An Artificial Neural Network Approach to Predict Rotor-Airframe Acoustic Waveforms

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Background: What is Rotor-Airframe Interaction and why is it relevant for small Unmanned Aerial Systems?

- A typical small Unmanned Aerial System (sUAS), or drone, has a compact design that results in a rotor operating in close proximity to the support arm.

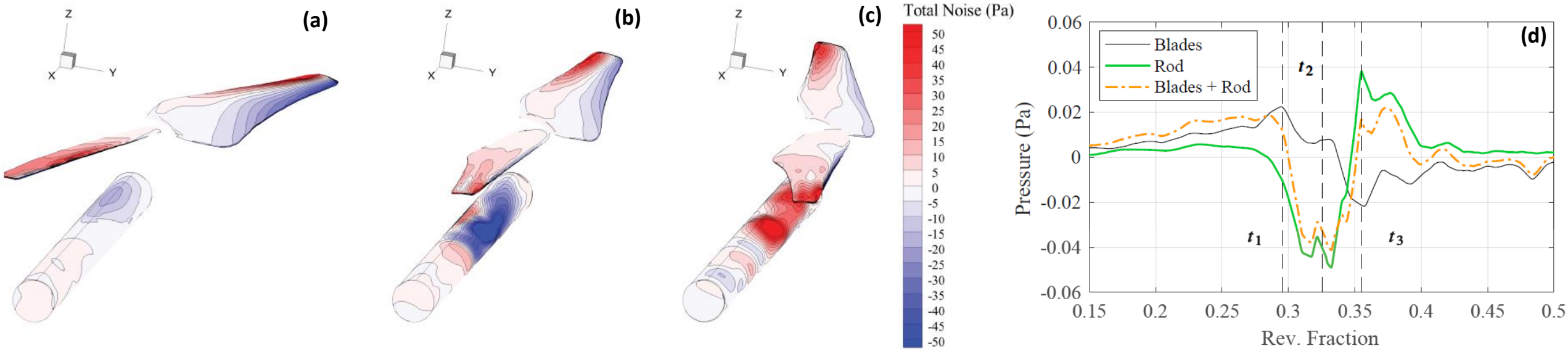
- Due to this compact design, the rotor will come into close proximity of the rotor arm and introduce an installation noise source known as the Rotor-Airframe Interaction (RAI).



Background: Is Rotor-Airframe Interaction noise important?

- Previous work conducted by Zawodny and Boyd has shown that the interaction, for compact spacing, can result in the RAI noise producing more tonal noise than the rotor itself.

- This is concerning because there is no low-fidelity model that can predict the impulse emitted by the rotor-airframe interaction in hover.



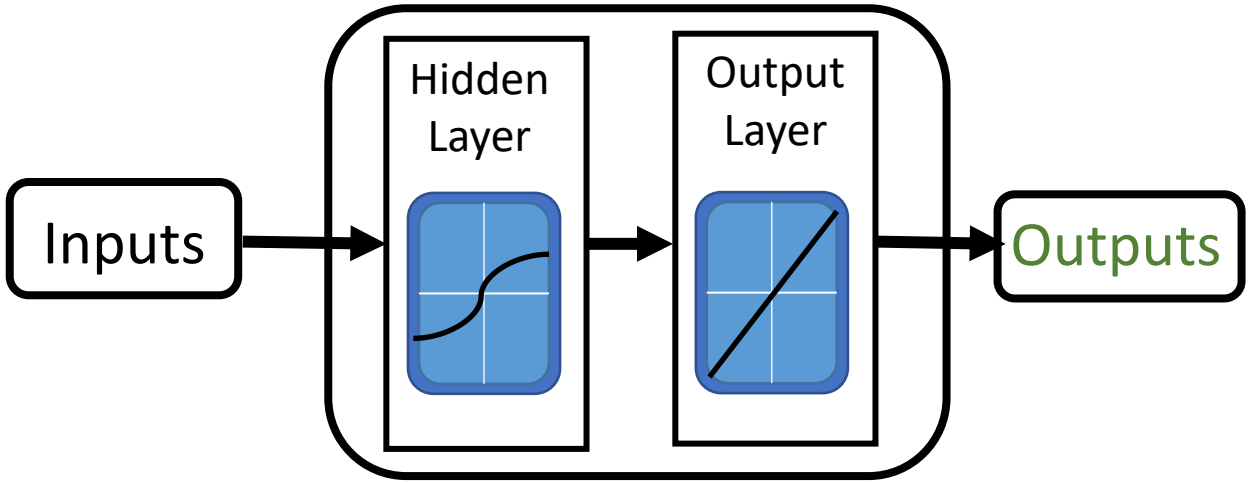
Zawodny, N. S., and Boyd, D. D., "Investigation of Rotor–Airframe Interaction Noise Associated with Small-Scale Rotary-Wing Unmanned Aircraft Systems," *Journal of the American Helicopter Society*, Vol. 65, 2020, pp. 1–17. doi.org/10.4050/JAHS.65.012007

Background: What is an Artificial Neural Network?

- Artificial Neural Networks (ANNs) are surrogate models that can recognize patterns, classify data, or make predictions after training on data.

- Training involves the adjustment of weights and biases in hidden and output layers to correlate the inputs with outputs.

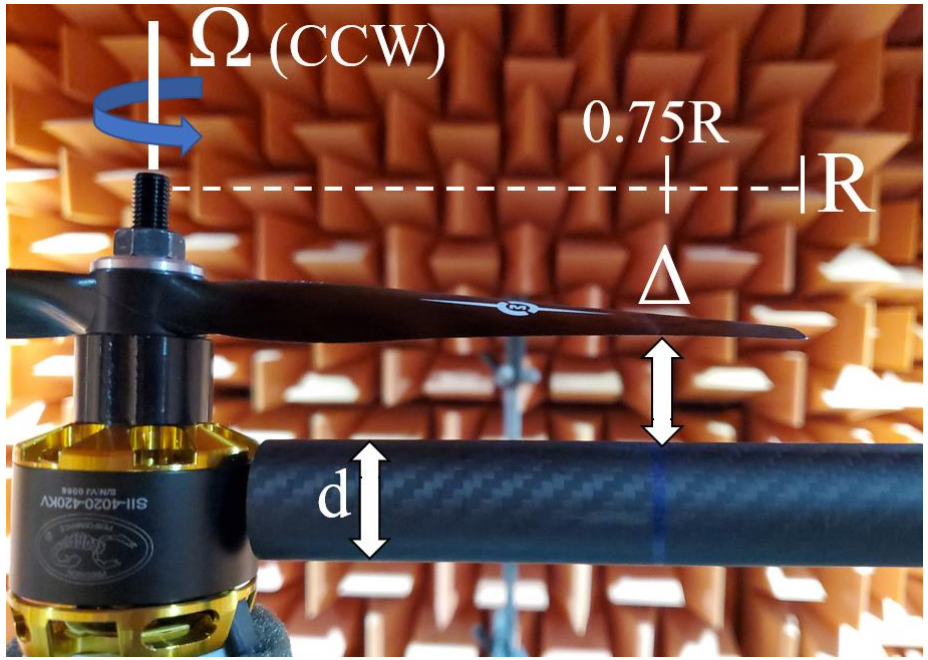
- With a sufficient number of training examples, an ANN can predict the output for unseen inputs.



