Test-Analysis Modal Correlation of Rocket Engine Structures in Liquid Hydrogen - Phase II

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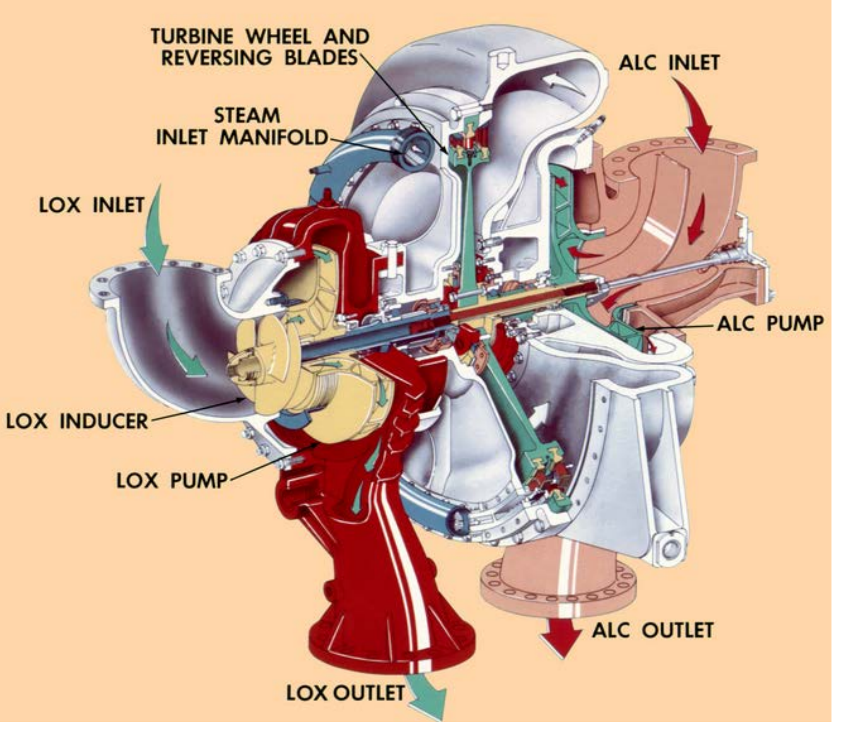
Background & Introduction

- Liquid rocket engines generally require turbopumps to provide necessary pressure head to fuel and oxidizer propellants.
- Distortions, cavitation, & other unsteadiness in fluid flow field generate harmonic and narrow-band excitation onto all flow path structural components
  - Structural Dynamic Analysis required to assess response for both High Cycle Fatigue and Ultimate Failure.
- Many uncertainties in natural frequencies of Pump-Side Components (Inducers and Impellers) including effects of:
  1. Young's Modulus during operation in cryogenic propellant (-423°F);
  2. Fluid-added mass;
  3. Components operate with a tight tip clearance, which alters mass affects;
  4. Compressibility/interaction with acoustic modes.
- Inability to measure natural frequencies during operation requires verified analytical capabilities

Typical Turbopump



Motivation

- Inducer in Low Pressure Fuel (Liquid Hydrogen, LH2) Pump in RS25 Engine for Space Launch System (SLS) predicted to operate at resonance with Higher-Order Cavitation (HOC) excitation driver.
- RS25 essentially same engine as well-tested Space Shuttle Main Engine, but operational conditions puts HOC more into range.
- Extensive response analysis performed, but due to uncertainties, analysis predicted failure even for SSME operation, which was clearly not accurate.
- Empirical, non-physics-based damage-fraction analysis therefore performed based upon one of the tested units, and acceptance criteria stemming from this analysis were imposed upon the inducer and the operation of the turbopump.
- Some of resulting speed and operational restrictions are quite undesirable, though, and possibly could be severe if testing shows the magnitude of HOC are greater than expected.

