Repeated failures on 2nd stage impeller linked to blade natural frequency excitation.

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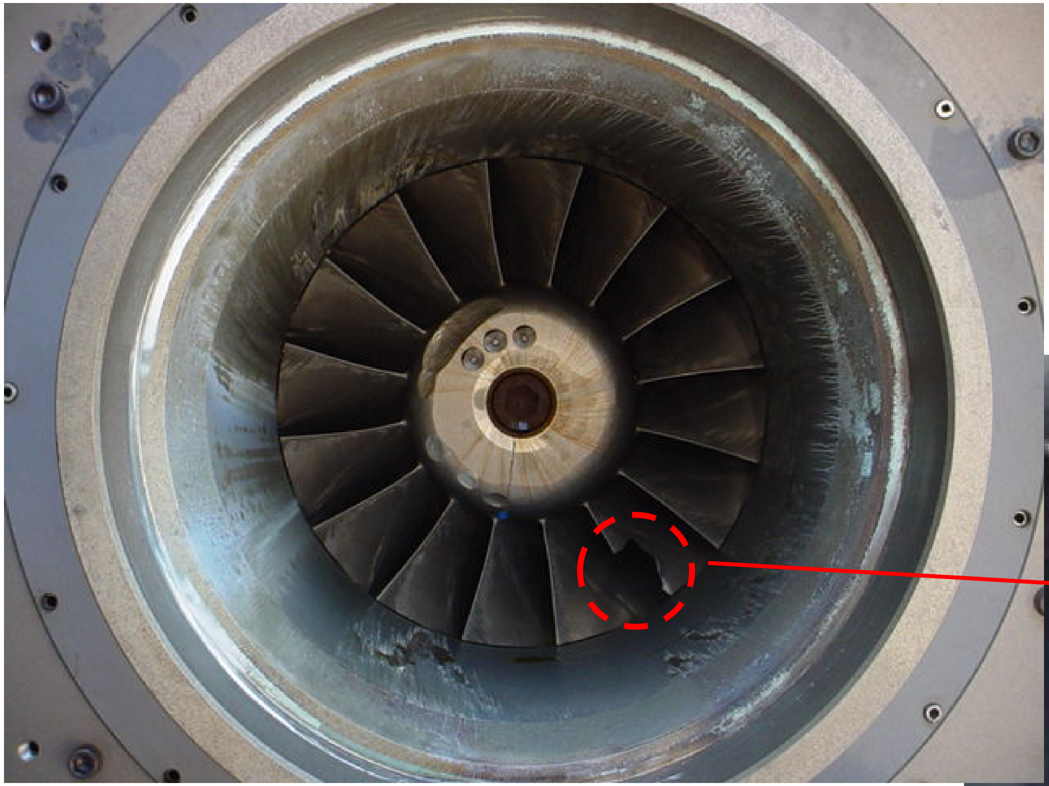
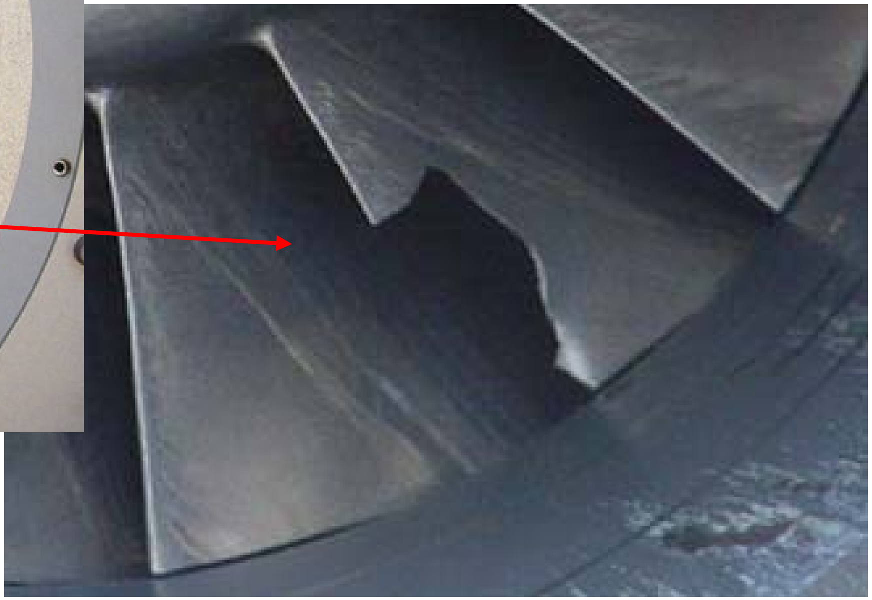
Problem Statement

- Three Stage integrally geared air compressor used for process air.
- Second stage impeller failed after 11 hours of operation.
- The failure occurred after a rebuild for a different failure and there was no spare impeller.