Experiment: What inputs will be investigated?

- We have evaluated several inputs that are influential to the RAI.

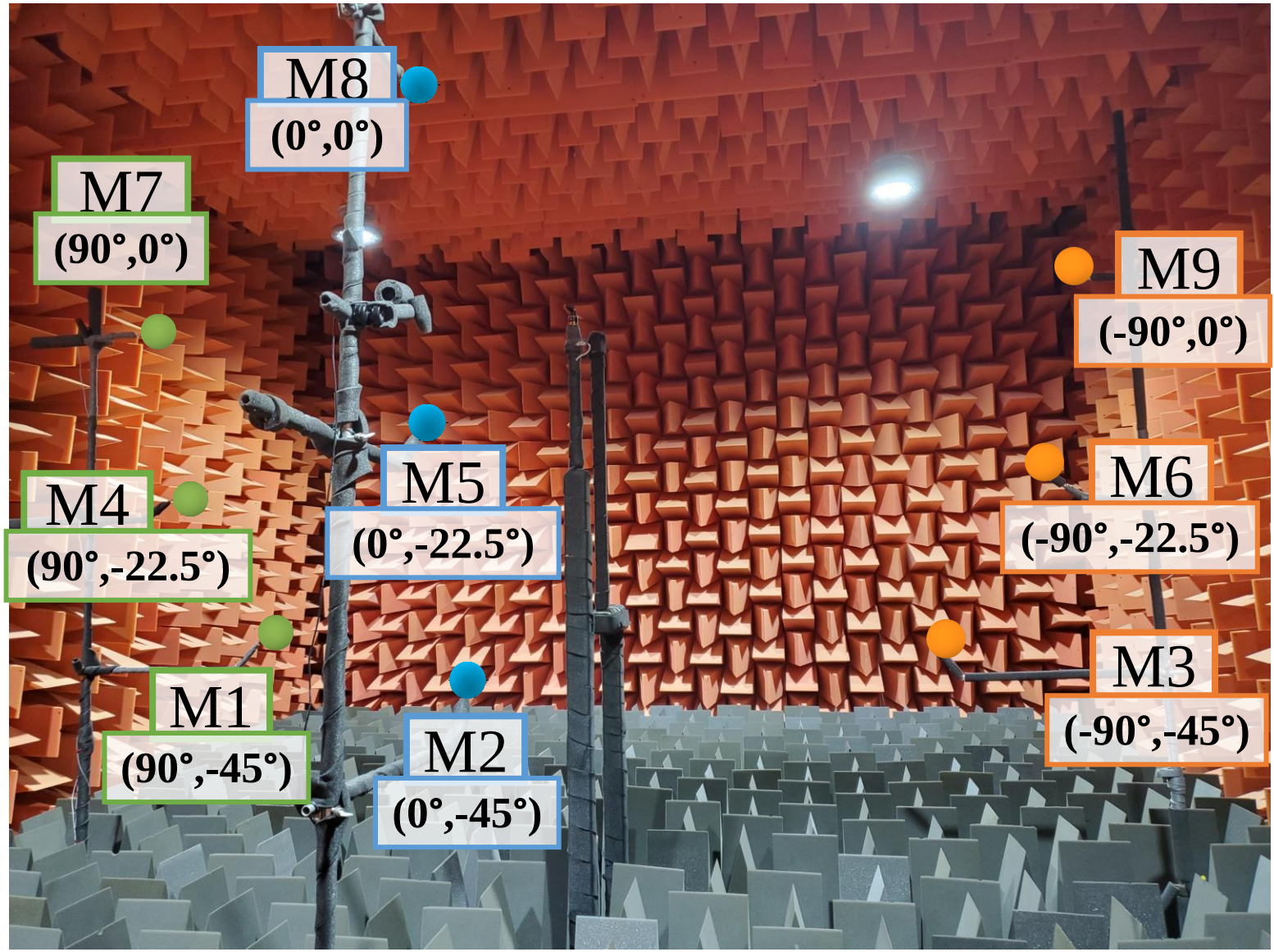
Symbol	Property
Δ/R	Blade-airframe proximity
$M_{tip}(\Omega,c_0)$	Tip Mach number
φ	Elevation angle
θ	Azimuth angle



- A single rotor-airframe with a radius of R = 140 mm rests above the cylindrical airframe with a cross-section diameter of d = 25.4 mm.

Experiment: Where was the experiment conducted?

- Conducted in the NASA Langley Structural Acoustic Loads and Transmission (SALT) anechoic chamber.
- The rotor stand is centered in the room with a detachable cantilever securing the airframe.
- Nine microphones were positioned at key locations.
- Key: MX (θ,φ)



