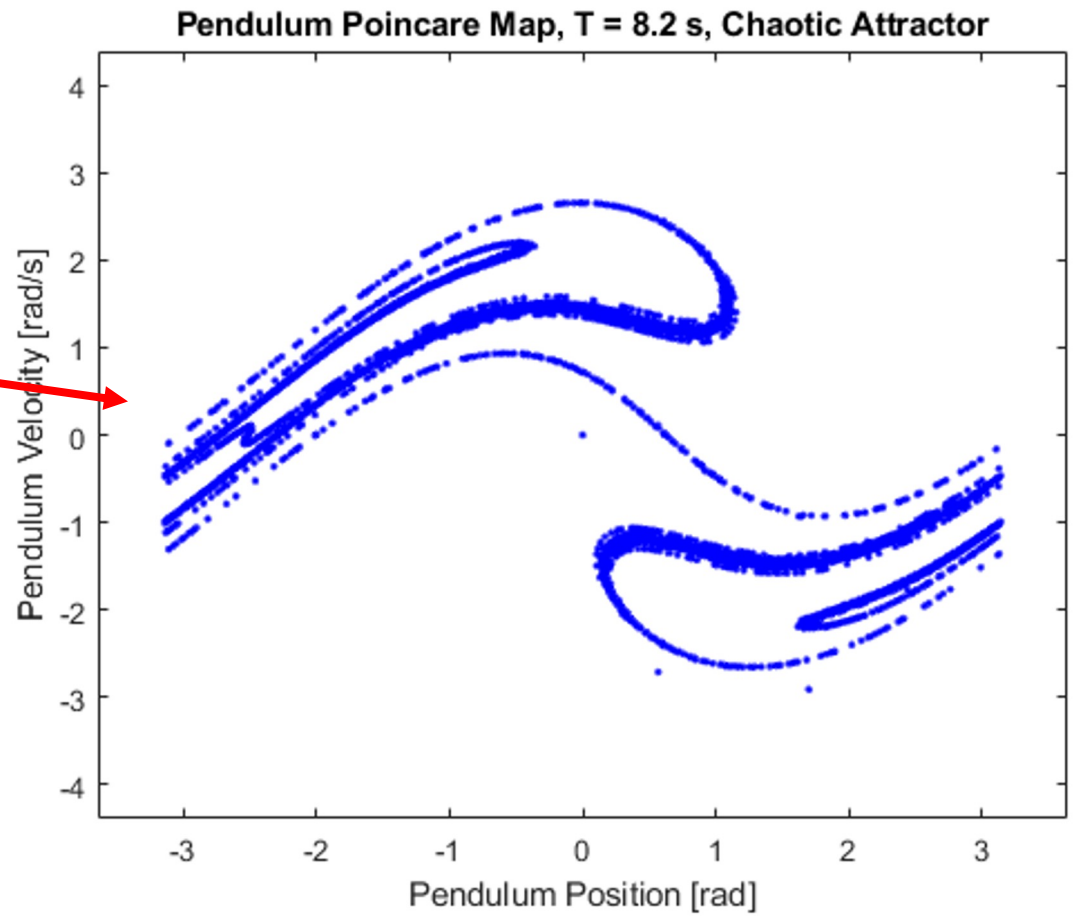



Positive Lyapunov Exponent | Asymptotically Periodic| Chaotic Attractor

# Chaos Criteria

## *Chaotic Attractor*






Positive Lyapunov Exponent | Asymptotically Periodic| Chaotic Attractor