Comprehensive Inducer Test/Analysis Program

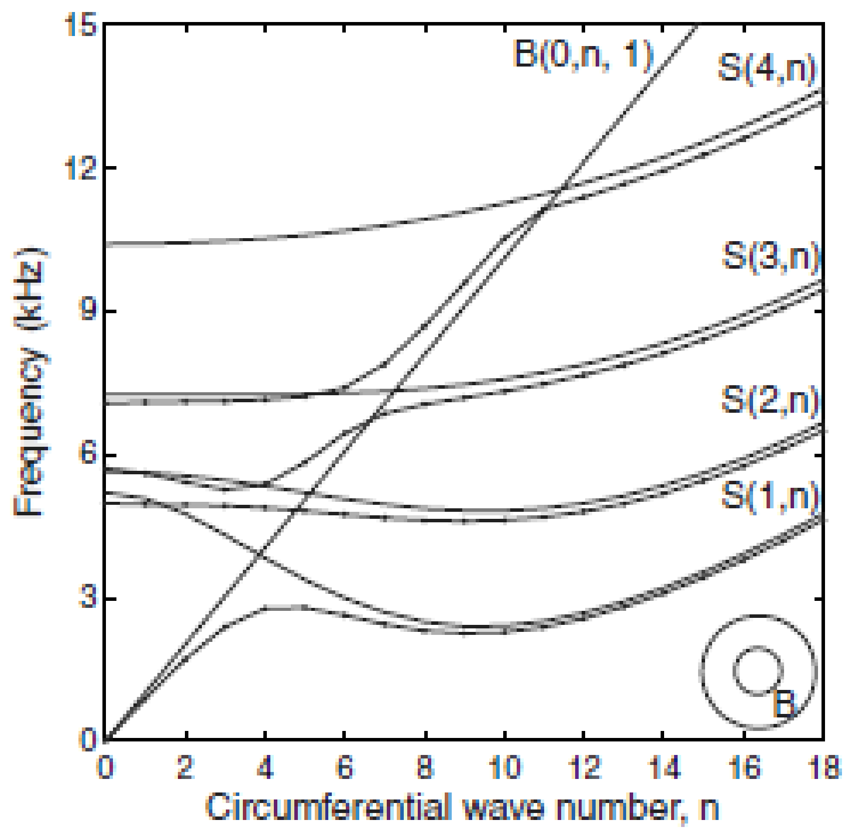
- Team is completing integrated test/analysis program to quantify uncertainties.
- Natural frequency testing of sub-scale water-flow test inducer in LH2 using unique facilities of MSFC's Cryogenic Test Laboratory.
- Phase I completed 2017
  - Cantilever Beam
  - Same Titanium alloy as RS-25 Inducer.
  - Simple geometry allowed high-fidelity, accurate modeling & comparison to academic methods for precise correlation.
- Phase II-A test completed 2018, analysis 2019-2020.
  - Cantilever beam with walls close to longitudinal edges to match experiment in literature.
  - Sub-Scale Stainless Steel Inducer in water with "medium" tight tip clearance.
  - Sub-Scale Stainless Steel Inducer in LH2, without tight tip clearance.
- Test of Inducer in LH2 with tight tip clearance in planning stages.
- Authors have not found any documentation of modal testing in LH2 in the literature.

Effects of Tight Tip Clearance in Literature

- Some useful background work published by Harrison ('07) using micro-cantilever beams, and analytical techniques by Green & Sader ('97).
- Most important publication used here is Xiu & Davis '18.
  - Analytical technique and experiment conducted on beams fixed on both short and long sides, with varying clearance from a wall along long edge.
  - Fixed along longitudinal wall is analogous to inducer blade.
  - Results include detailed curves of fluid-added mass as a function of a non-dimensionalized boundary distance.
  - Although not quite analogous, test at MSFC performed with beam fixed on short edge to provide methodology validation.
- Recently authors discovered comprehensive review by Dehkharquani '18 of significant amount of work in the last 2 years focusing on water turbines, and test/analysis program by DeLaTorre, '16.
  - Will provide validation for this effort.