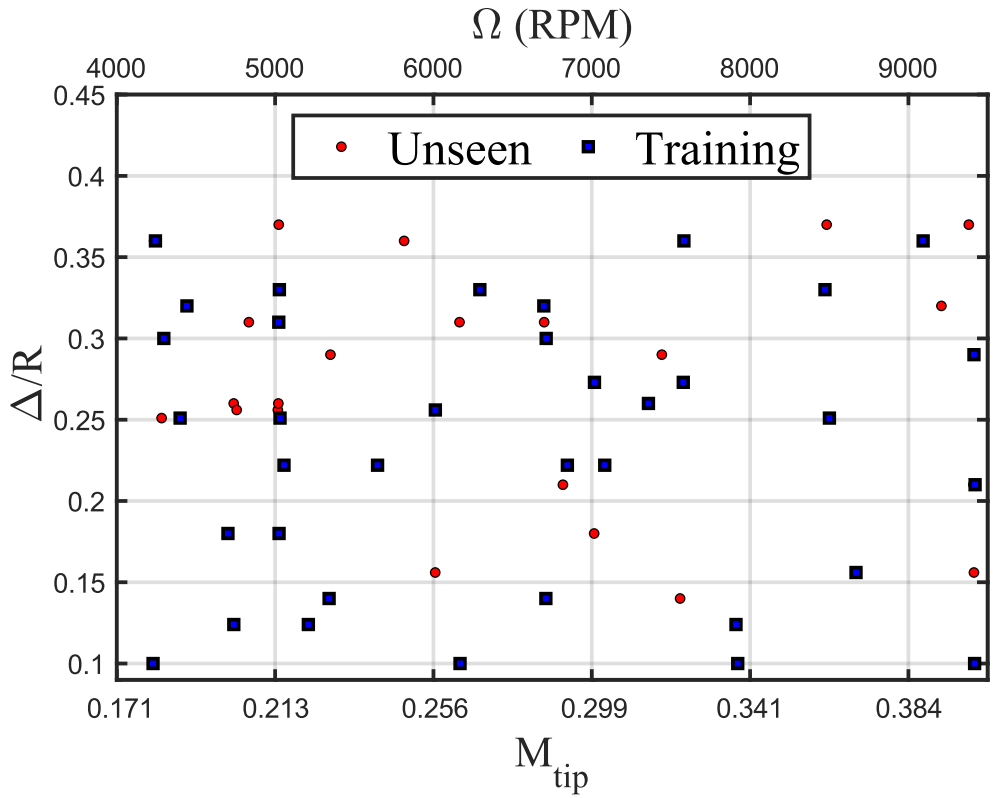
Experiment: How is the domain sampled?

- Two datasets were sampled from the domain of interest.

Category	M_{tip}	Δ/R	# Runs
Isolated	0.172 – 0.404	--	30
RAI	0.172 – 0.404	0.1 – 0.37	51

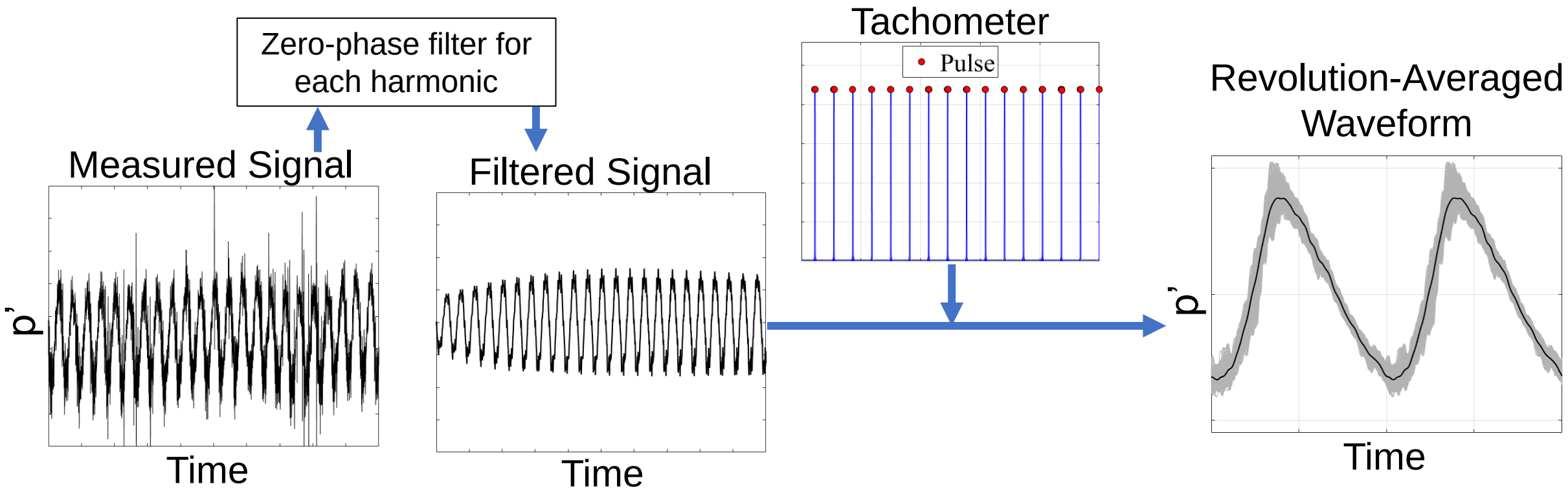
- For the RAI experiment, 35 of the 51 runs were used to train the ANNs.

- The other 16 runs were kept as an unseen dataset to evaluate each ANN on its ability to predict novel conditions.



Methodology: How is the RAI waveform emission sampled?

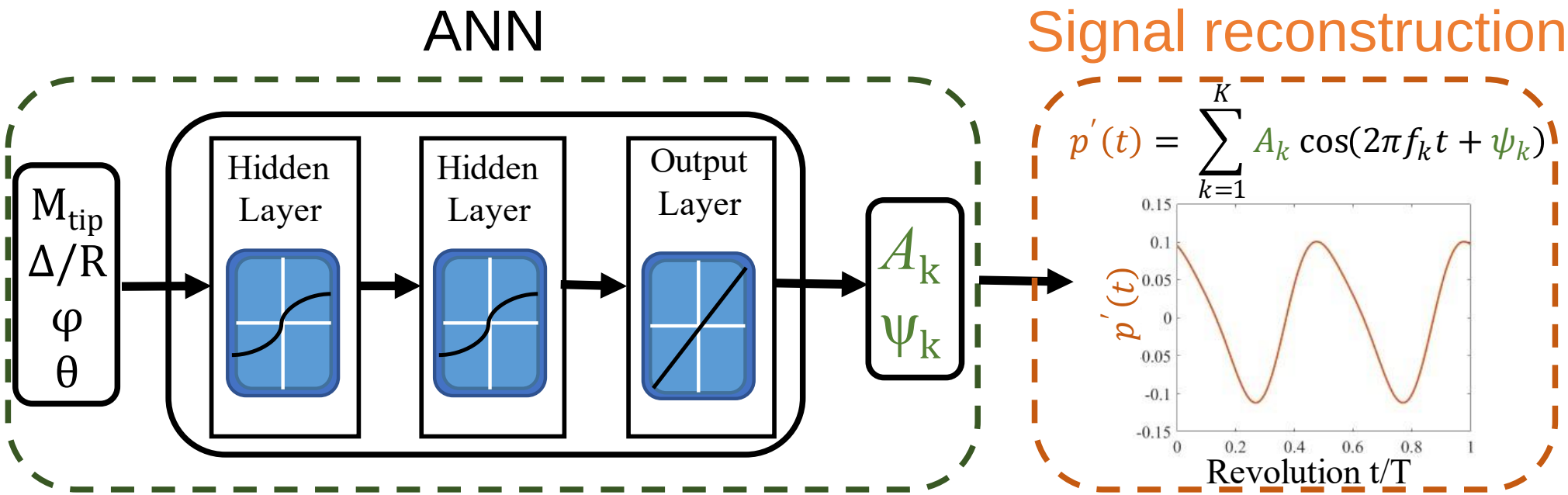
- The measured signal is filtered so only the harmonic content, ±10 Hz around each BPF, is retained.
- This filtered signal is then segmented with the tachometer pulses to categorize the individual revolutions.
- The individual revolutions are summed to produce the revolution-averaged waveform.



