Estimating Inducer Blade Damping in Water with On-Blade Strain Measurements

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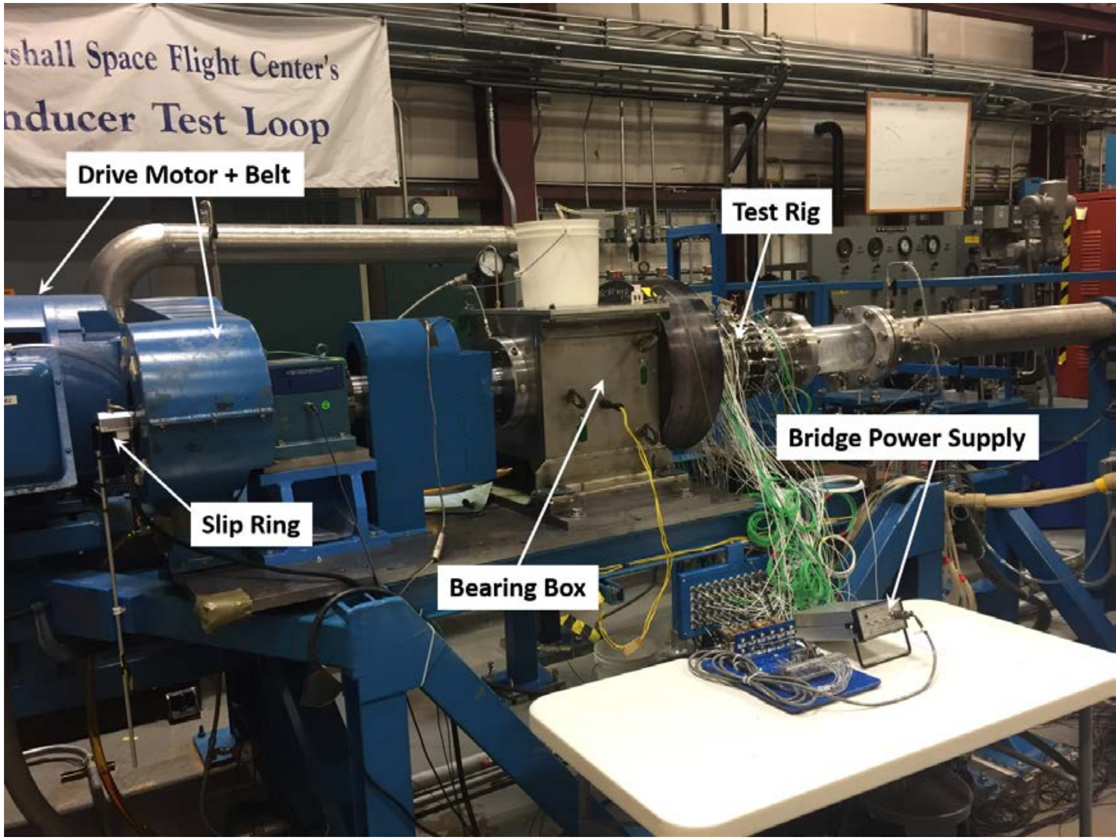
Introduction

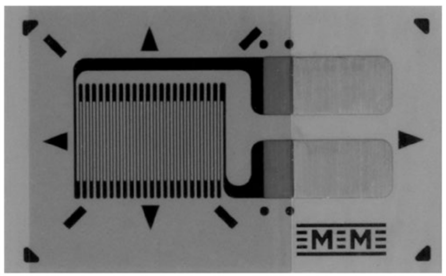
A water flow test of a subscale inducer (RS25 Low Pressure Fuel Pump) was conducted at MSFC in July 2017 and Feb-May 2018



Objective: Measure on-blade strain response to various forms of excitation, with intent to estimate critical damping ratio of blade structural natural frequencies in real operating conditions

Strain Gauge Instrumentation

GAGE PATTERN DATA



actual size

GAGE DESIGNATION See Note 1	RESISTANCE (OHMS) See Note 2	OPTIONS AVAILABLE See Note 3
CEA-XX-062UB-350	350 ± 0.3%	**P2**, SP35

DESCRIPTION

General-purpose gage. Exposed solder tab area is 0.10 x 0.045 in (2.5 x 1.14 mm).

GAGE DIMENSIONS

Legend
ES = Each Section CP = Complete Pattern
S = Section (S1 = Section 1) M = Matrix

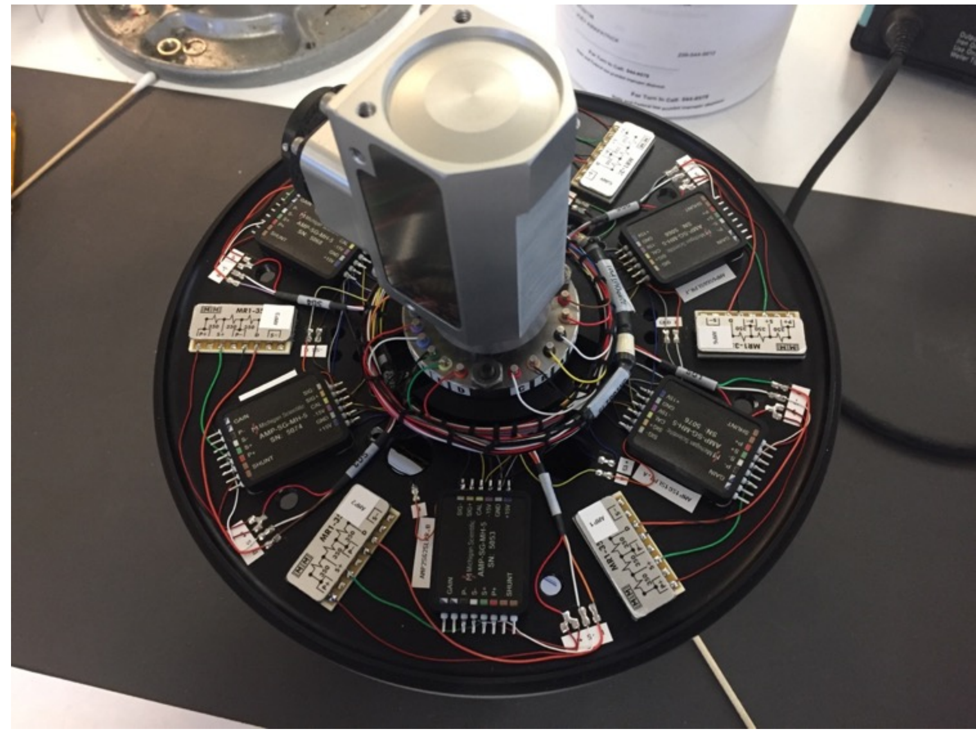
inch / millimeter

Gage Length	Overall Length	Grid Width	Overall Width	Matrix Length	Matrix Width
0.062	0.110	0.120	0.250	0.21	0.34
1.57	2.79	3.05	6.35	5.3	8.6