# Irregular Waves

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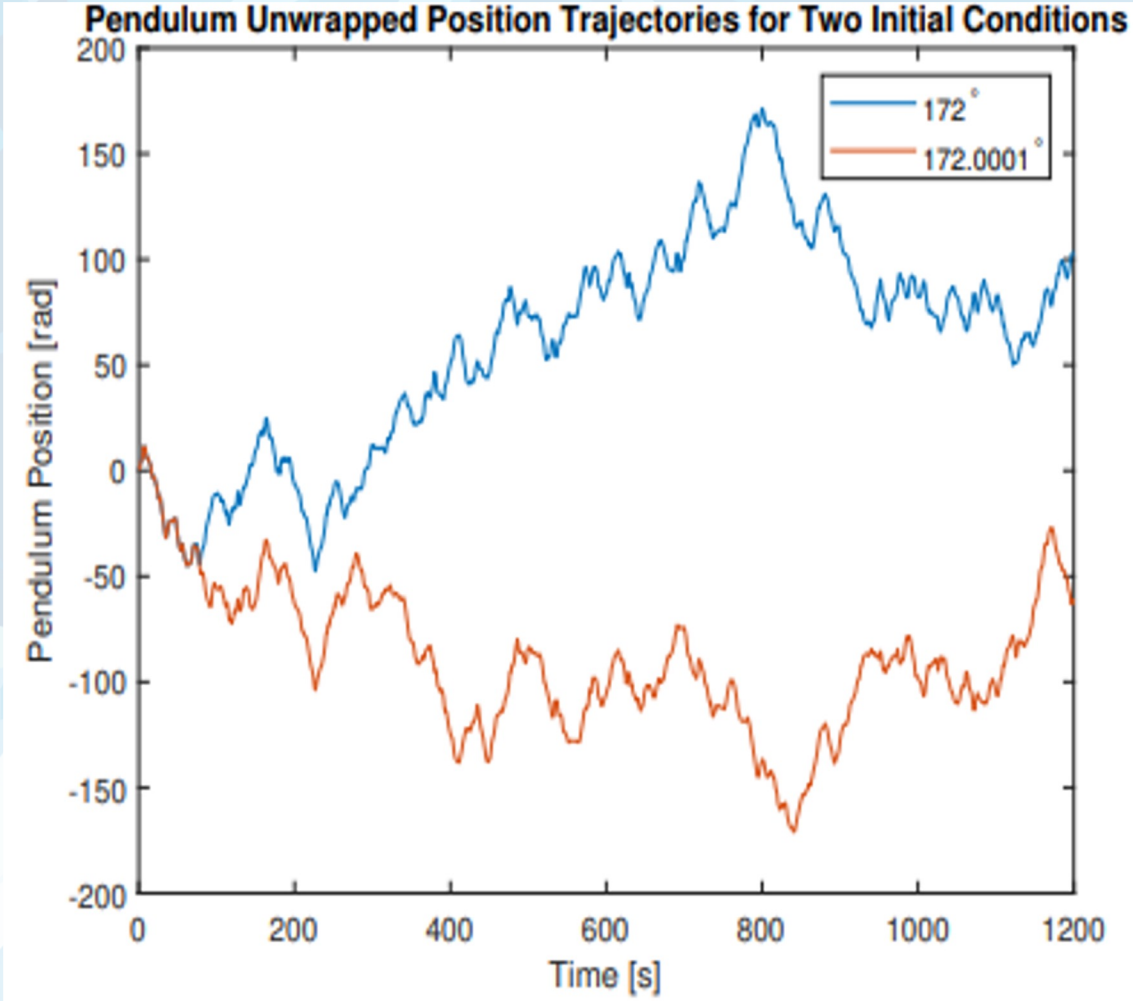
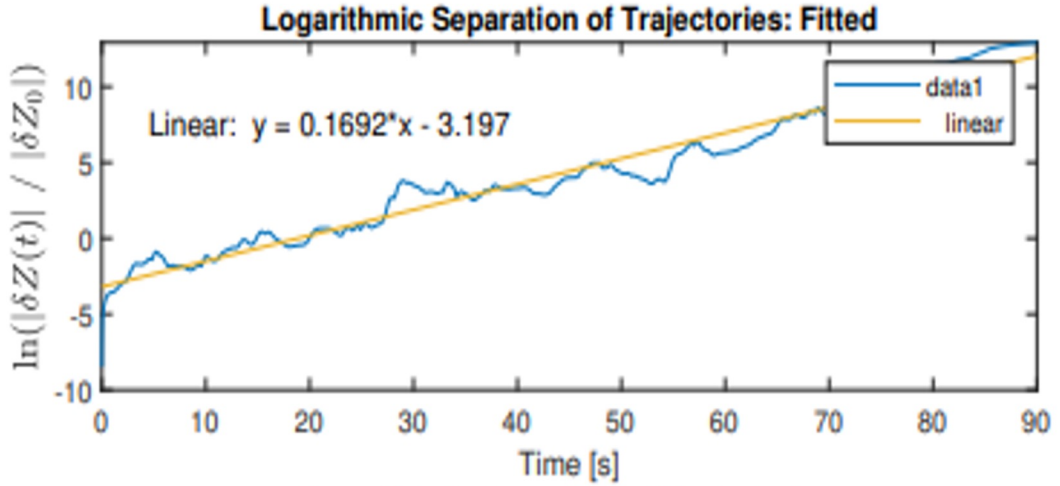
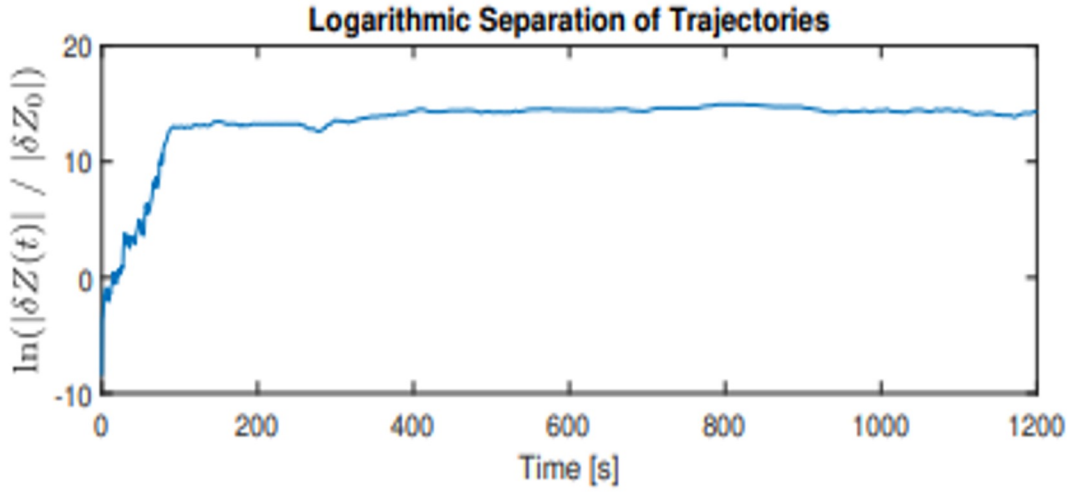
## *Lyapunov Exponent*