Methodology: How is an ANN used to model the RAI tone?

- Now, we can train an ANN to correlate inputs M_{tip}, Δ/R, φ, and θ with A and ψ for each harmonic, k.

- We are modeling the RAI in the frequency domain, but we can also reconstruct the time-domain signal.

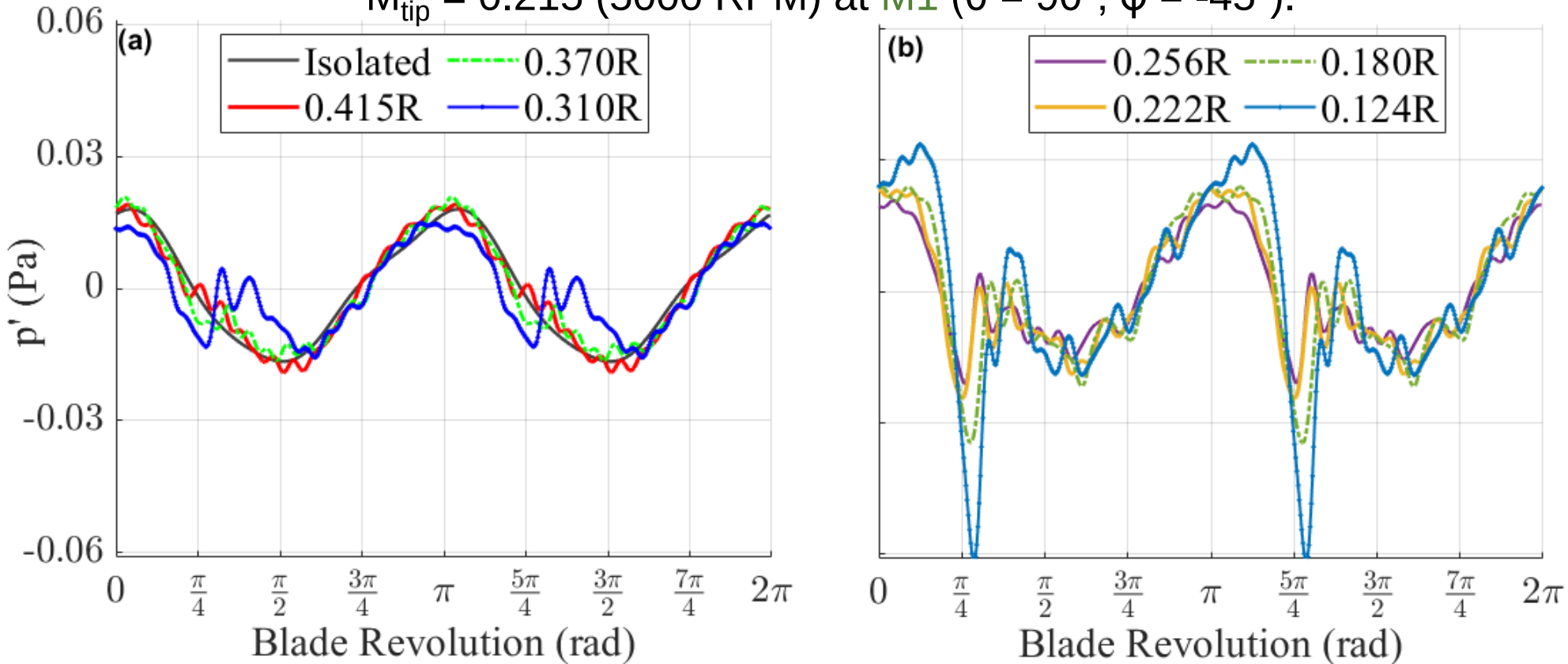


Result: What is the rotor-airframe proximity relationship with RAI?

- At large proximities, Δ/R > 0.37, the tonal emission has little deviation from the isolated waveform.