Effects of Compressibility in Literature

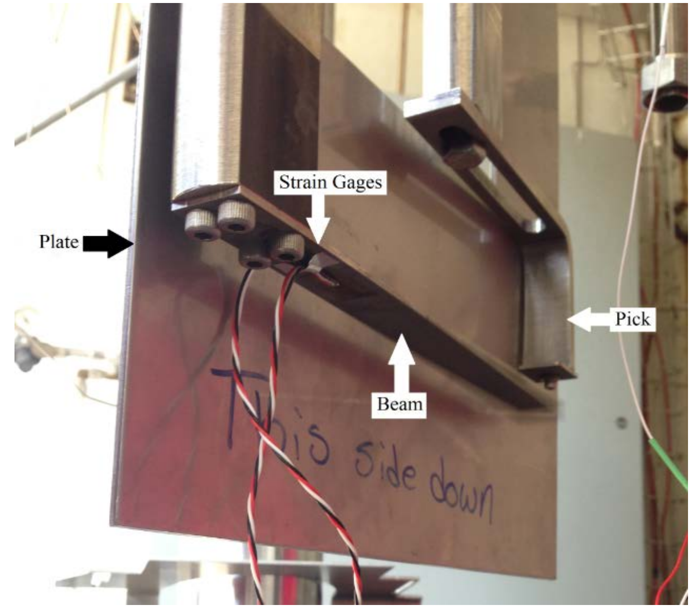
- Davis, et al, ’08, investigated acoustic/structure system modes that exist when acoustic and structure modes of the same nodal diameter also have close the same frequency (eigenvalue veering).
- The independent acoustic and structure modes are replaced by system modes with both structural and acoustic response, and which are below and above the crossing of the structural & acoustic-only lines.
- This means that tracking of modes of interest via both Modal Assurance Criteria and visual animation is critical.



Used by permission, Davis, Virgin, Brown ‘07

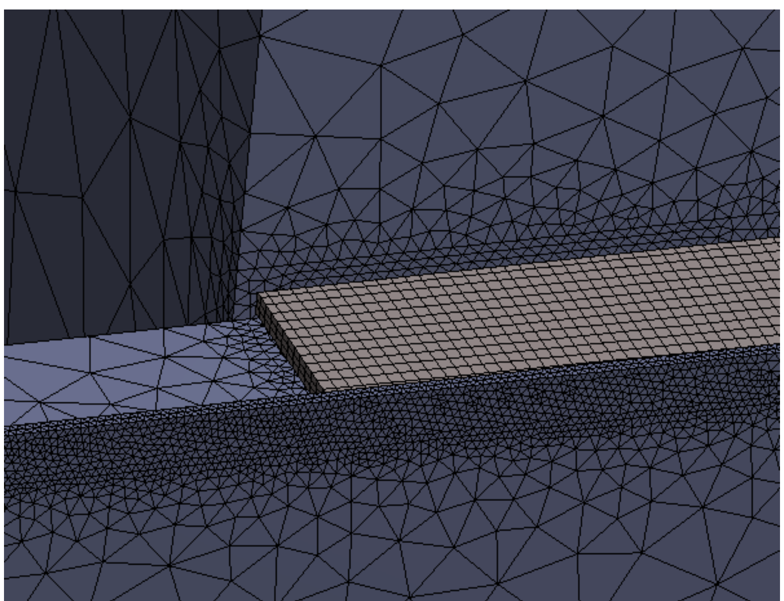
Cantilever Beam Tight Tip-Clearance Modal Test & Analysis

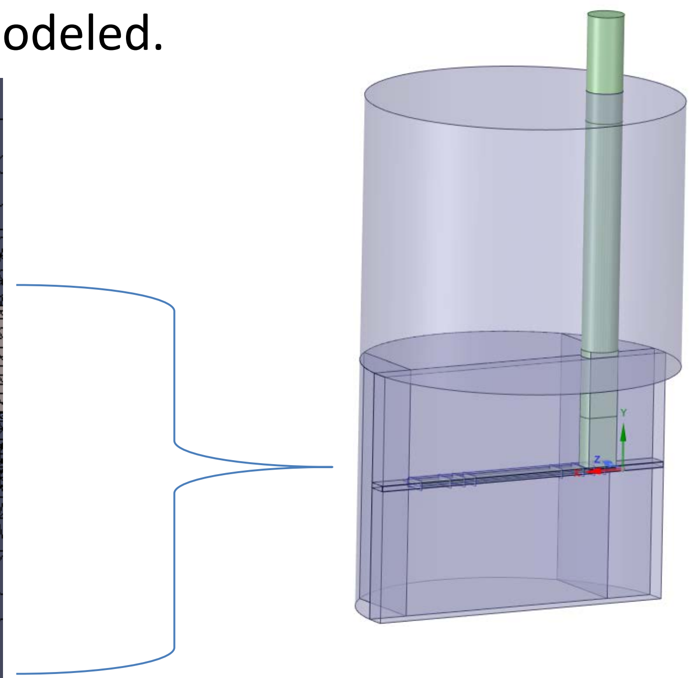
- Phase II-A testing performed to quantify the effect of tight-tip clearance on the fluid-added mass, and in turn the natural frequency
  - Two removable and adjustable side plates added to the cantilever beam ping-test setup described in Phase I.
  - Purpose to validate theoretical predictions and optimize meshing techniques.
- Water, air, and liquid Nitrogen test to provide another temperature data point for the Young's Modulus versus Temperature relationship discussed in Phase I.