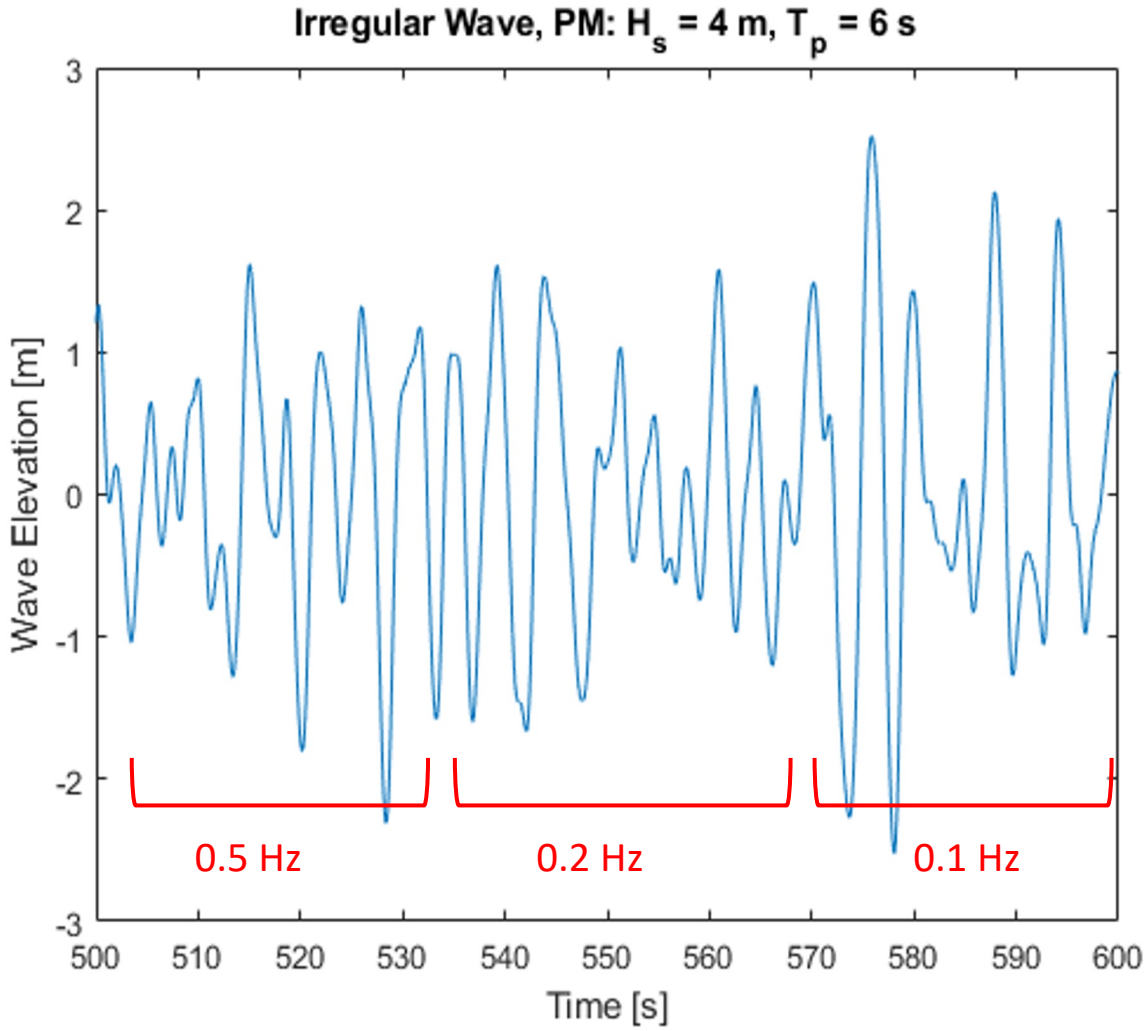



# Irregular Waves

## *Chaotic Attractor: Modification of Traditional Tools*

- What sampling time to use for the Poincare maps?



