Natural Frequency Testing and Model Correlation of Rocket Engine Structures in Liquid Hydrogen – Phase I, Cantilever Beam

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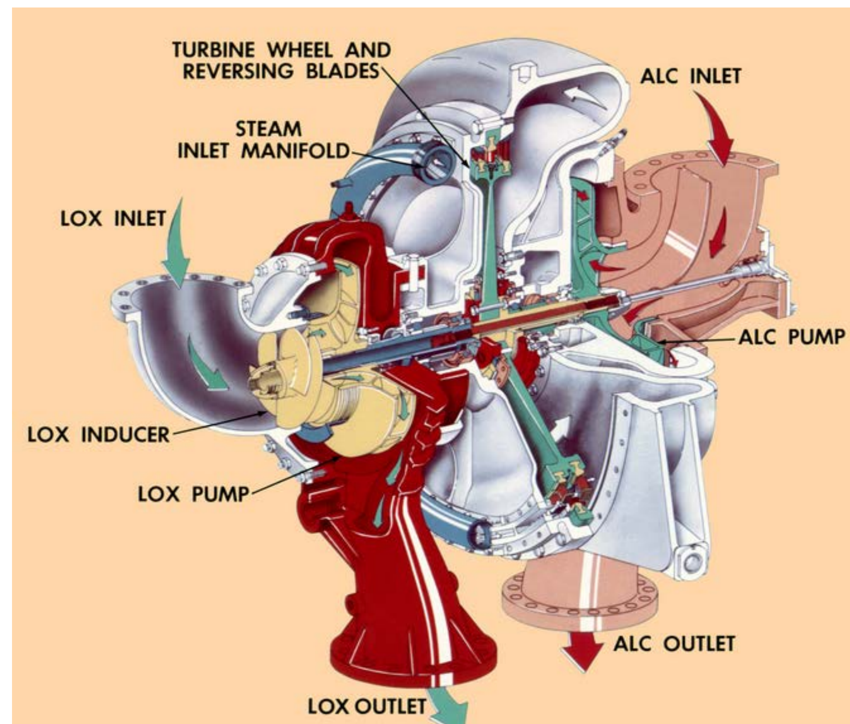
Background & Introduction

- Liquid Rocket Engines generally require turbopumps to provide necessary pressure head to fuel and oxidizer propellants.
- Distortions, other Unsteadiness in Fluid flow field generate Harmonic, Narrow-Band Excitation onto all Structural Components in Flow Path, requiring Structural Dynamic Analysis to assess response for both HCF and Ultimate Failure.
- For Pump-Side Components (Inducers and Impellers), several major complications:
  1. Structural Components immersed in liquid propellant, which alters not only natural frequencies {f}, but also modes
  2. Propellant, and therefore components, are frequently Cryogenic, which has a very significant effect on Young's Modulus, and therefore {f}.
  3. Components operate with a tight tip clearance, which alters mass affects.