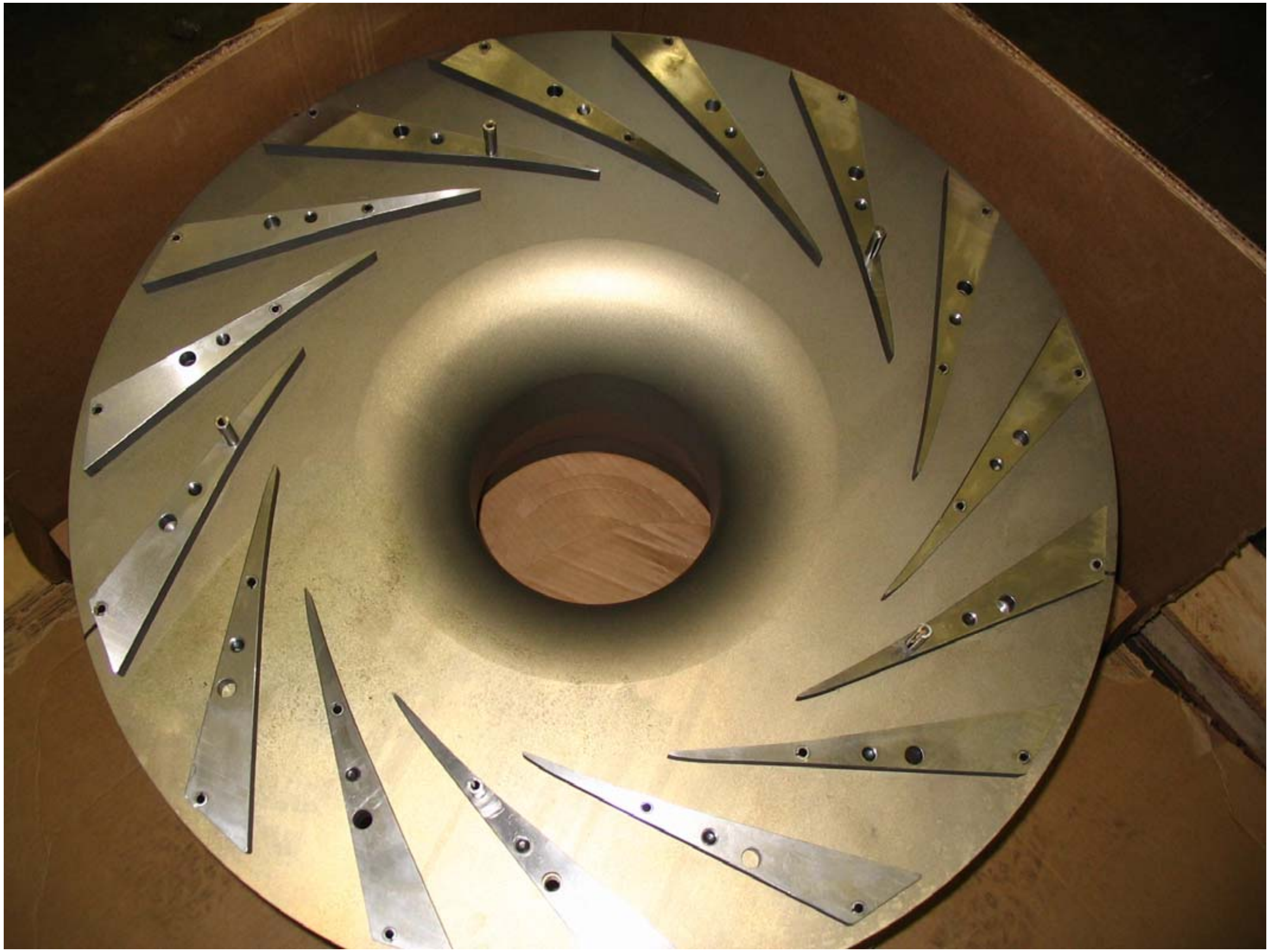
Integrally geared compressor

Failed Impeller Still Mounted in the Housing





2nd Stage Diffuser



Approach

- Discussions between the Engineering Departments of the Manufacturer and the User decided:
  - Based on the short time of operation before the failure and the type failure. The failure was probably due to **diffuser vane passing frequency** (number of diffuser vanes times stage running speed) **coinciding with impeller blade natural frequency.**
  - Manufacturer would temporarily repair the impeller by cutting the failed blade and the one opposite to maintain balance.
  - Manufacturer also **scarfed the blades to increase the blade natural frequency**.