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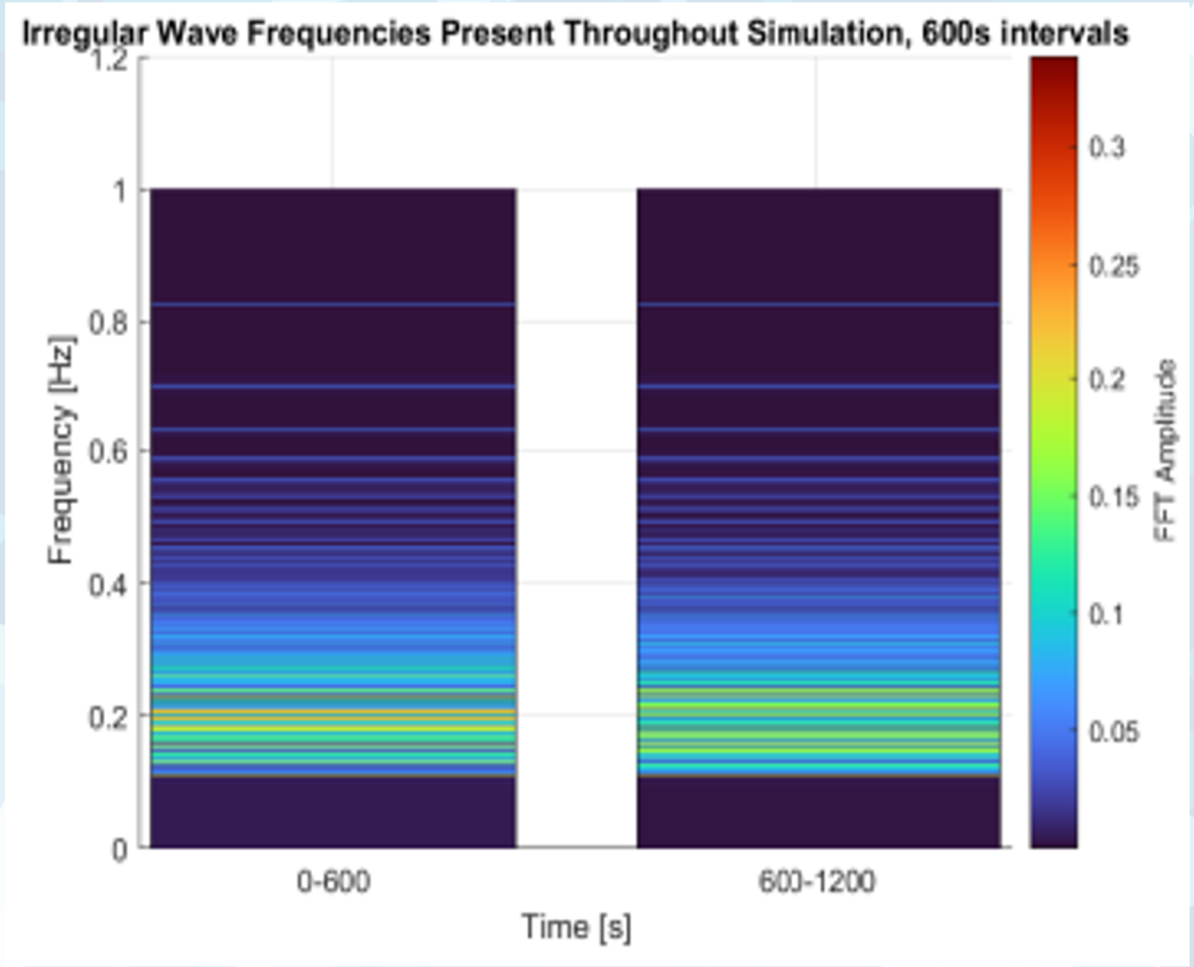