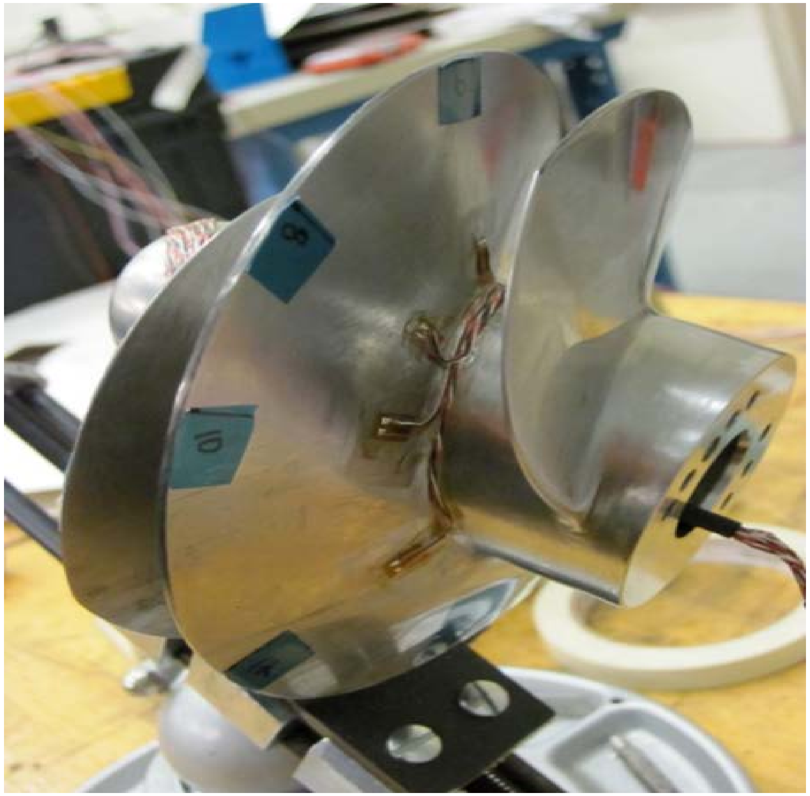
Typical Turbopump



Testing of J-2X Inducers

- During design of J-2X engine 2006-2012, issue became very important as Liquid Oxygen Inducer predicted to operate at resonance with Higher-Order Cavitation excitation driver.
- Extensive Test/Analysis Program performed to assess risk, including high speed water-flow testing and modal testing in water.
- Same issue now has arisen for implementation of the Space Shuttle Main Engine (now called RS-25) in the new operating conditions of the Space Launch System for the low pressure hydrogen turbopump (LPFP) inducer.

J-2X Subscale Inducer, Not to Scale



1^{st} of 2-Phase Program

- New integrated test/analysis program has been initiated to address risk in comprehensive manner, including
  - Updated waterflow test
  - Hydroelastic analysis and testing
  - Acoustic modeling
  - Natural frequency testing of sub-scale water-flow test inducer in LH2 using unique facilities of MSFC's Cryogenic Test Laboratory.
- 2-Phase LH2 Modal Test Program to Enable Dynamic Model Correlation:
  1) Cantilever Beam
     - Same Titanium alloy as RS-25 Inducer.
     - Simple geometry allows high-fidelity, accurate modeling & comparison to academic methods for precise correlation.
     - Since test in LH2, only {f}, not [Φ], will change, so only pluck test necessary, not complete modal test.
     - Can apply lessons learned to inducer testing.
  2) Sub-Scale Stainless Steel Inducer that will be used in Water-Flow Test.
- Authors have not found documentation of modal testing in LH2 of any kind in the literature.

Literature Survey

- A number of publically available sources provide data relating E of Titanium alloy at cryogenic temperatures, as well as several proprietary sources.