GAGE SERIES DATA — See Gage Series datasheet for complete specifications

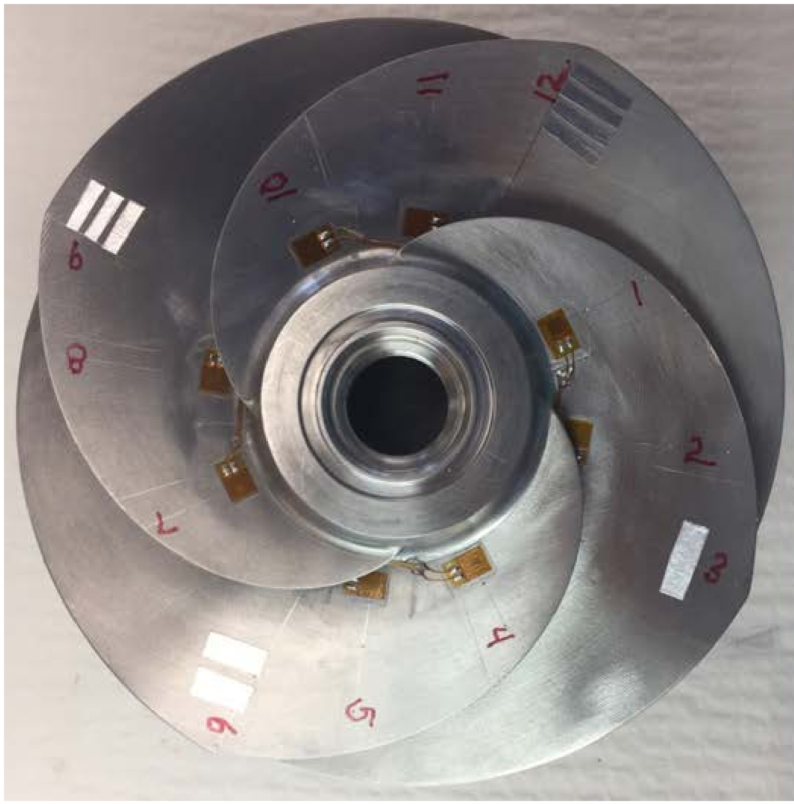
Series	Description	Strain Range	Temperature Range
CEA	Universal general-purpose strain gages.	±3%	−100° to +350°F (−75° to +175°C)