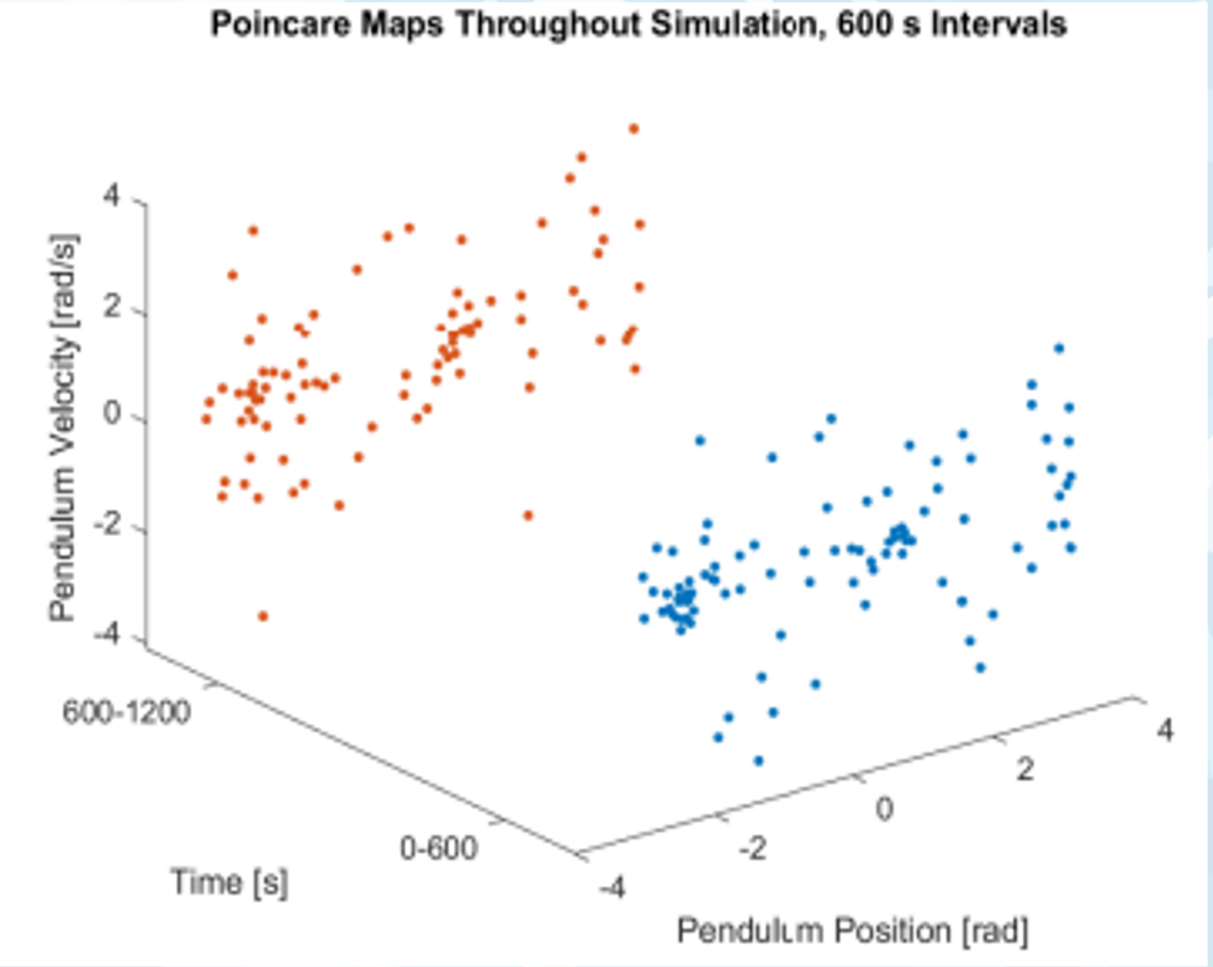

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