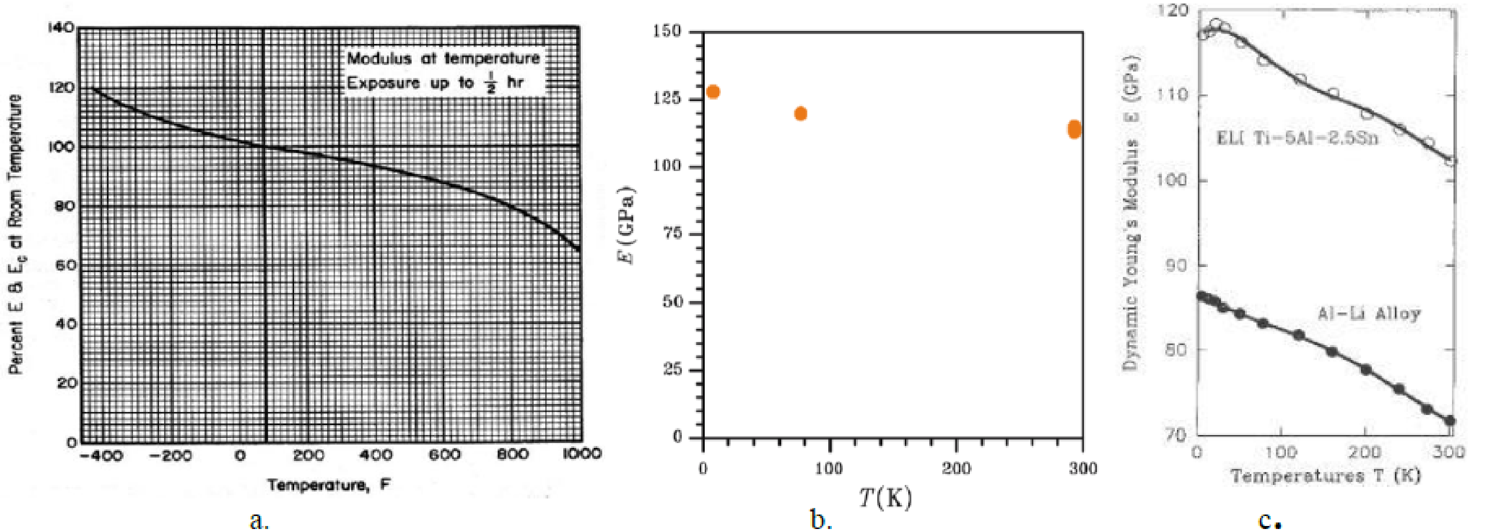


Fig. 2 Public Data Relating Young's Modulus of Ti 5-2.5 to Temperature; a) MMPDS, b) Ghisi & Mariani, c) Zhang

- Great deal of both analytical and numerical work on effect of liquid mass on {f}.
- Lindholm (1965) provided excellent baseline experimental work, generating expression for added mass and final frequency

$$A_{m1} = \tfrac{\pi}{4}\rho_f a b^2 \qquad \frac{\omega_f}{\omega_v} = \frac{1}{\sqrt{1+\frac{A_{m1}}{m_b}}}$$

- Liang provided a factor accounting for aspect ratio and for different cant beam mode families

$$A_{m1} = 0.25 C_f \frac{\pi \rho_f b}{\rho_p h_p} \qquad C_f = \frac{2 * aspect\_ratio}{1 + 2 * aspect\_ratio} \qquad \omega_f = \omega_v \sqrt{\frac{1}{1+\frac{A_{m1}}{C_f}}} \ .$$

Test Procedure

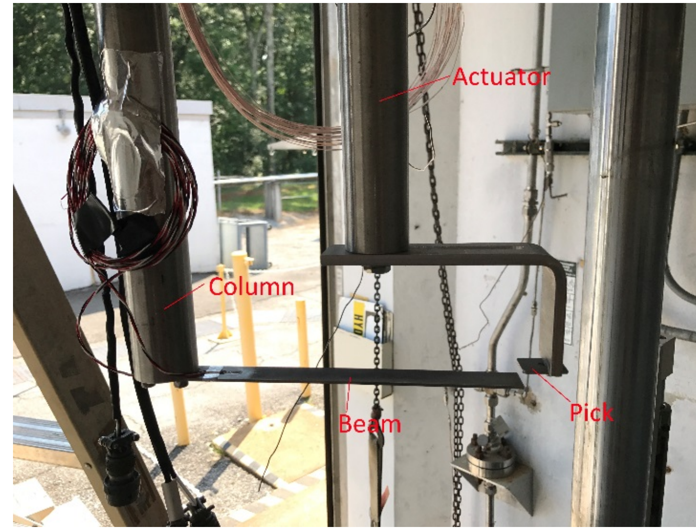
- To quantify the decrement of structural natural frequencies in LH2 (mass loading effects) and isolate the effect of temperature (material property effects) on the structural natural frequencies, following plan developed.

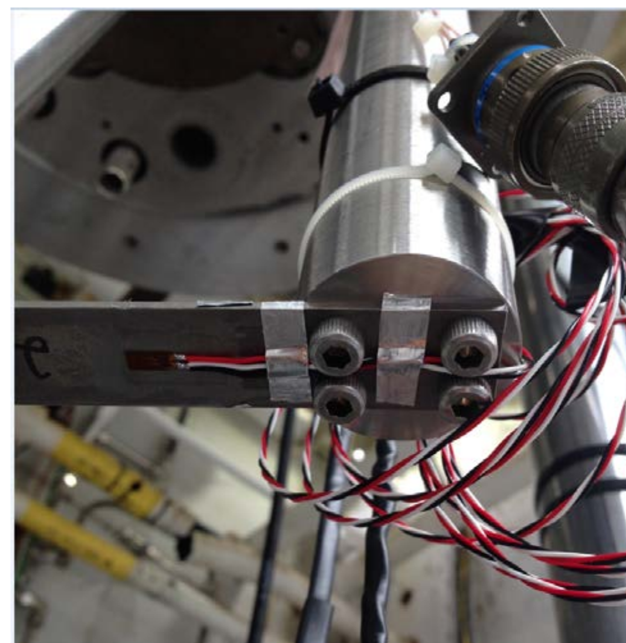
  1. Ping test in air at room temperature (RT).
  2. Fill Cryostat with LH2.
  3. Ping test in LH2 (-423°F).
  4. Quickly displace LH2 with Helium, ping test in this "Boil-off" configuration (slightly higher temp than LH2).
  5. Allow to slowly warm up to RT, fill tank with water, ping test.