Strain gauge info

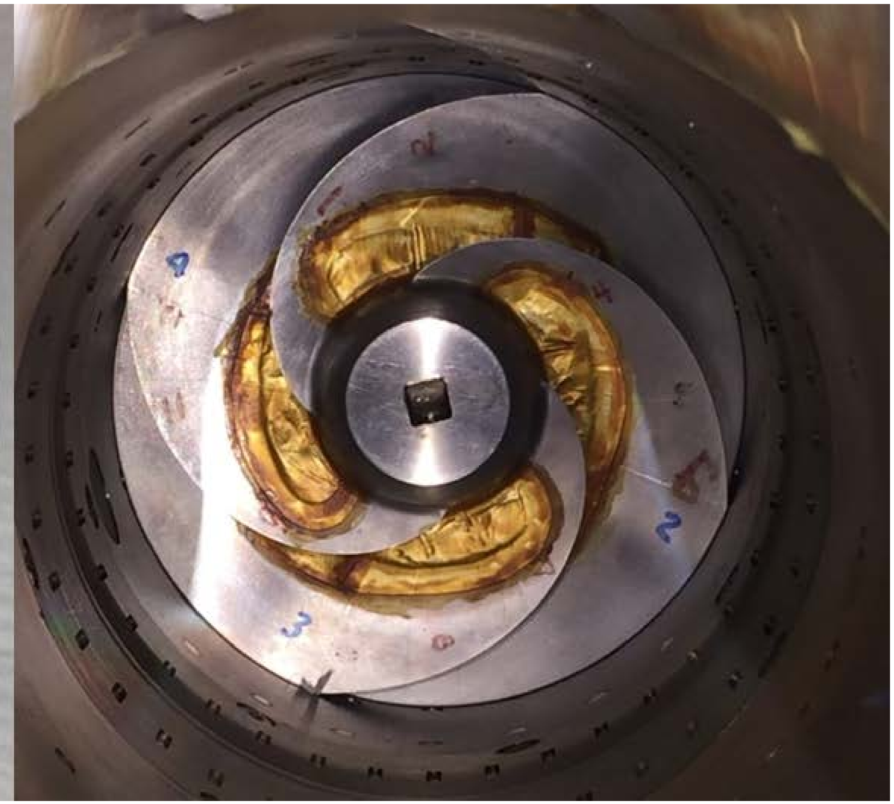


Slip ring with amplifiers and bridge completion circuits

Strain Gauge Instrumentation



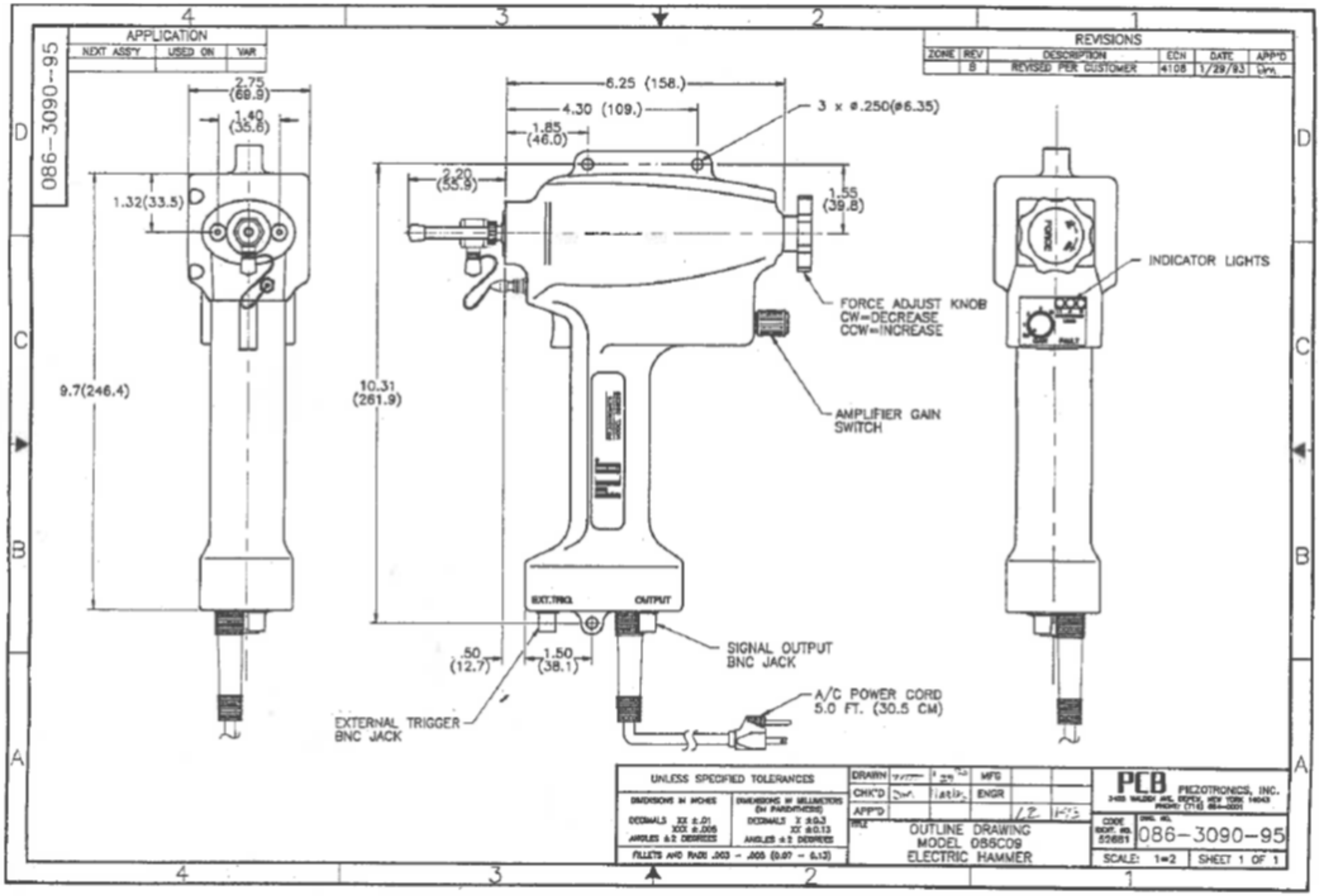
Gauges installed on blades



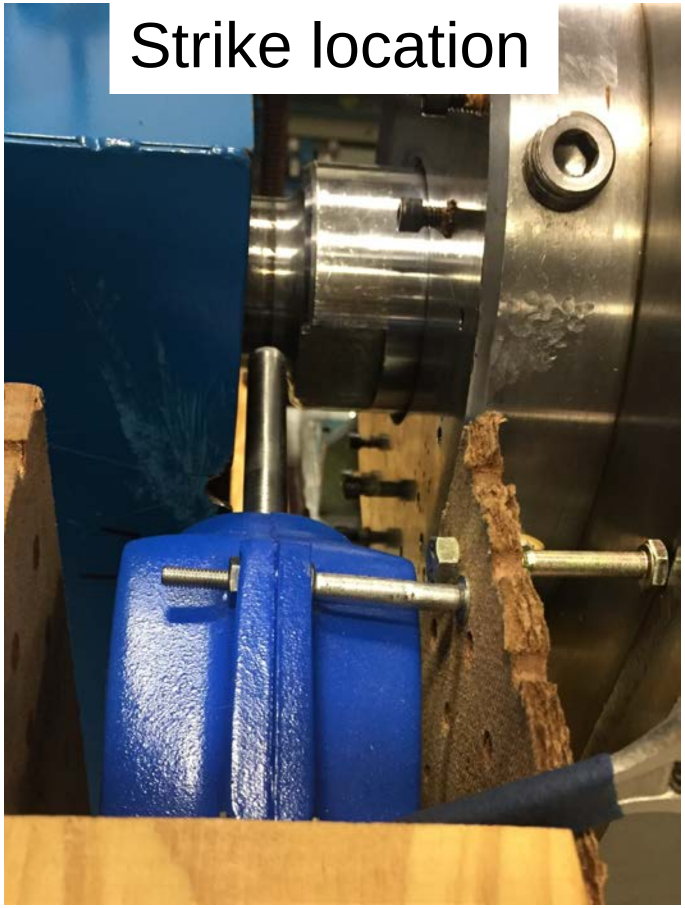
Waterproofing
(rubber coating + metal foil)