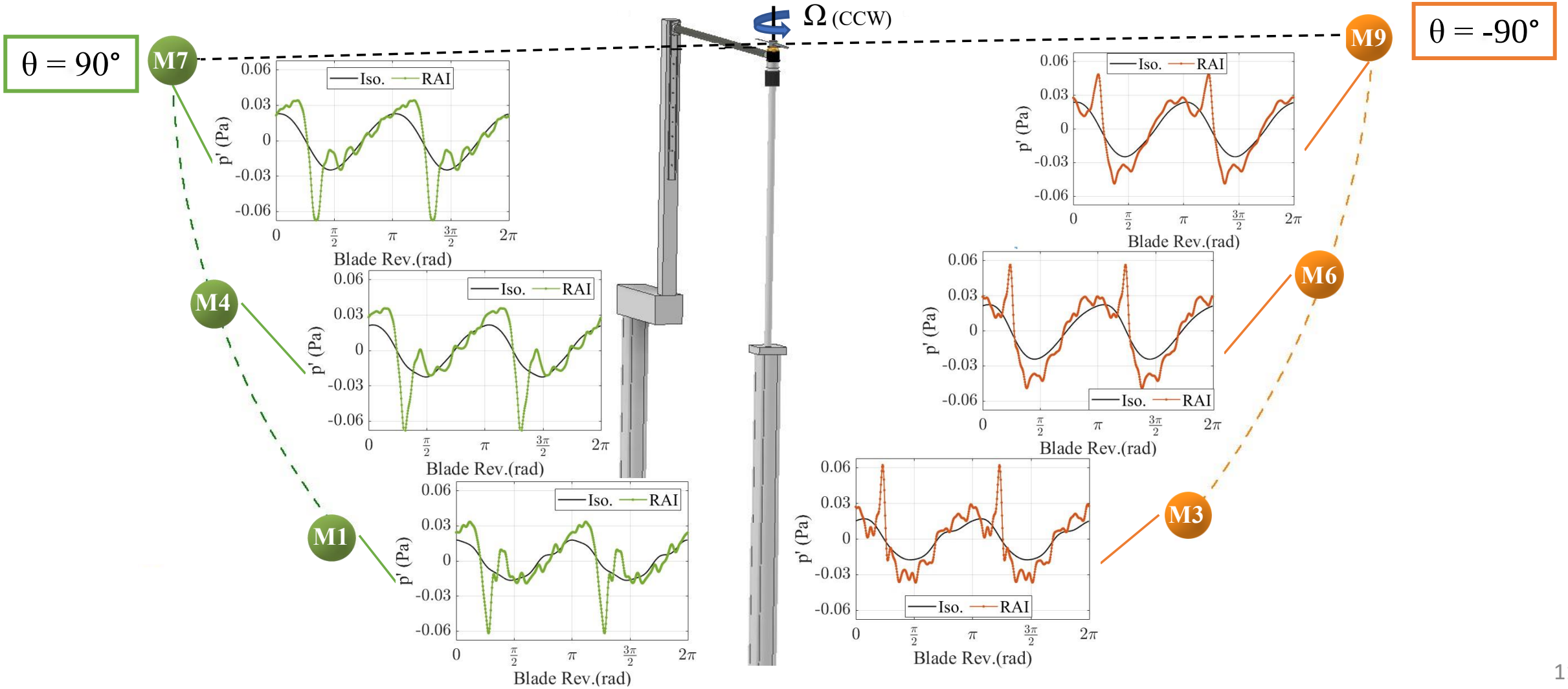
- Below Δ/R = 0.37, an impulse emerges within the waveform.

M_{tip} = 0.215 (5000 RPM) at M1 (θ = 90°, φ = -45°).



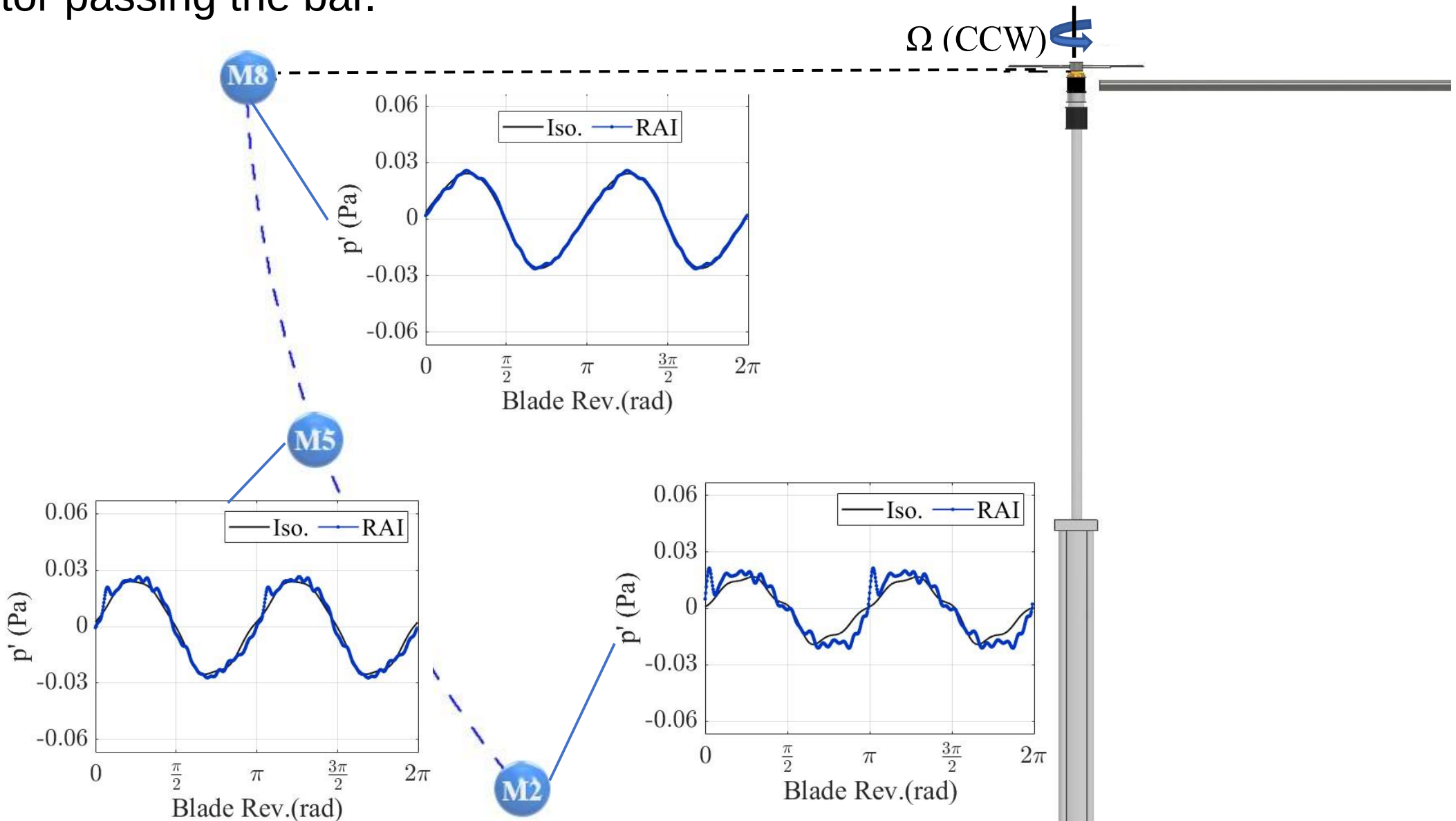
Result: Is the RAI impulse highly directive?

- Let's investigate directivity with run: $\Delta = 0.124R$, $M_{tip} = 0.215$ (5000 RPM).
- Yes, observers normal to the airframe experience a strong impulse noise.