Cantilever Beam Test in Cryogenic Test Facility

Facility in operation

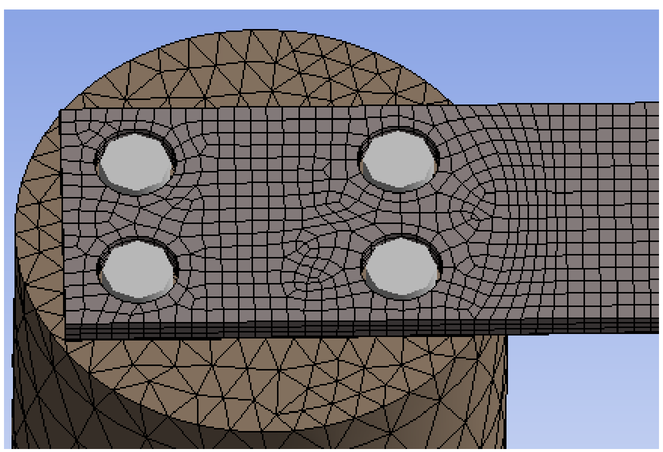
- Innovative test apparatus design provides excellent excitation of close-to-fixed-end beam.
- 4 thermocouples in Cryostat.
- Strain Gages on top and bottom of beam at peak strain location to provide time histories → natural frequencies