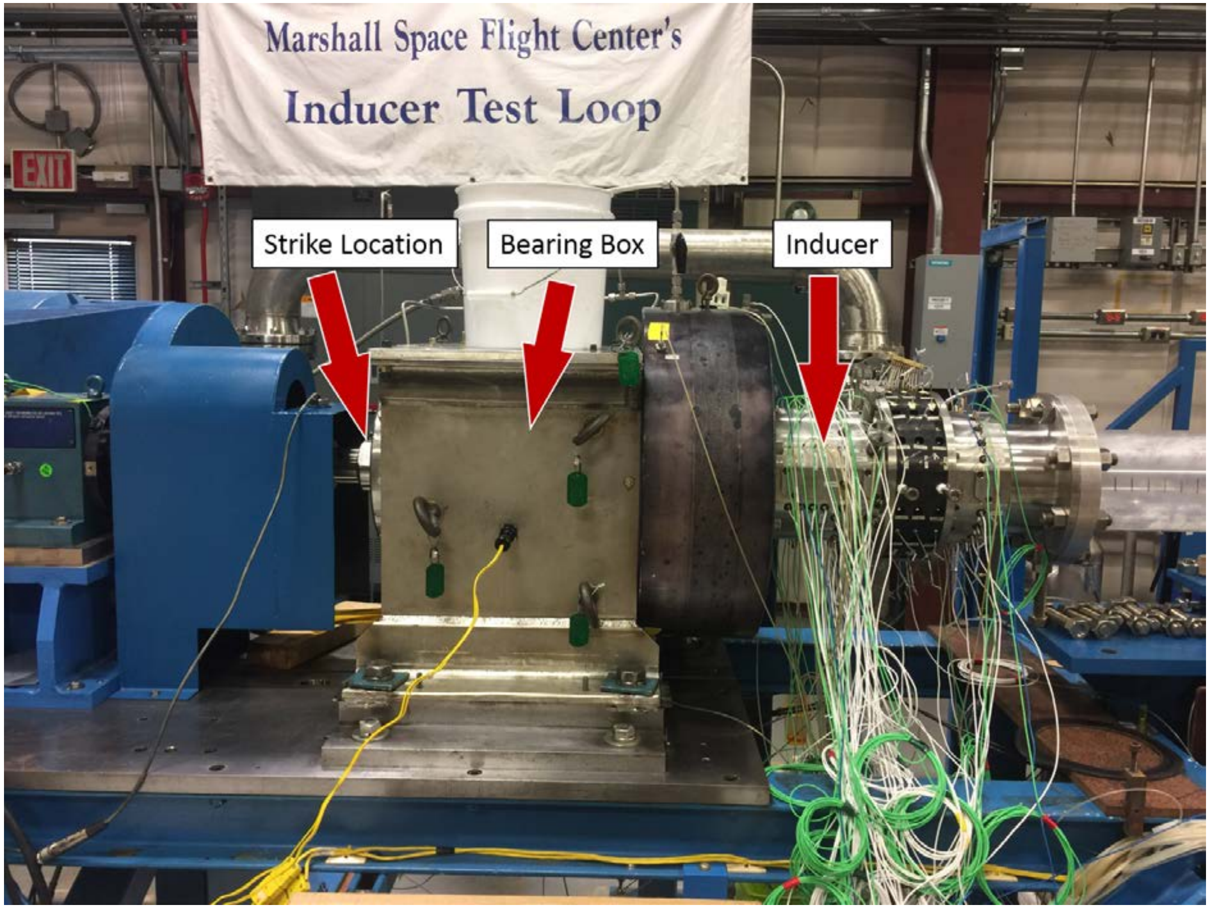
Excitation Method: Ping Test

An ‘electric hammer’ was used to strike the inducer shaft

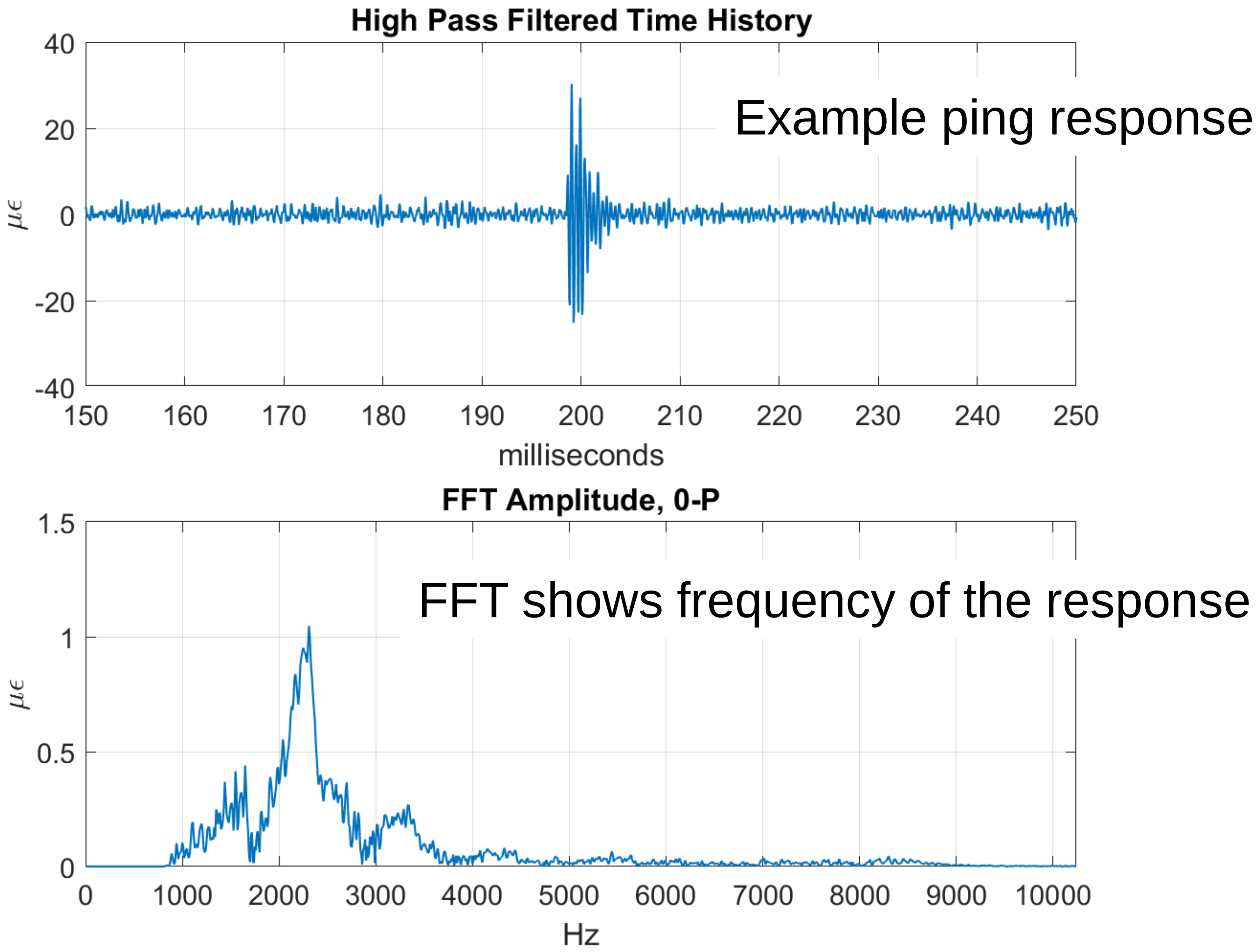


Excitation Method: Ping Test





Ping Data Analysis



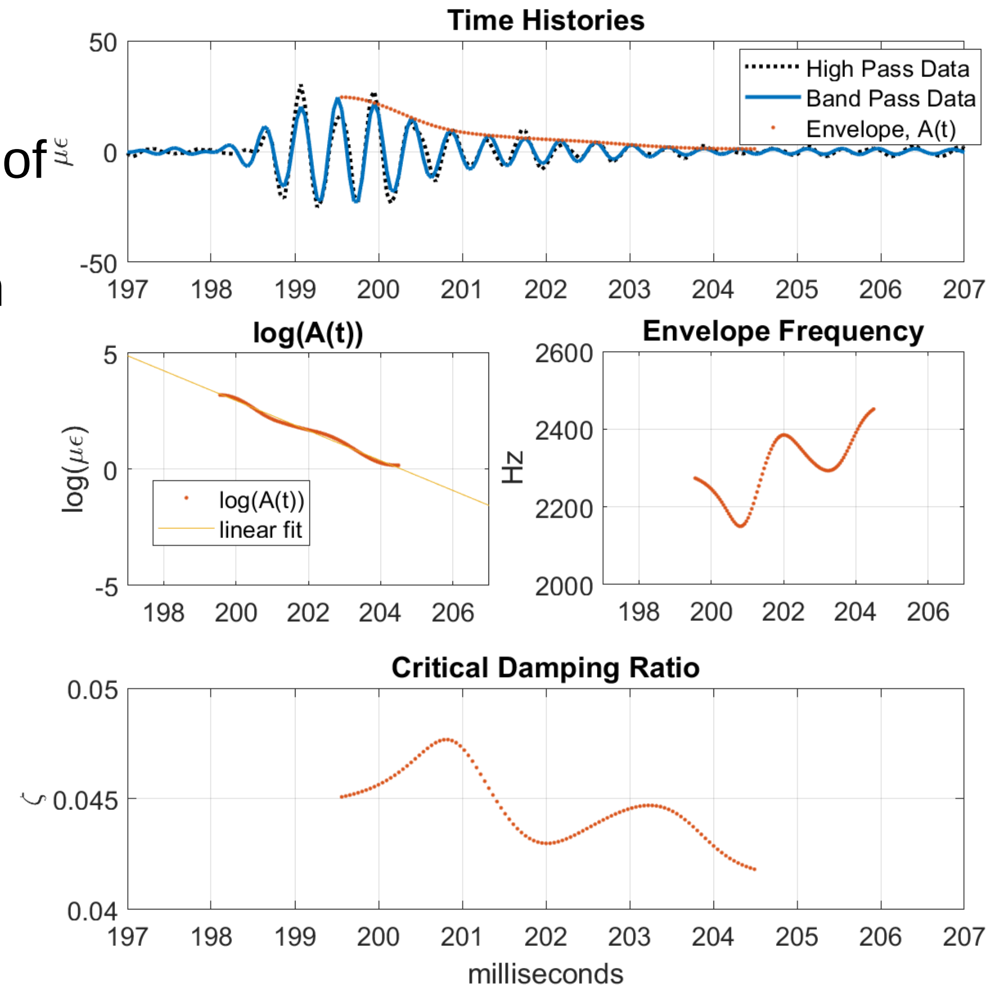
Ping Data Analysis

- Filter data around natural frequency
- Compute amplitude envelope of blade response
- Compute critical damping with impulse response formula