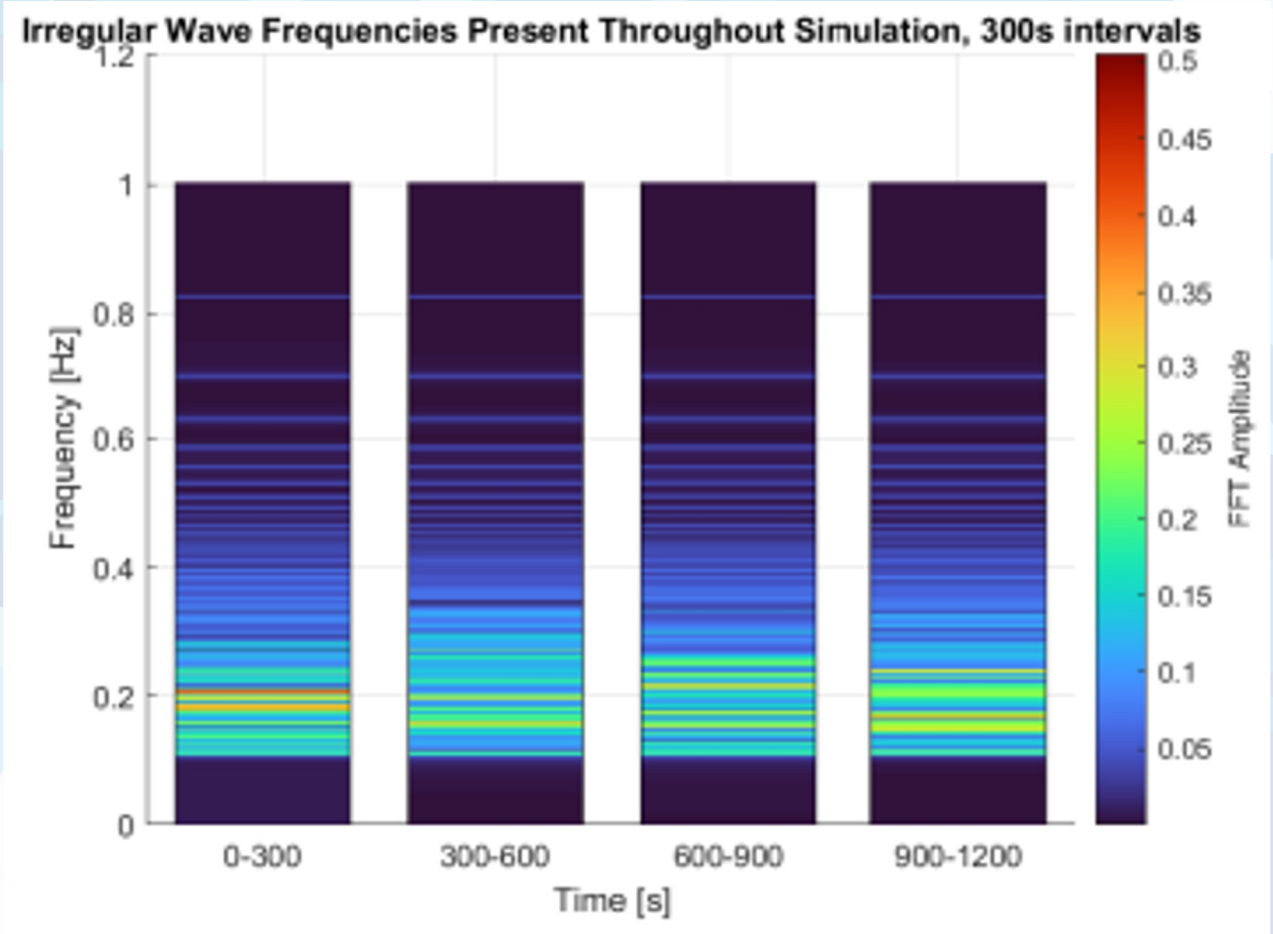