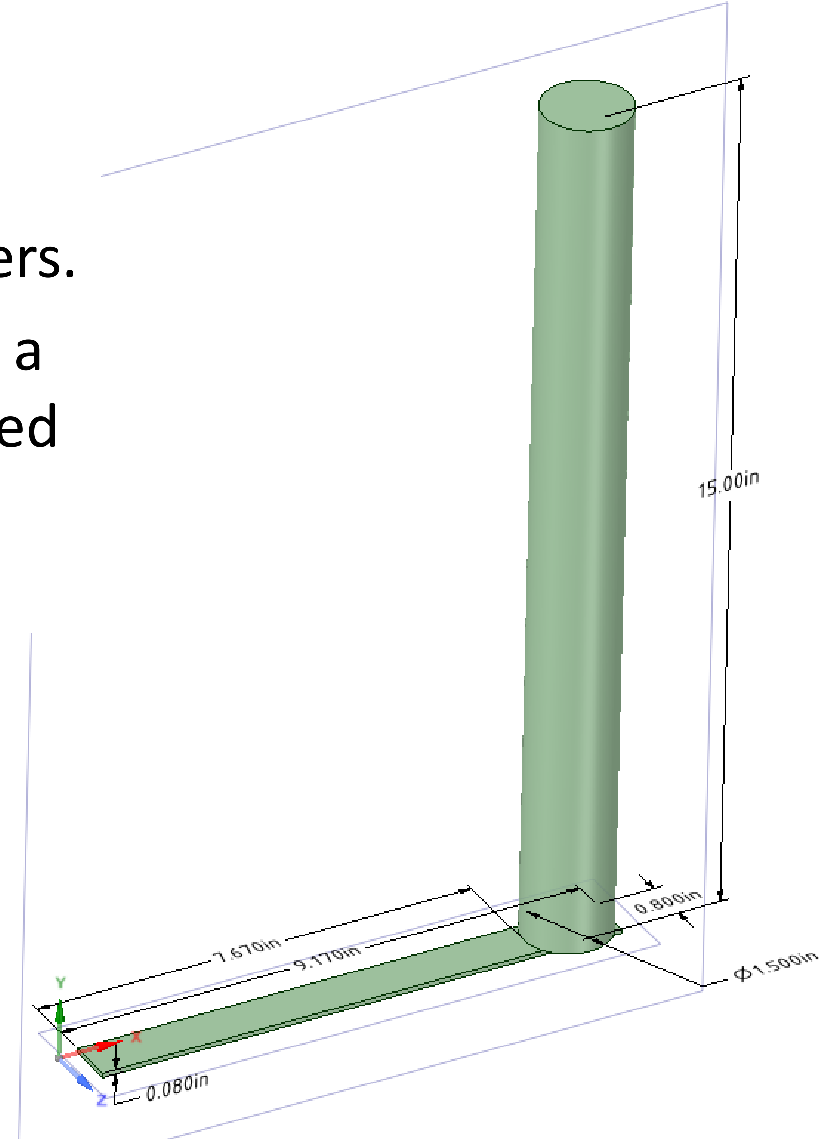




Geometry & Model (With Reaction Column)

- Volume, weight of beam precisely measured to get density.
- The beam and Reaction Member Column are connected by four fasteners.
  - This interface initially modeled as a bonded contact, then as pre-loaded bolts to reduce uncertainties as much as possible.

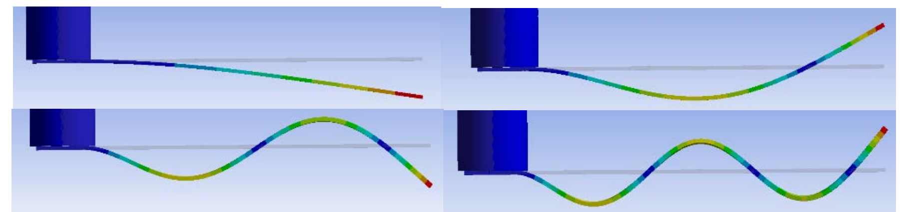




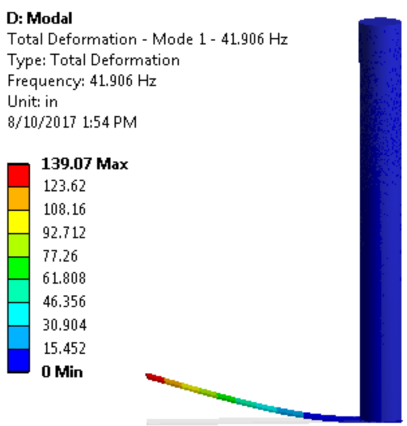
Pre-Test Analysis, Measurement of Actual Configuration

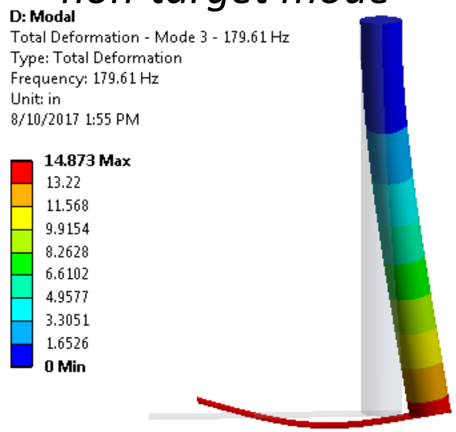
- Pre-test numerical (ANSYS) analysis showed target "primary" cantilever modes have almost no column content, but columns was eventually modelled to eliminate uncertainty.