$$\zeta = \frac{1}{\sqrt{1 + \left(\frac{\omega_d}{\beta}\right)^2}}$$

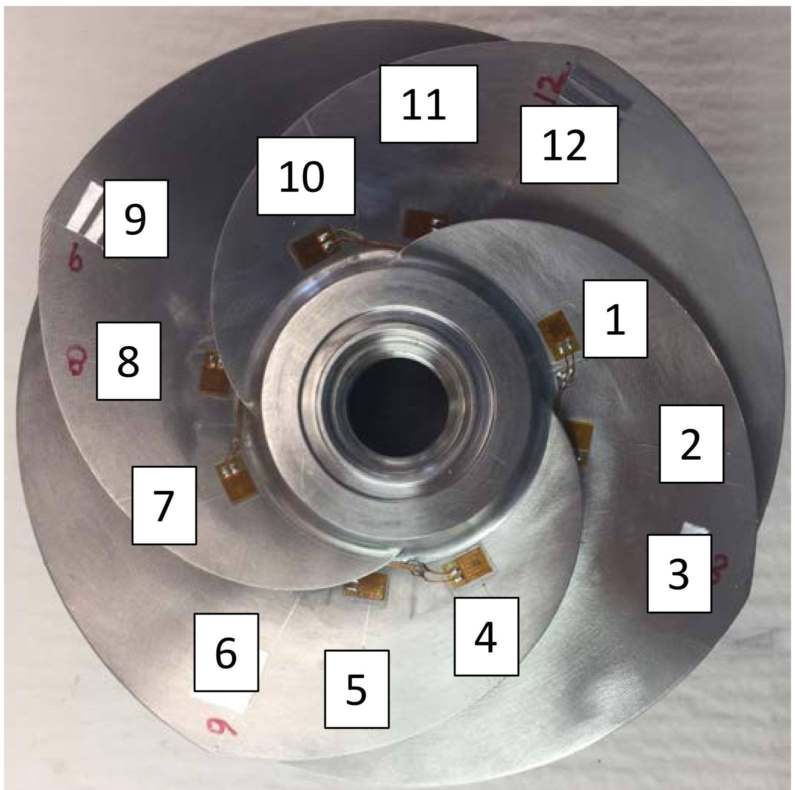
ω_d: Damped natural frequency

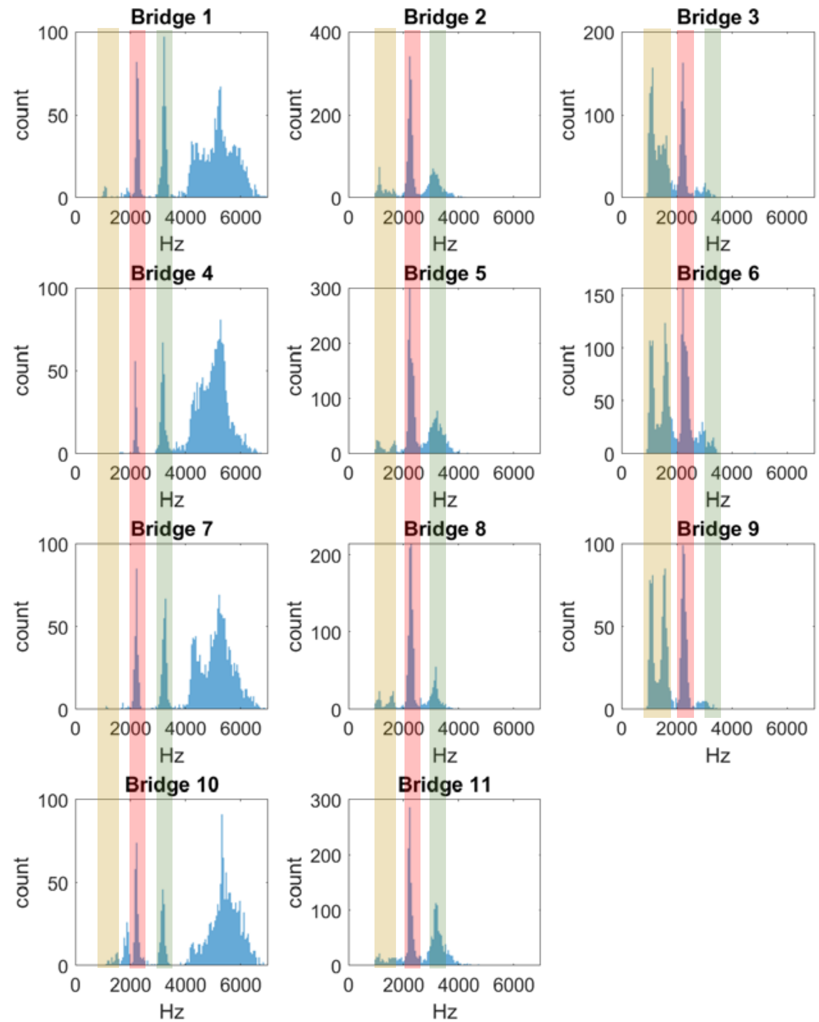
β: Exponential decay rate of amplitude envelope



Ping Test Results

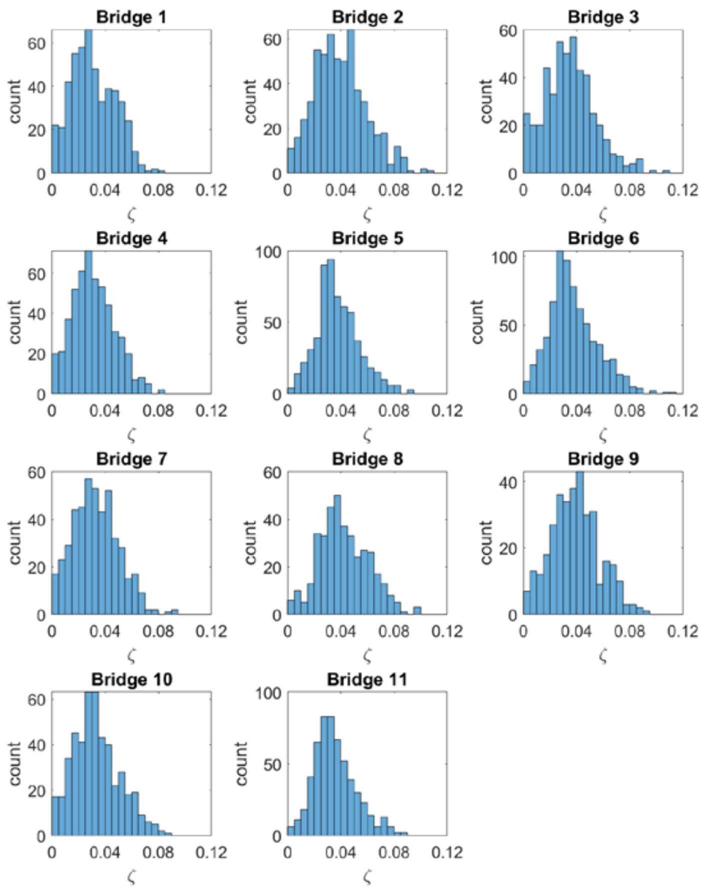
Histograms show the frequency distribution of the highest amplitude responses over many pings