Acoustic Modal Analysis of Cant Beam tight clearance

- ANSYS modal acoustic models were generated for the tight clearance test configurations
  - Due to tight fluid clearances surrounding the beam, fluid volumes were sliced as needed to better control mesh densities throughout the volume.
  - General practice was to ensure at least two elements through the tight fluid clearance.
  - Testing included 2 possible clearances (.06” and .02”) on either side, each combination of these modeled.





Tight-Tip-Clearance Cantilever Beam Results

- Focusing on the first cantilever mode since it is most similar to the inducer mode of interest, results are excellent, with the numerical results matching test generally within 3%.
- 2-sided, .020” clearance on each side.

LH2-2S-T Configuration					
Mode (Test Order)	Test (Hz)	ANSYS Acoustic FEM (Hz)	% Error	Clearance Effect	
				Test	ANSYS
1	38.50	39.40	2.34%	-9.41%	-6.46%
2	256.00	250.91	-1.99%	-4.30%	-5.45%
3	726.25	718.42	-1.08%	-3.26%	-3.89%
4	1438.25	1431.20	-0.49%	-2.49%	-2.74%

Sub-Scale Inducer Modal Test/Analysis in Water

- To enable examination of realistic geometry, testing initiated on sub-scale Low Pressure Fuel Pump inducer previously built for water flow testing.
- Problematic mode for RS25 is 2nd in-phase 0 nodal diameter (ND); sequential order within this family refers to number of half-waves along periphery starting at leading edge.
- Inducer glued to a block to exercise the hub flexibility and the block placed on a foam pad to enable well-defined boundary conditions.
- Modal punch device used to apply impact loads to the inducer, Laser Doppler Vibrometer (LDV) to measure response, which was processed to generate natural frequencies and mode shapes.
  - Acrylic strip placed on surface of water to enable smooth optical transition for laser beam.

- Model correlation proved problematic.
- Inducer exhibited mode localization due to mistuning, which made the model correlation difficult.
- Addition of water does appear to tune the system somewhat, which makes sense as the fluid-added mass is entirely symmetric.

Sub-Scale Inducer in Water Modal Correlation Results

- ANSYS modal acoustic models in air and water created.
- Adjustments made to results
  - +9.6% for fillets since they were not included in the acoustic FE model, but based on previous structure-only FE model.
  - -5.3% effect of strain gages and waterproof tape on inducer, which was determined from air modal testing.
- Test/Analysis percent errors less than 5%.

Air Test Mode	Modal Test Result Air (hz)	Water Test Mode	Modal Test Result Water	Large Volume Effect (%)
4	3410.1	1	1735.4	-49.1%
2	3301.6	2	1776.3	-46.2%
1	3268.8	3	1783.8	-45.4%
3	3369.9	4	1859.2	-44.8%
8	3723.7	5	2021.6	-45.7%
5	3664.6	6	2146.9	-41.4%
6	3671.7	7	2153.4	-41.4%
7	3701.4	8	2276.5	-38.5%
10	4137.8	9	2474.7	-40.2%
9	4118.0	10	2691.9	-34.6%

Ansys Model

Modal Test Result

Sub-Scale Inducer Modal Test/Analysis with "Medium" Tight Tip Clearance in Water

- Modal test with cylinder providing 0.035" radial clearance.
- The ANSYS acoustic finite element model compared well to test data.
- For mode of interest, tip clearance effect calculated to be -15.32% from test and -12.85% from analysis. Effect varied between -10% and -21% for all modes.