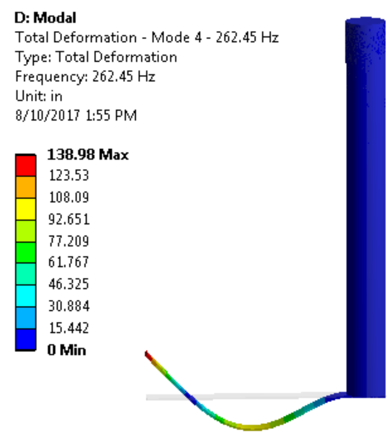
Target "Cantilever" Modes



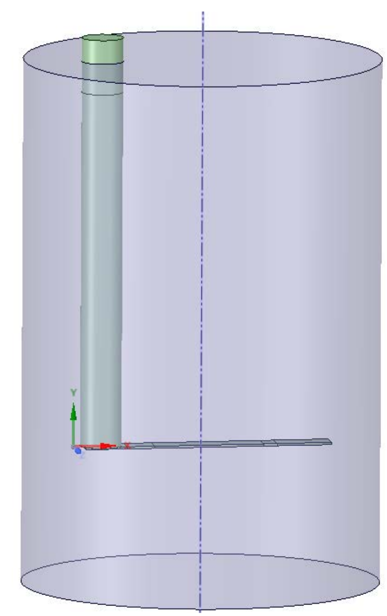
Column Motion in non-target mode







- ANSYS Acoustic Fluid Volume created using Cryostat dimensions



Correlation Procedure

1. Vary room temperature (RT) Young's Modulus to best match 4 measured natural frequencies, → 4 new calculated frequencies.
2. If the resulting RT Modulus is within the expected range
   a) Apply ANSYS acoustics to determine predictions for frequencies in water and compare to measured frequencies.
   b) Repeat for the Boil-off case.
3. If optimized Modulus at Boil-off conditions is within the spread of available data. If so, extrapolate to LH2 temperature and calculate the natural frequencies using ANSYS and compare to measured frequencies.
4. Apply purely analytical techniques developed by Lindholm and Liang to obtain frequency predictions, compare with ANSYS.

Testing and Results

- Testing performed August, 2017; thermocouple data not considered precise (apparent 13°F error), and strain gages not entirely steady in water. Otherwise, data good.
- Step-by-step correlation procedure isolating effects of temperature and added-mass generated excellent results; frequency errors < 1% for all cases
- ANSYS Acoustic elements validated for use in predicting fluid added-mass effect.

Table 1 Modal Test and Analysis Summary

Air RT					Boil-off and LH2 Temperature		
Mode (Test Order)	Test (Hz)	ANSYS FEM Opt-imized E	% Error		Test (Hz)	ANSYS FEM Optimized E (Hz)	% Error
1	43.00	42.88	-0.28%		45.00	42.88	-.28%
2	270.00	270.00	-0.00%		283.00	282.33	-0.24%
3	756.25	758.5	0.30%		792.25	793.08	0.10%
4	1481.25	1488.10	0.46%		1553.00	1555.90	0.19%
Optimized E	*1.7957E+07*				*Optimized E*	*1.96237E+07*	

Water RT				Added Mass Frequency Factors				LH2			Added Mass Frequency Factors			
Mode (Test Order)	Test (Hz)	ANSYS Acoustic FEM	% Error	Test	ANSYS	Lind-holm	Liang	Test (hz)	ANSYS Acoustic FEM (Hz)	% Error	Test	ANSYS	Lind-holm	Liang
1	25.25	25.46	0.82%	0.587	0.594			42.50	42.12	-0.89%	0.944	0.939		
2	161.75	160.30	-0.90%	0.599	0.594			267.50	265.37	-0.80%	0.945	0.940		
3	459.75	459.49	-0.06%	0.608	0.606			750.75	747.48	-0.44%	0.948	0.943		
4	911.00	918.34	0.81%	0.615	0.617			1475.0	1471.50	-0.24%	0.950	0.946		
				0.602	0.603	0.622	0.597				0.947	0.942	0.948	0.941

Conclusion and Follow-On Work

- Well-controlled test and correlation effort on effect on natural frequency of structures in Liquid Hydrogen performed.
- Excellent agreement between test and analysis obtained
  - Provides improved confidence in Titanium E vs Temp curves at cryogenic .
  - ANSYS acoustic modeling validated for this application.
- Data can now be applied to RS-25 program, and experience applied to Phase II of test on RS-25 Inducer.
- Other follow-on testing plans on the cantilever beam include
  - Place plates along sides of beam to examine effects of tight tip clearance.
  - Perform test in Liquid Nitrogen to generate another data point at a well-defined temperature.
  - Increase surface pressure to reduce possible bubbles around inducer.