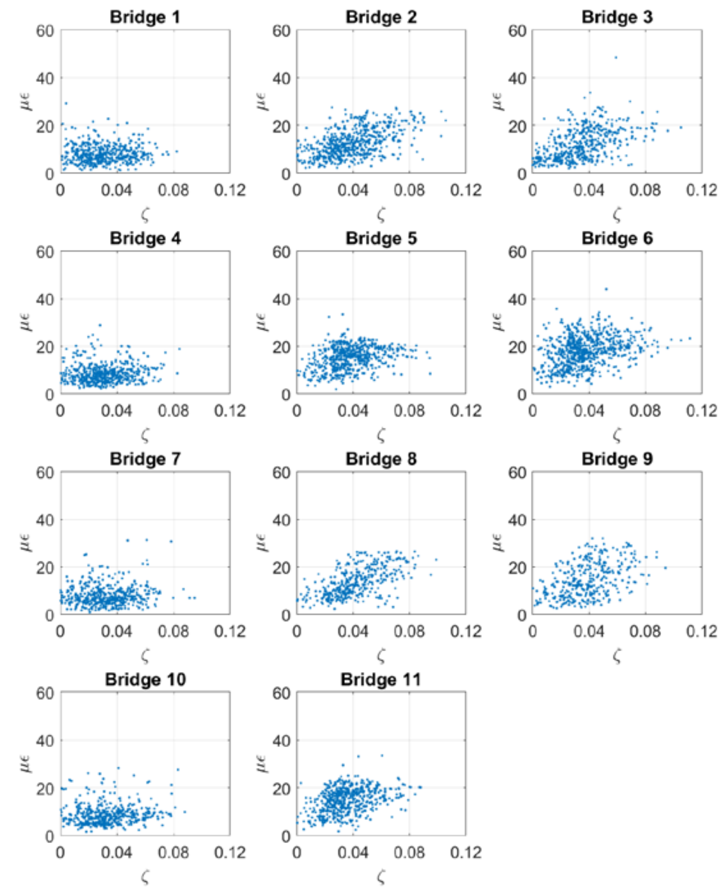


Ping Test Results

Damping histogram for ~2 kHz response

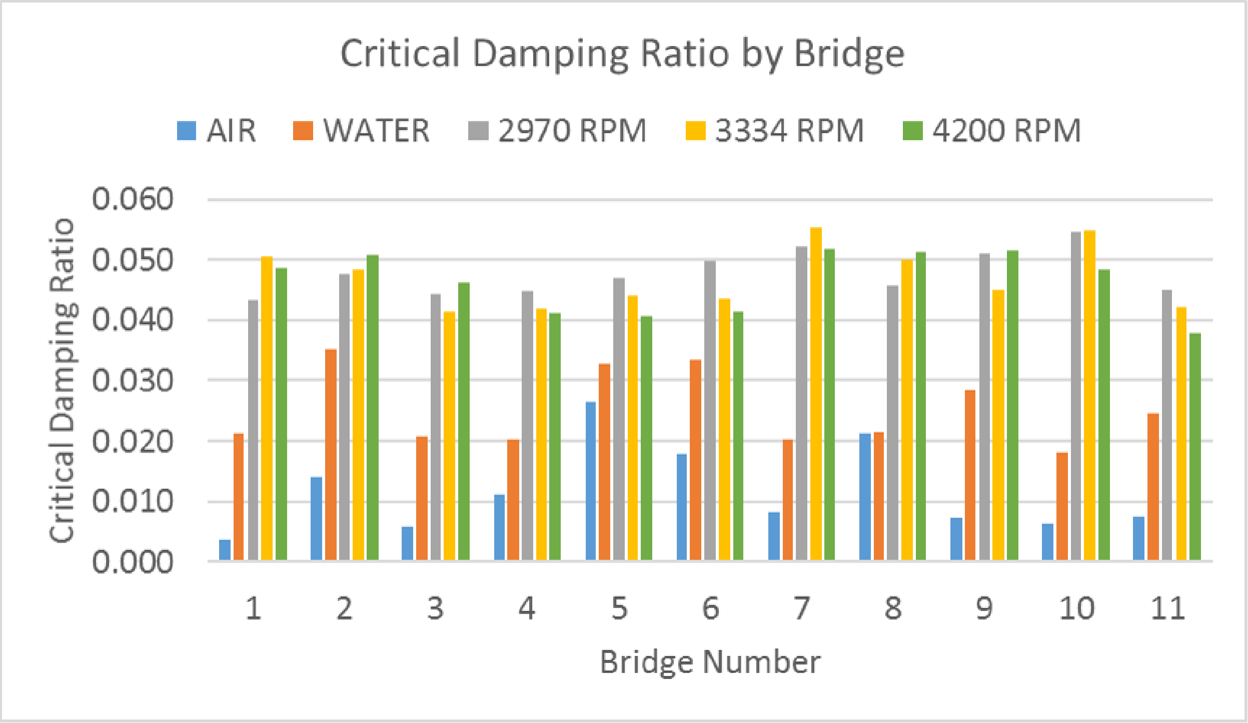


Peak strain vs damping ratio for ~2 kHz response



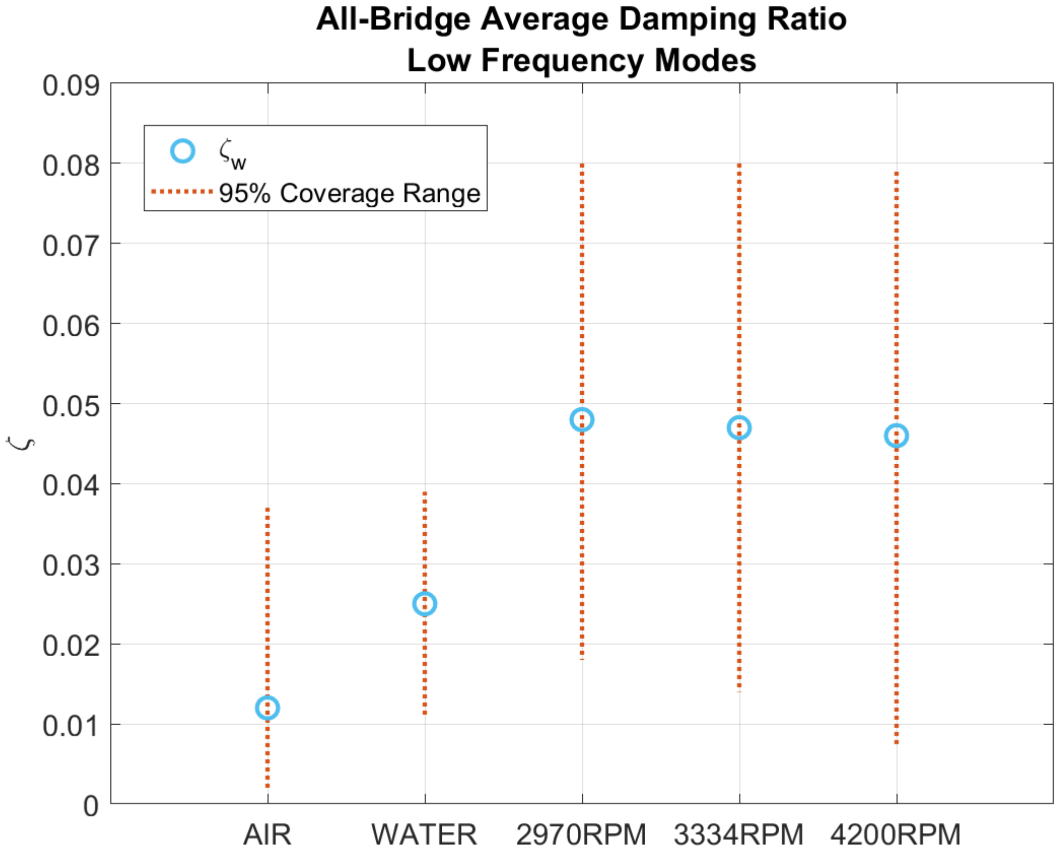
Ping Test Results

Average critical damping ratio for various conditions



Ping Test Results

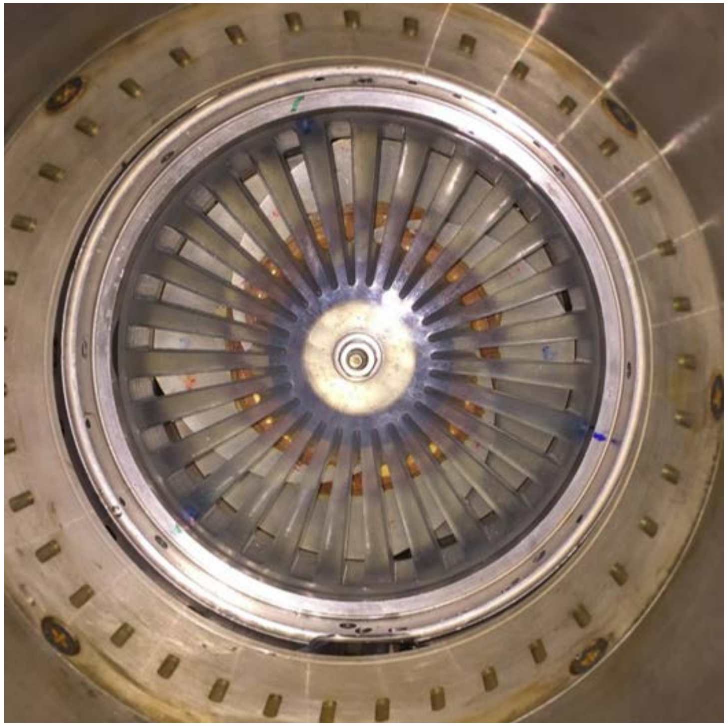
Ping test data show quite a bit of variation over many pings



Excitation Method: Stator Plate

Given facility speed limits, the 26th harmonic of shaft speed (27N) crosses the fundamental blade modes. Two stator plate designs were tested