Test/ Analysis	Media	Strain gages and water-proof tape	Com-press-ibility	Large or Tight (.035") Radial Clearance	Tested Freq. (Hz)	Analytical Freq. (Hz)	Adjusted Analytical Freq. (Hz)	Error from Test	Large Volume only Effect (analysis)	Tip Clear-ance Effect	Com-press-ibility Effect - (analysis)	Total Reduction from Air (test-test; analysis-analysis
Test	Air	**yes**	n/a	Large	**3369.9**							
Test	Air	**no**	n/a	Large	3547.1							
Test	Water	yes	yes	**Large**	**1859.2**							*-44.8%*
Test	Water	yes	yes	**Tight**	**1574.3**					-15.3%		-53.3%
Analysis	Vacuum	n/a	n/a	Large		3232.0	***3371.2***	**0.04%**				
Analysis	Water	n/a	**no**	Large		1721.9	***1796.1***		***-46.7%***			-46.7%
Analysis	Water	n/a	**yes**	Large		1716.4	**1790.3**	**-3.7%**	-46.7%		-0.3%	-46.9%
Analysis	Water	n/a	no	Tight		1500.7	**1565.3**		-46.7%	**12.8%**		-53.6%
Analysis	Water	n/a	yes	tight		1482.1	**1545.9**	**-1.8%**	-46.7%	-12.8%	1.2%	-54.1%

Sub-Scale Inducer Ping Test and Analysis in LH2

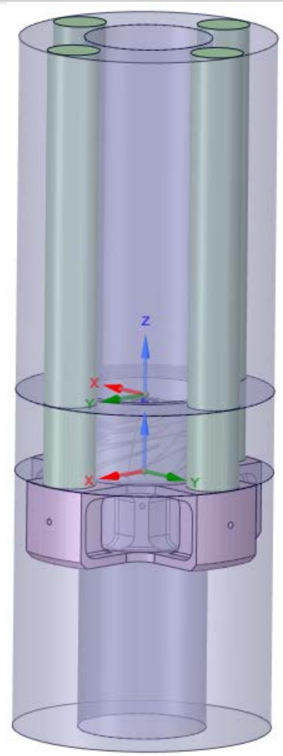
Cryostat opened

- 6 strain gages mounted to inducer.
- Test in air was initially performed to serve as a baseline, followed by the standard test in LH2.
- Test then performed with extra 15 psi of pressurization to qualitatively enable a non-bubbly condition compared to standard configuration.
- LH2 then allowed to boil off and tests performed to give cryogenic and several other cold temperature pings without presence of fluid.
- Test in liquid Nitrogen also performed to provide an additional fluid/temperature data point

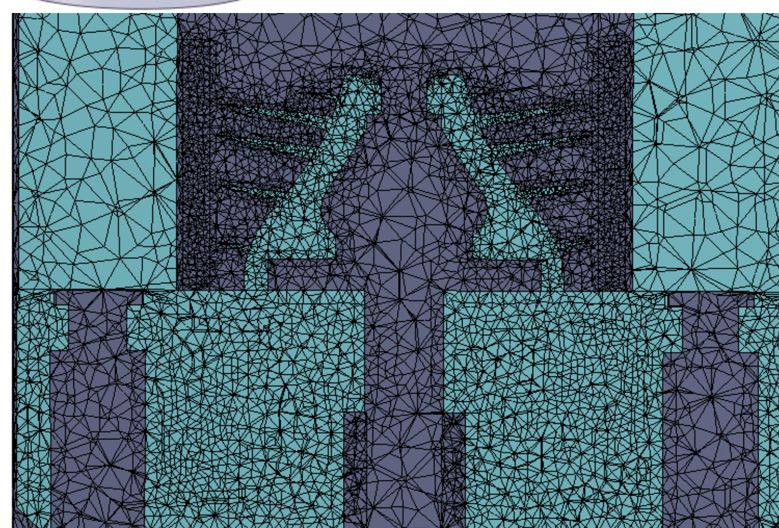
Cryostat Excitation Mechanism

Inducer Ping test in LH2 Modeling, Correlation Procedure

- Strain gage analysis was conducted and modal matches between air and LH2 were made based on the same relative resonant peak location and the same strain gage phasing.
- ANSYS finite element models were constructed for the cryostat air and cryostat LH2 tests, facility star piece and columns included in the model.
- MAC's and judgement required to match modes due to limited gages.
  1. Determine the mode of interest in air in the cryostat.
  2. Select the analytical mode of interest in incompressible LH2.
  3. Select analytical mode of interest in compressible LH2.
  4. Compare ANSYS cryostat compressible LH2 mode of interest to measured modes in LH2 cryostat test.
     - Measured mode of interest in LH2 originally believed to be 3480 Hz, but phase information is not understood and the total reduction from air and estimated reduction from cryo air appears out of family with other matched modes, so 3548 Hz mode tracked instead.