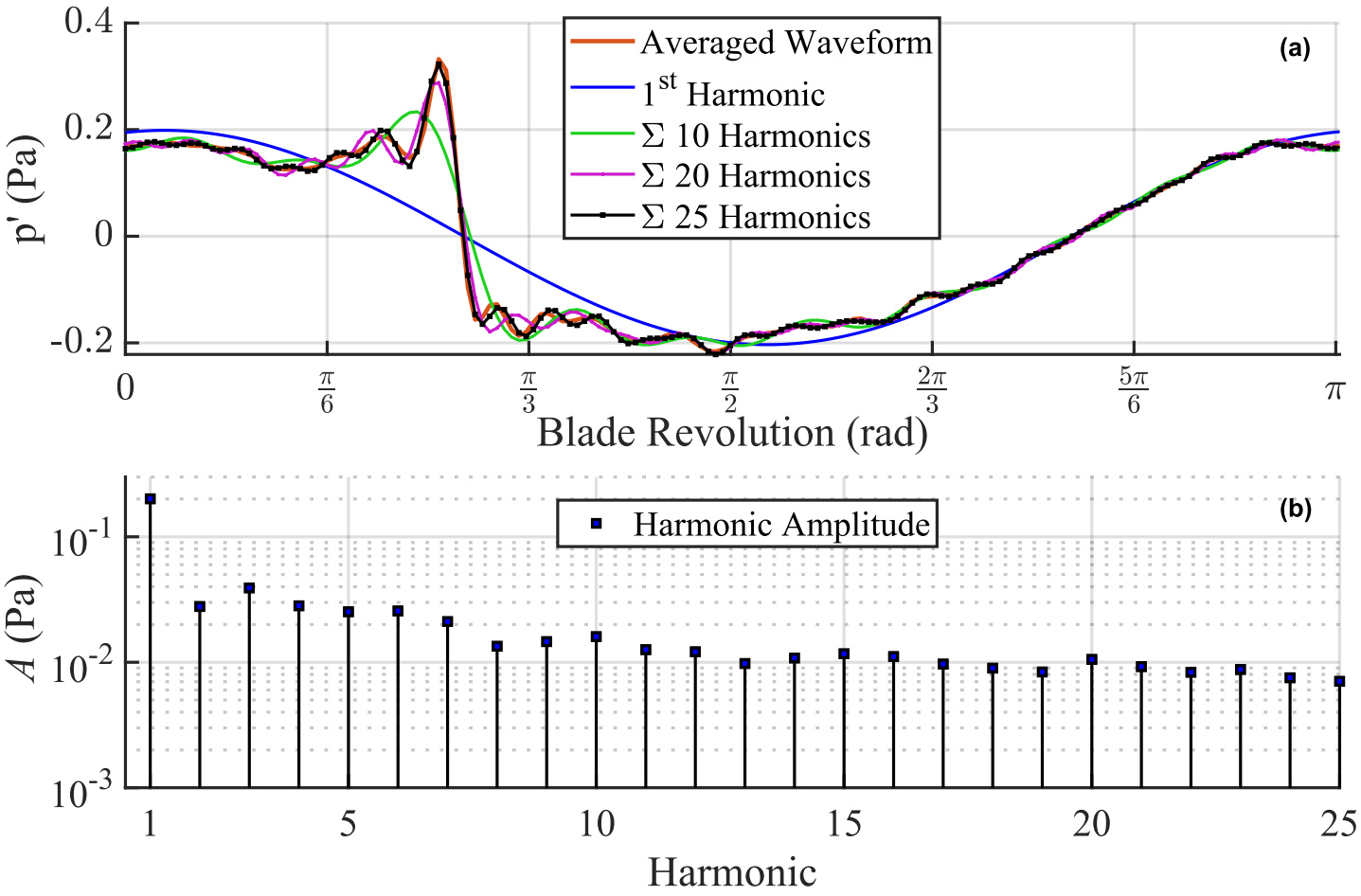
Result: Is the RAI impulse highly directive?

- Observers coplanar to the bar, which have no surface normals, are hardly influenced by the rotor passing the bar.



ANN Prediction: How many harmonics are excited by the RAI?

- Microphones that were below the plane of rotation, normal to the airframe, and observing a rotor operating at a large M_{tip} with a small Δ/R experienced the greatest impulse noise.
- This combination of parameters could excite as many as 25 harmonics.
- This meant 25 amplitude and 25 phase ANNs had to be constructed to model the waveform.



ANN Prediction: How well does the ANN predict unseen runs?

- Two different error metrics were used to evaluate the ANNs performance on unseen conditions. Why?

$$P_A = 100\left(1 - \frac{1}{M}\sum_{j=1}^{M}\left|\frac{A_j - \tilde{A}_j}{A_j}\right|\right)$$