9-Vane

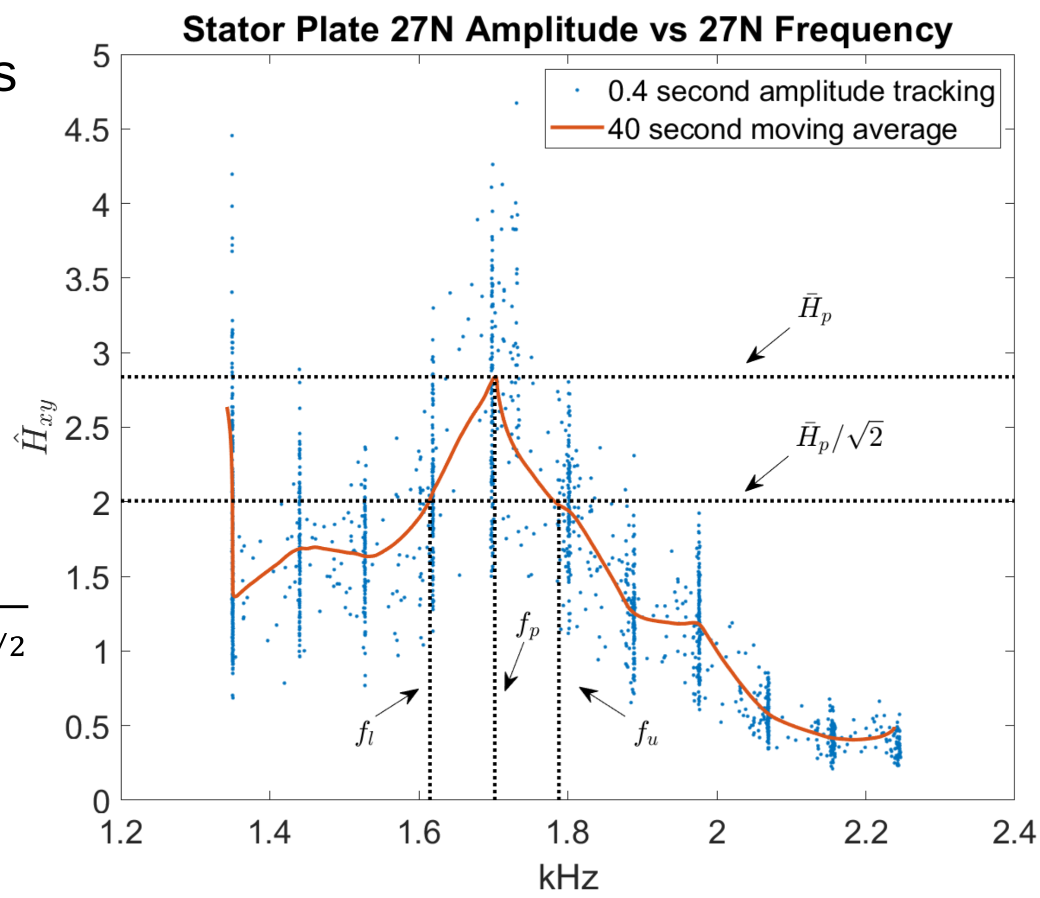


27-Vane

Stator Plate Data Analysis

- Dwell at a series of frequencies around the natural frequency
- Compute the frequency response function using strain amplitude measured at 27N
- Apply half quadratic gain formula to estimate damping

$$\zeta = \sqrt{\frac{1}{2} - \left(4 + 4\left(\frac{f_u - f_l}{f_p}\right)^2 - \left(\frac{f_u - f_l}{f_p}\right)^4\right)^{-1/2}}$$

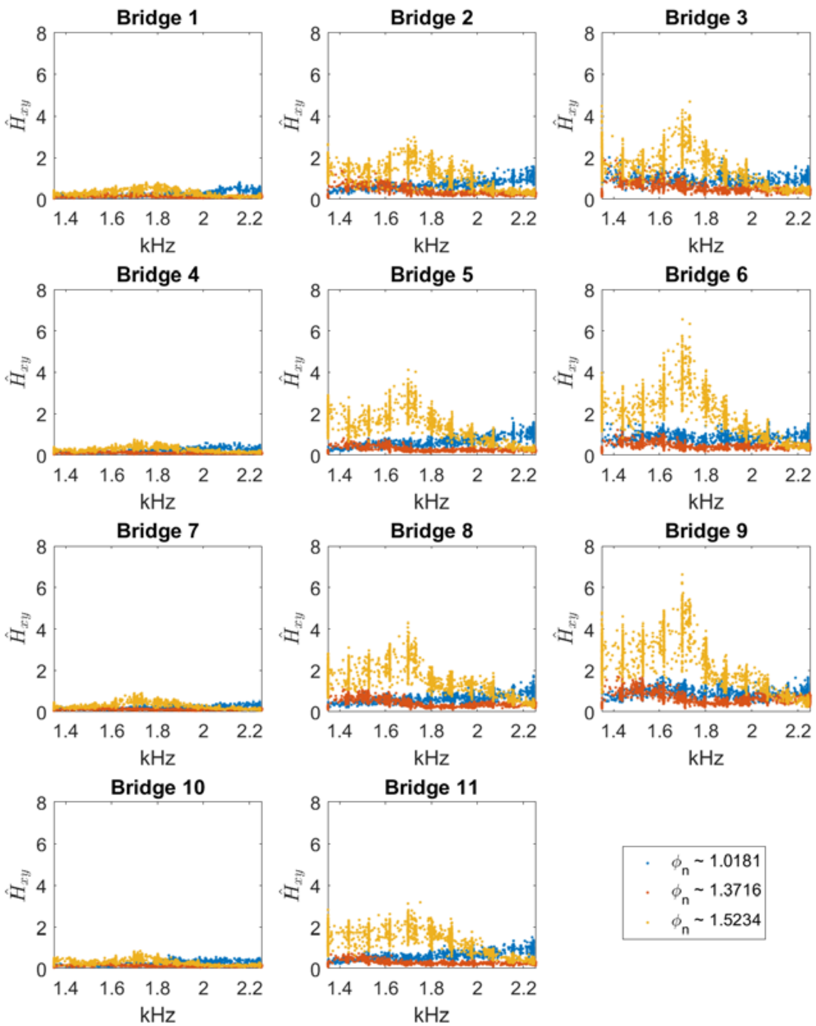


Stator Plate Testing

Both stator plates did appear to generate a forcing function at 27N, with some caveats:

1) Response was noted only at very high (off-design) flow coefficients
2) The middle and downstream gauge locations responded more than the upstream location
3) Response is only at ~1.5-1.7 kHz

Configuration	f_p	ζ
-	Hz	-
9 vane far	1703	0.078
27 vane constant flow	1600	0.055
27 vane boustrophedonic	1551	0.055



Damping Summary

- On average, results showed blade critical damping ratios of 4-7% when operating in realistic conditions
- There was significant variation in damping estimates
- Different excitation methods resulted in different frequencies responding
- Damping increased from air to still water, and again from quiescent to spinning
- Damping had moderate correlation with response amplitude
- Damping had no significant correlation with cavitation number or flow coefficient (?!?)

Acknowledgements

This test effort was sponsored by the SLS Liquid Engine Project Office at Marshall Spaceflight Center

MSFC Test Branch ET20 operated the facility and provided/installed instrumentation

MSFC Fluid Dynamics Branch ER42 designed strain gauge circuitry, generated requirements, conducted test and data acquisition, and performed data reduction/analysis

BACKUP

Critical Damping Ratio Analysis

Identify blade natural frequencies

Ping Test

- Filter data around natural frequency
- Compute amplitude envelope of blade response
- Compute critical damping with impulse response formula

Stator Test

- Sweep shaft speed
- Track strain response at 27N
- Compute pseudo-frequency response function with half-quadratic gain formula