Modeling of entire cryostat found to be necessary for accurate acoustic results.



Results Sub-Scale Inducer in LH2

- Excellent results, analytical predictions of effects from Fluid-added mass validated.

Test/ Anal-ysis	Fluid	Com press ibility	Tested Freq. (Hz)	Adjusted Analytical Freq. (Hz)	Error from Test (%)	Modulus Effect (%)	Fluid-Added Mass Effect (%)	Com-press-ibility Effect (%)	Total Reduc-tion from Air (%)
T	Air	-	3548.0						
T	**LH2**	**-**	**3480.0**						**-1.92%**
A	Vacuum	NO		3468.0	-2.26%				
A	Cryo Vacuum	NO		3554.7		2.50%			
A	LH2	NO		3377.6		2.50%	-4.98%		-2.60%
A	**LH2**	**Yes**		**3367.4**	**-3.23%**	**2.50%**	**-4.98%**	**-0.30%**	**-2.90%**

Combined Effects Extrapolated to Full Scale Inducer

- Ultimate goal of test/analysis program is to ease or eliminate restrictions on full-scale RS-25 Low Pressure Fuel Pump (LPFP) inducer by reducing uncertainty in natural frequency.
- Calibrated modeling techniques applied to full scale inducer.
- Comparisons made with modal test of full scale inducer in air & water performed by contractor.

Test/ Analysis	Media	Temp	Compressibility	Radial Clearance from Blade OD (in)	Error from Test	Modulus Effect	Fluid Added Mass Effect	Compressibility Effect	Tip Clearance Effect	Total Reduction from Air
T	Air	RT	No	large						
T	Water	RT	No	large			-57.5%			-57.5%
A	Vacuum	RT	No	large	1.9%					
A	Water	RT	No	large	0.2%		-58.2%			-58.2%
A	Vacuum	Cryo	No	large		4.6%				
A	LH2	Cryo	No	large		4.6%	-12.8%			-8.9%
A (m1)	LH2	Cryo	Yes	large		4.6%	-12.8%	-4.2%		-12.7%
A (m2)	LH2	Cryo	Yes	large		4.6%	-12.8%	-0.9%		-9.7%
A	LH2	Cryo	No	0.035"		4.6%	-12.8%		-9.9%	-17.9%
A	LH2	Cryo	Yes	0.035"		4.6%	-12.8%	-9.7%	-9.9%	-25.9%
A	LH2	Cryo	No	0.015"		4.6%	-12.8%		-13.2%	-20.9%
A	LH2	Cryo	Yes	0.015"		4.6%	-12.8%	2.5%	-13.2%	-18.9%
A	LH2	Cryo	No	0.005"		4.6%	-12.8%		-17.2%	-24.6%
A	LH2	Cryo	Yes	0.005"		4.6%	-12.8%	2.9%	-17.2%	-22.4%

Conclusions & Future Work

- Integrated Test/Analysis program performed at NASA/MSFC to examine effect of a number of factors complicating natural frequency prediction of LH2 pump structures.
- For mode of interest, natural frequency reduction in tank of water -58%, large volume of LH2 almost -5% , for all measured modes, between 5% and 8%.
- Tip clearance effects measured for cantilever beam and inducer are substantial.
  - For cantilever beam, 1st natural frequency reduced as much as 20% in water and 9% in LH2 with tight clearance on both sides.
  - Tight tip clearance modal test in water for subscale inducer showed natural frequency of mode of interest reduced by 15% and reduction as high as 21% for other modes. Calibrated ANSYS model predicted tip clearance effect to within 2.5% of test results.
  - The analytical trend of results for tip clearance effect were quantified and agree reasonably well with theory (correction from paper). The average tip clearance effect is -11% for the range of tip clearances analyzed for the full scale induce.

- A third phase of inducer testing with a tight tip clearance in LH2 is being considered to further validate analytical capability to predict the tip clearance effect for the inducer.
- Calibrated ANSYS modal acoustic techniques extended to SLS RS-25 LPFP full-scale inducer, effects due to elastic modulus, large volume, tip clearance, and compressibility tracked & quantified separately.
  - These adjustments initially appear to mitigate inducer HOC resonance concerns for SLS.
  - The demonstrated success to model structures in turbopump structures in LH2 with tight clearances will benefit future flight programs and other pump and water turbine industries as well.