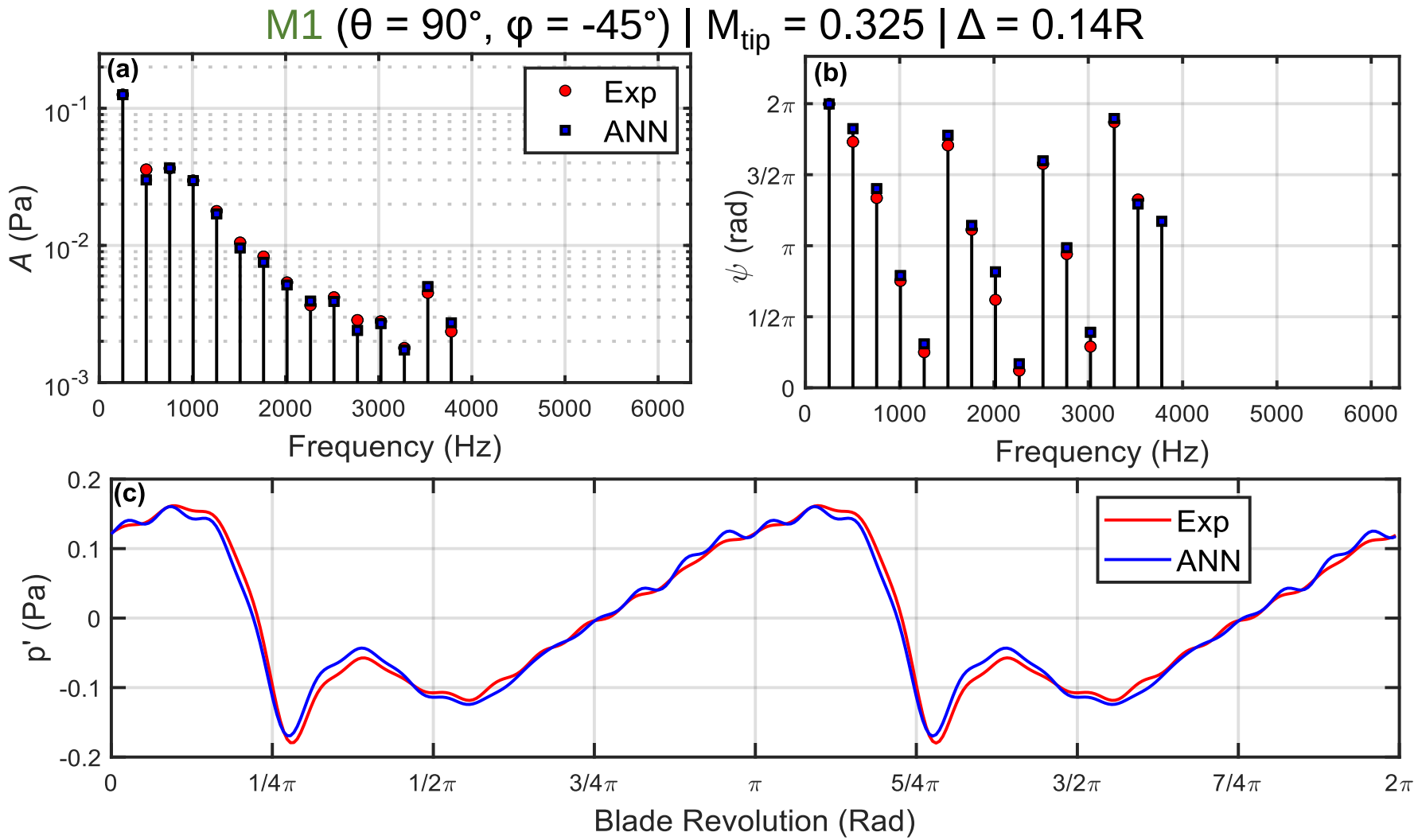
$$P_\psi = 100\left(1 - \frac{1}{M}\sum_{j=1}^{M}\left|\angle e^{i\{\psi - \tilde{\psi}\}}\right|\right)$$

	M1	M2	M3	M4	M5	M6	M7	M8	M9	Ave.
$P_A(\%)$	88.2	87.6	88.7	86.5	71.7	87.0	88.0	93.9	82.8	86
$P_\psi(\%)$	70.8	73.0	70.9	83.3	64.3	59.7	82.3	92.8	81.4	75

- What does a P_A of 86% and P_ψ of 75% mean? Is this sufficient to predict the waveform?

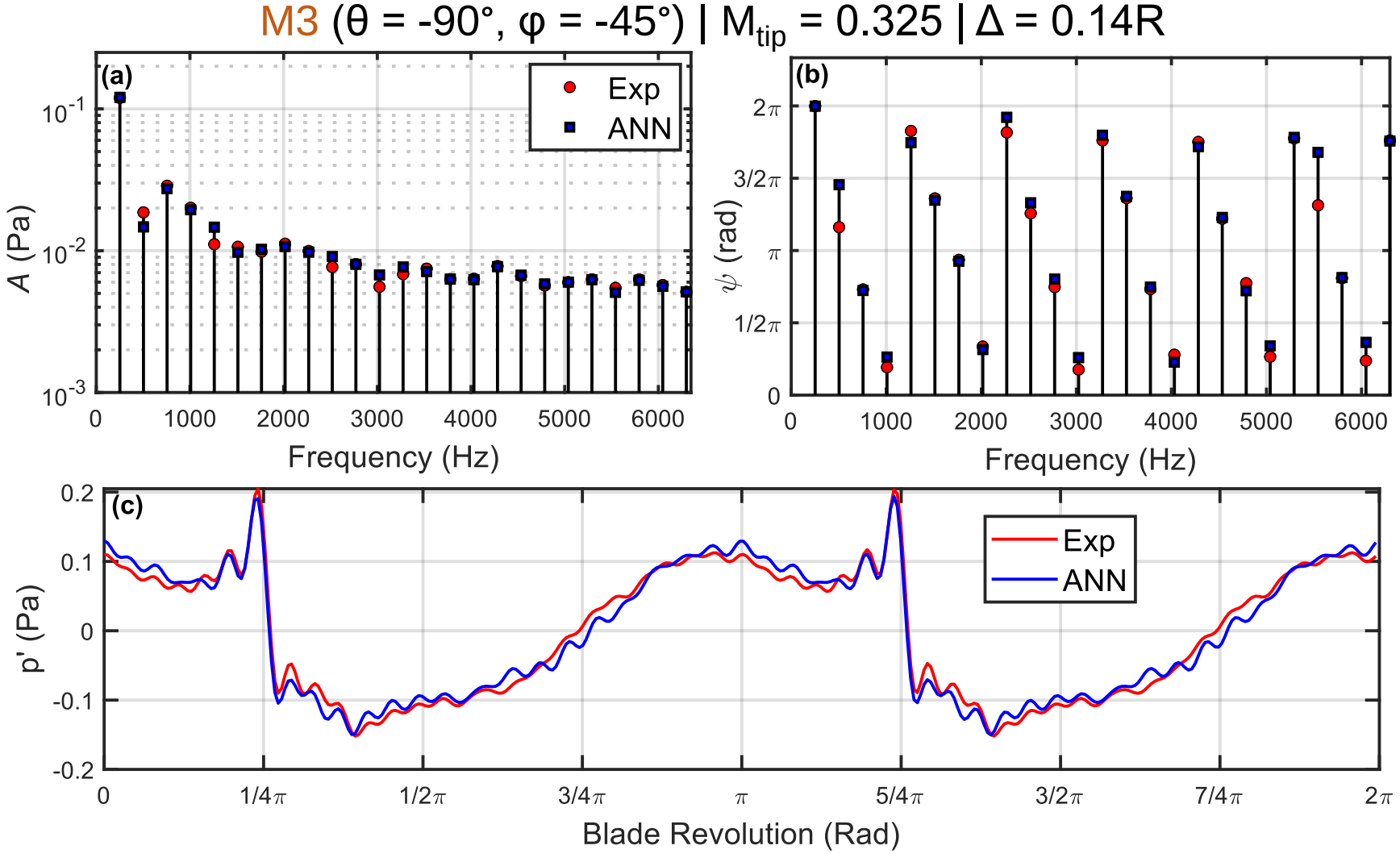
ANN Prediction: Can the ANN predict the RAI for unseen runs?