Ping Data Analysis

Single degree of freedom impulse response

$$\mu(t) = Ae^{-\zeta\omega_n t}\cos(\omega_d t + \phi)$$

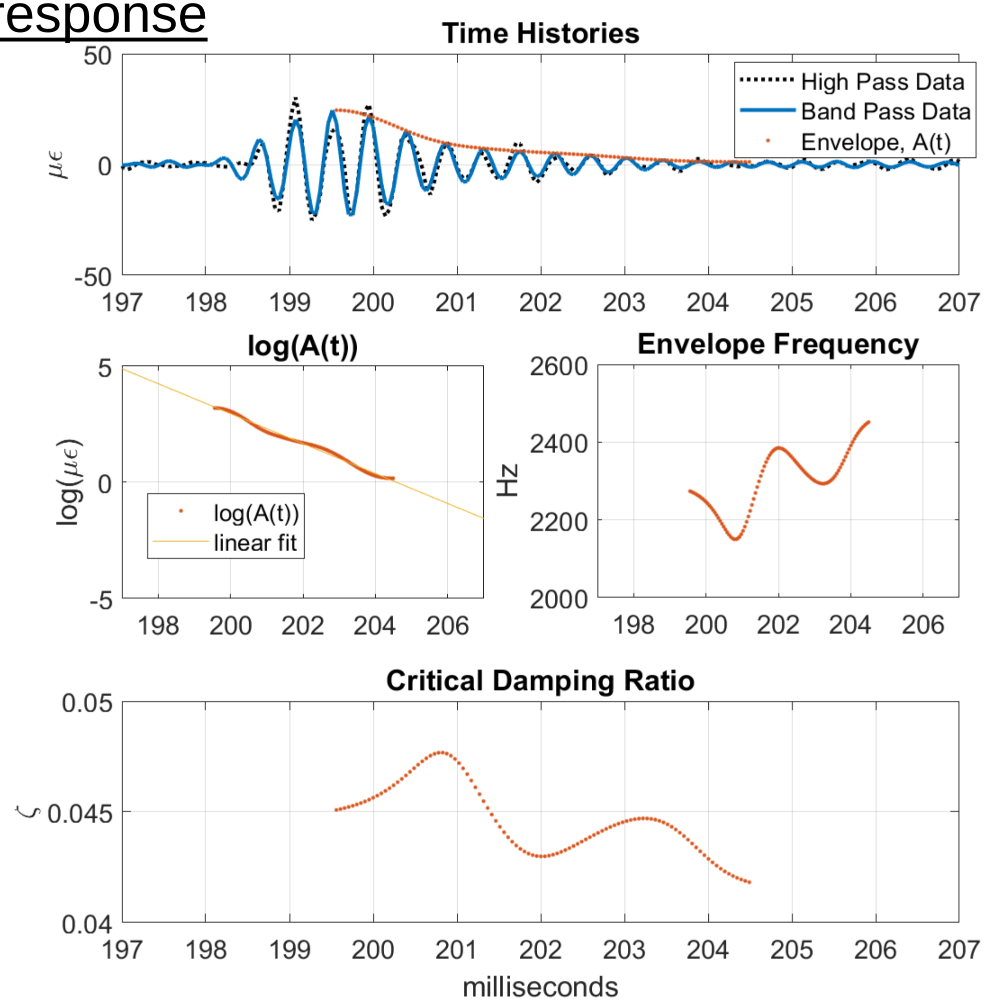
$$\omega_d = \omega_n\sqrt{1-\zeta^2}$$

Amplitude envelope

$$X(t) = Ae^{-\zeta\omega_n t} = Ae^{-\left(\frac{\omega_d\zeta}{\sqrt{1-\zeta^2}}\right)t} = Ae^{-\beta t}$$

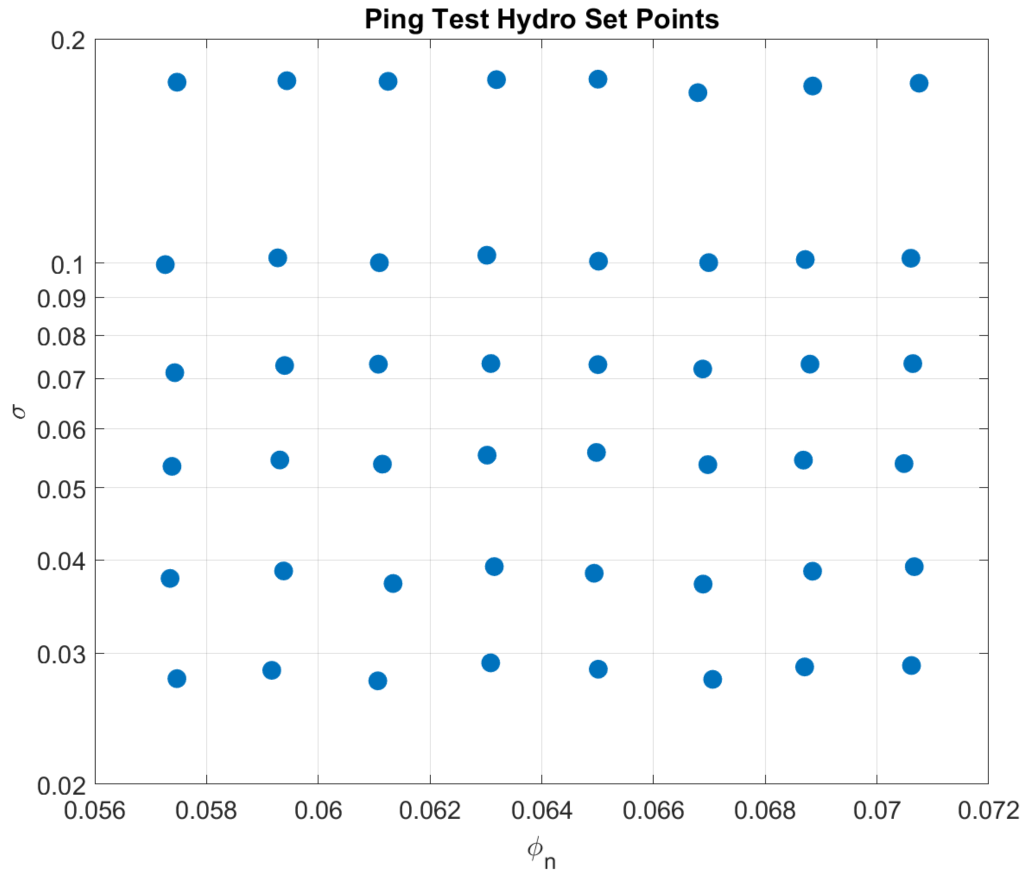
$$\log\big(X(t)\big) = \log(A) - \beta t$$

$$\zeta = \frac{1}{\sqrt{1+\left(\frac{\omega_d}{\beta}\right)^2}}$$



Ping Hydro Set Points

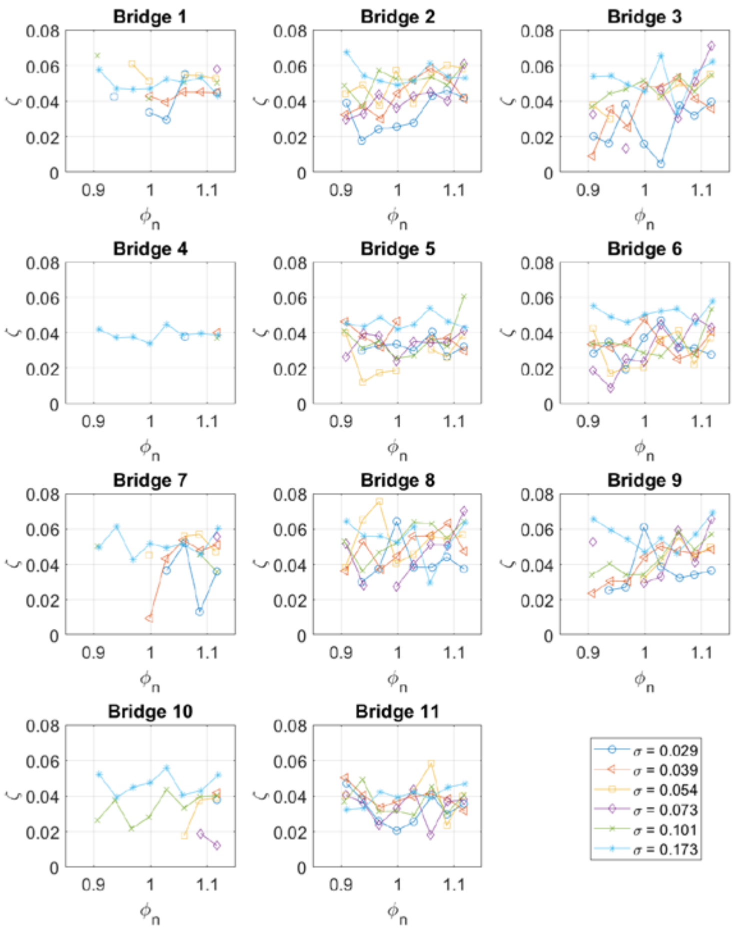
Non-cav to approaching breakdown



~90-110% rated flow

Damping vs Hydro Conditions

Damping vs Flow Coeff



Damping vs Cav Number