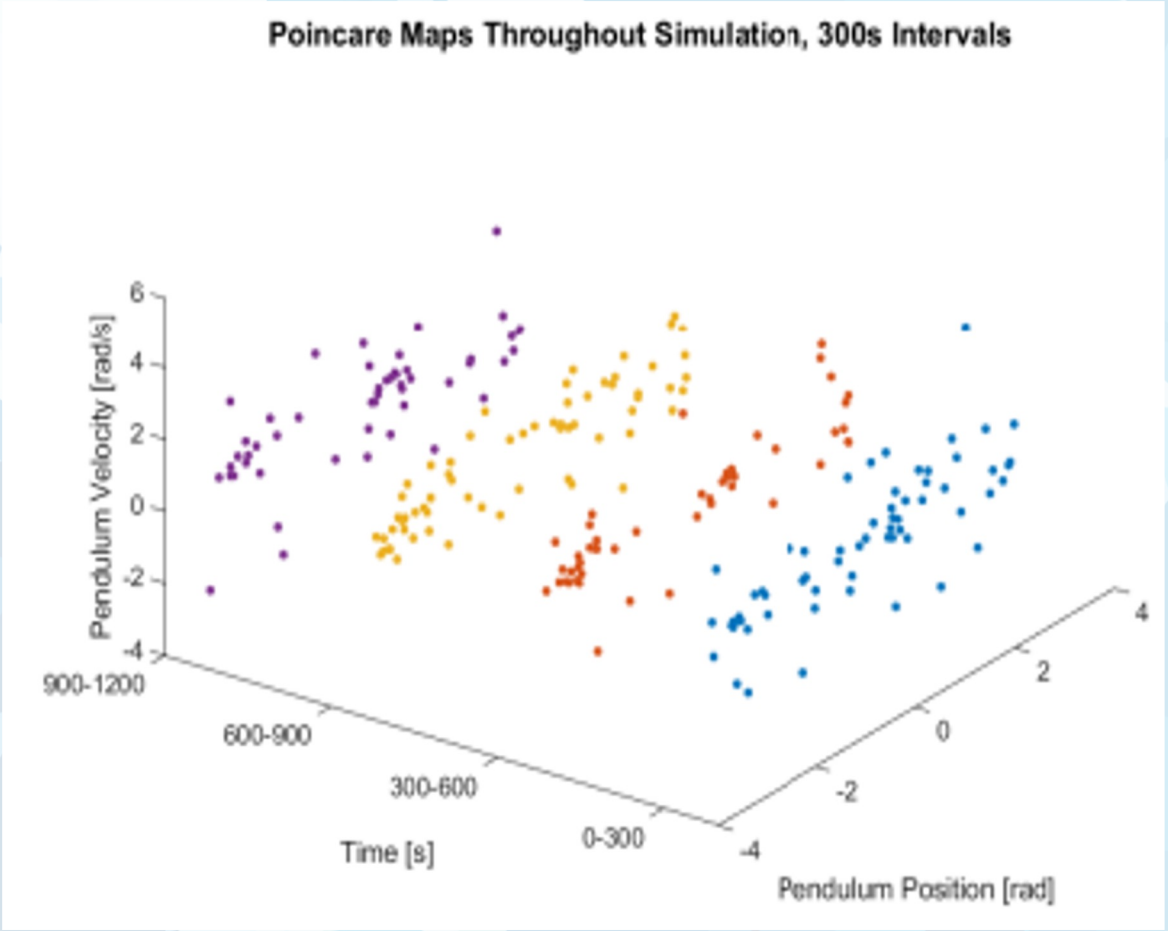

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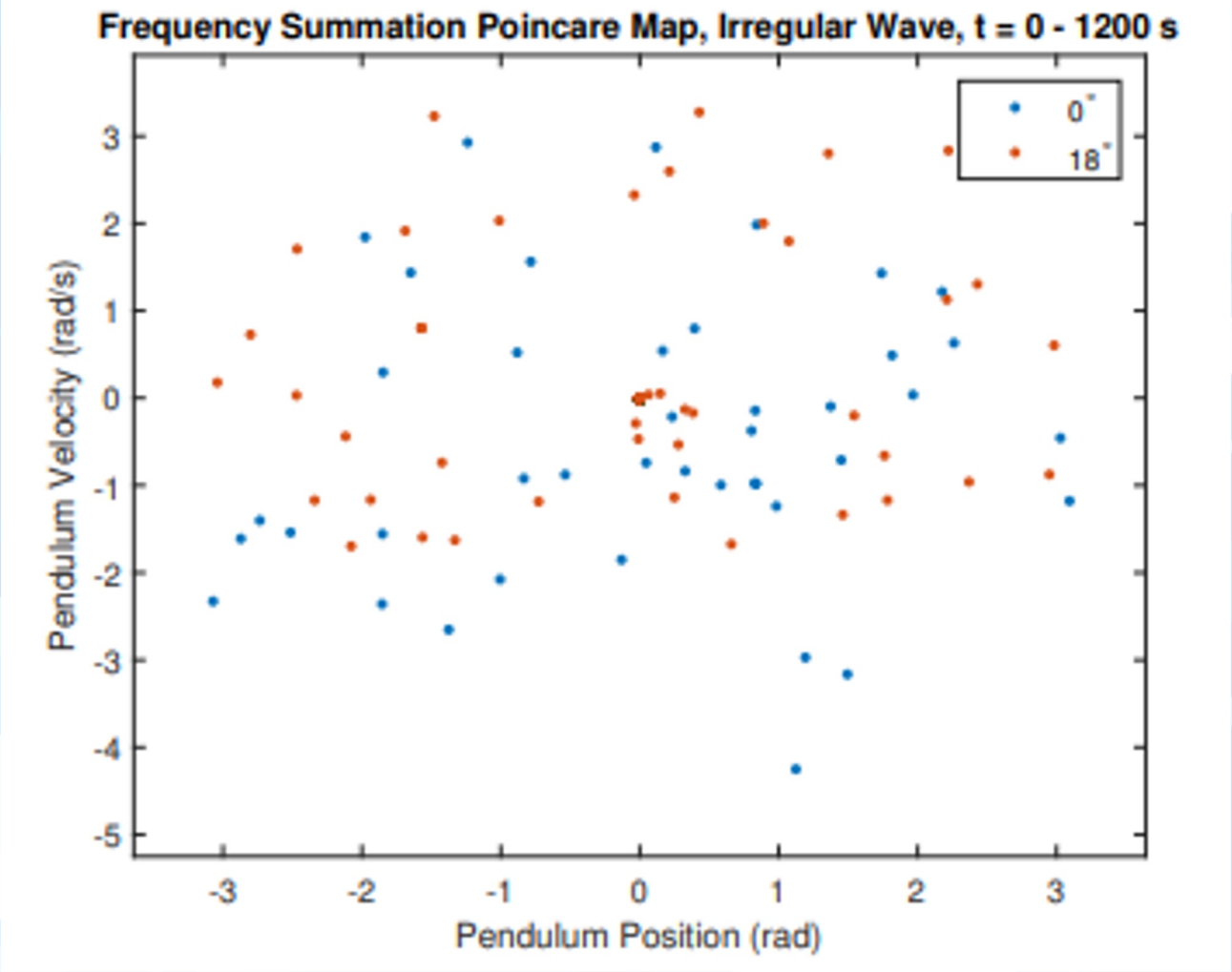