- The systems of ANNs have been sufficiently trained to predict the waveform for an unseen condition at M1 and M3.



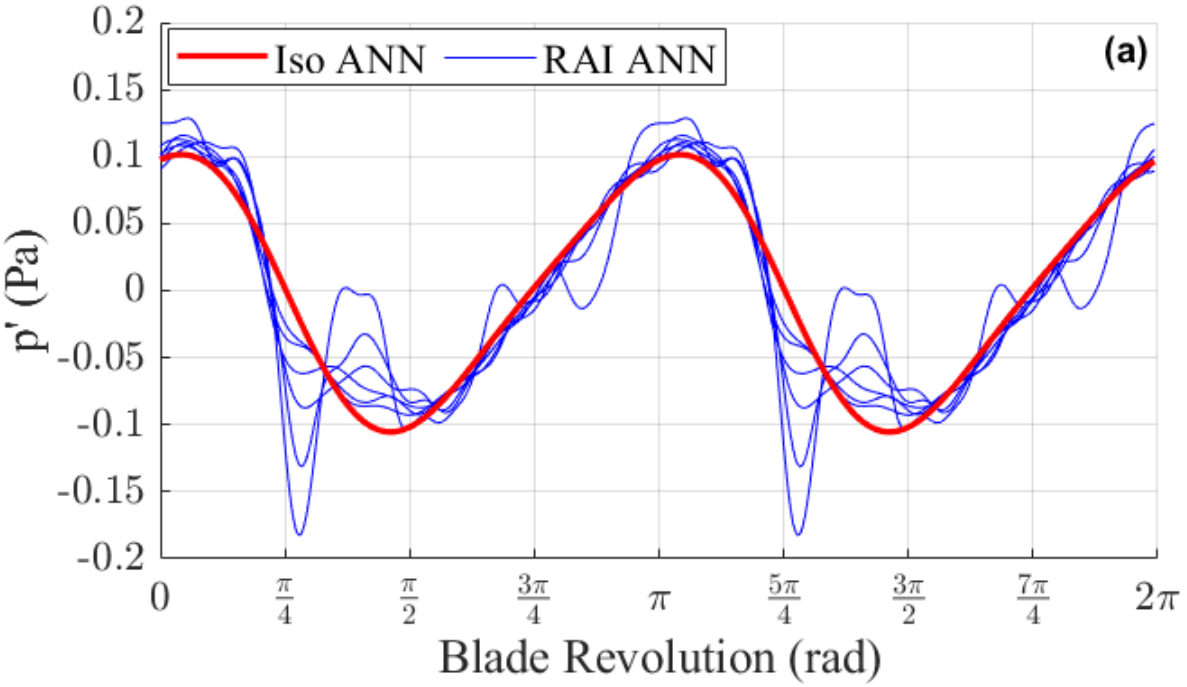
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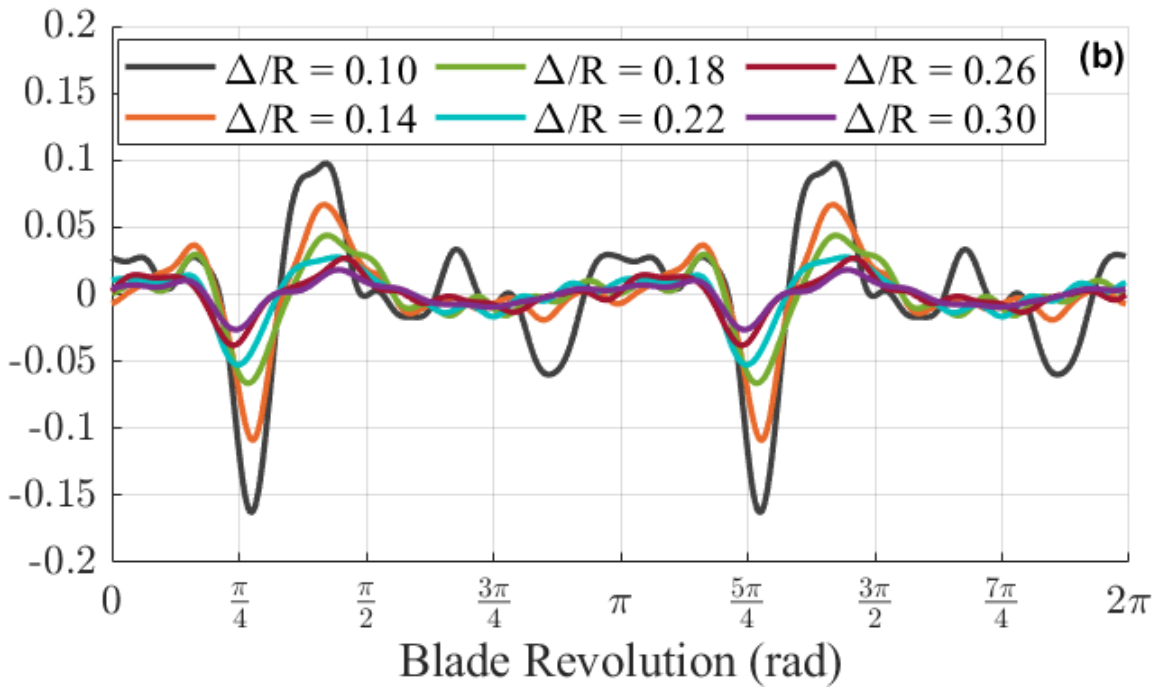
- The systems of ANNs have been sufficiently trained to predict the waveform for an unseen condition at M1 and M3.



ANN Prediction: Does the ANN make predictions that align with experimental results?

- After a system of ANNs have been trained to model both the isolated rotor and the RAI, the impulse noise can be separated from the steady loading noise, and we can inspect the impulse prediction.





Conclusion

- The rotor-airframe interaction noise is a significant source of installation noise.
- This installation noise produces an impulse signal when a rotor approaches and departs from an airframe.
- The impulse can excite as many as 25 harmonics.
- A low-fidelity tool for estimating the tonal noise emission for the RAI for a single rotor-airframe condition has been developed.