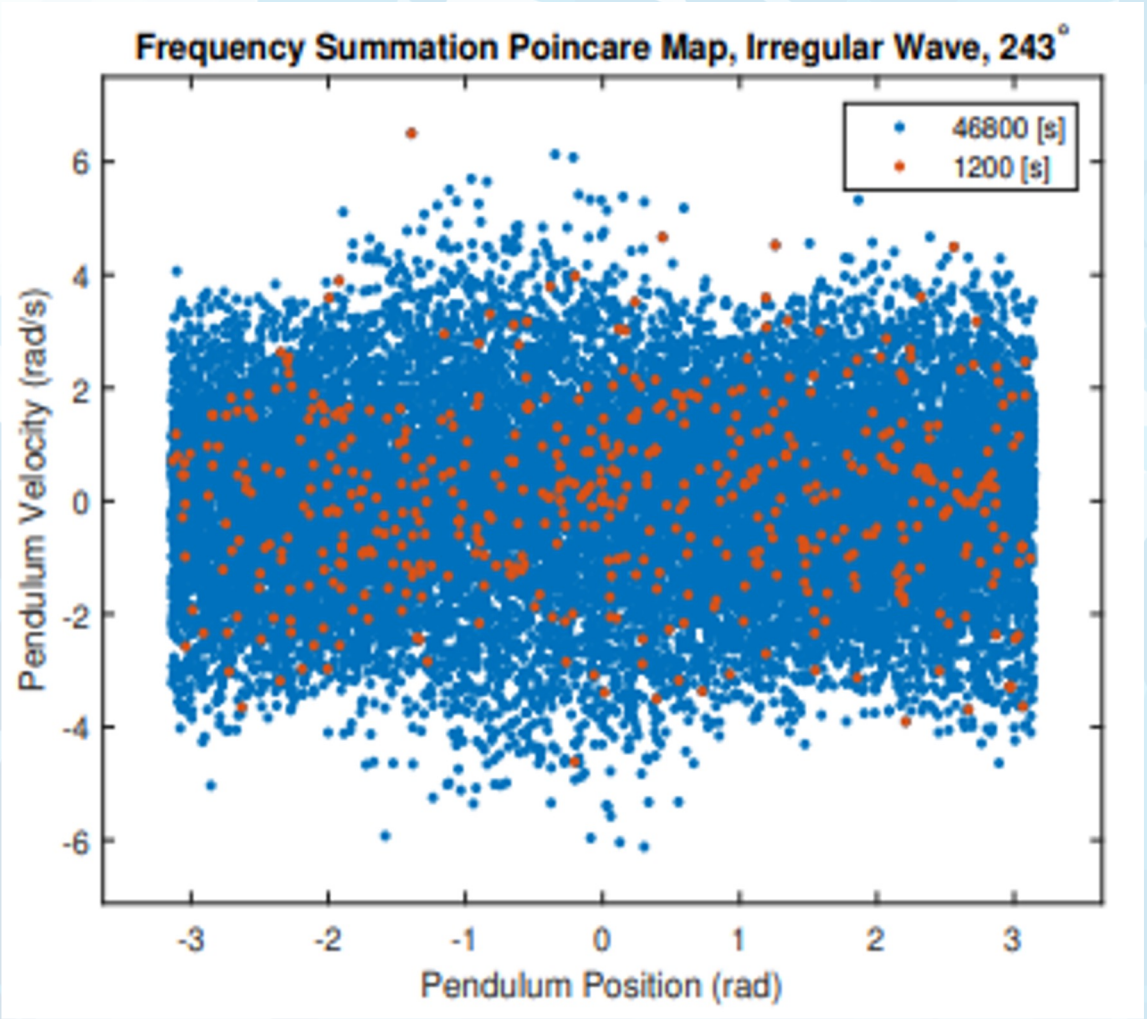

# Discussion & Conclusion

- Evaluation in irregular sea states is necessary
- Pendulum PTO WEC operating in realistic setting did not exhibit chaotic behavior
  - Lack of chaotic attractor
- Implementation of control techniques in chaos theory not recommended

"Does the pendulum PTO WEC continue to exhibit chaotic behavior when operating in an irregular sea state? How does this affect proposed ideas or applications?"

No. The pendulum PTO WEC operating in an irregular sea state does not exhibit chaotic behavior. The proposal of control used in chaos theory is not recommended.

# Questions?