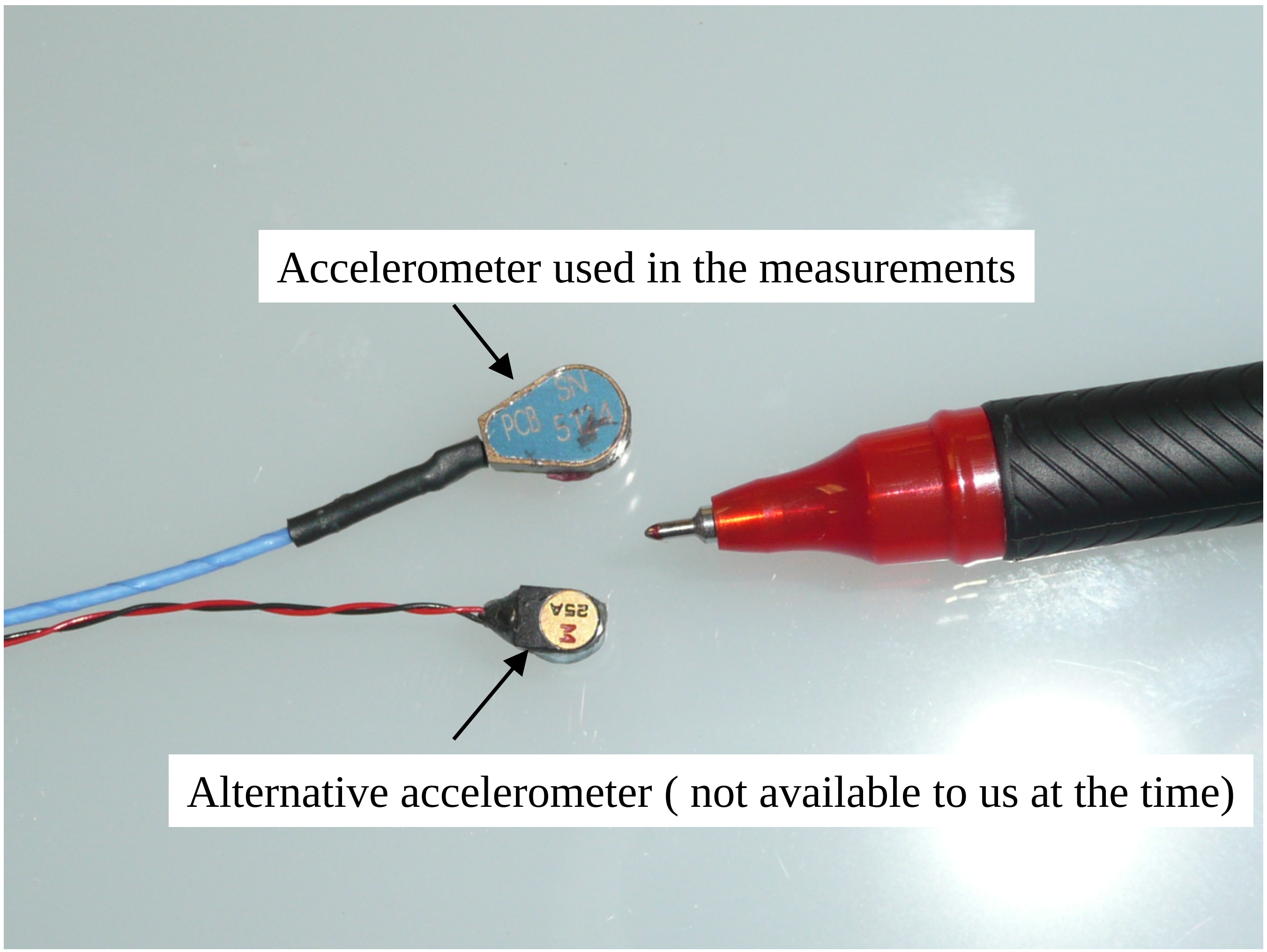
Approach (continued)

- User requested:
  - Verification that the blade natural frequency was not going to be excited again
  - If possible, verify that indeed blade resonance was the cause of the failure
  - 2 new impellers. One to replace the repaired impeller and another as a spare
  - Because of time, the first would be made from a casting (manufacturer standard for this impeller) and the second from a forging.

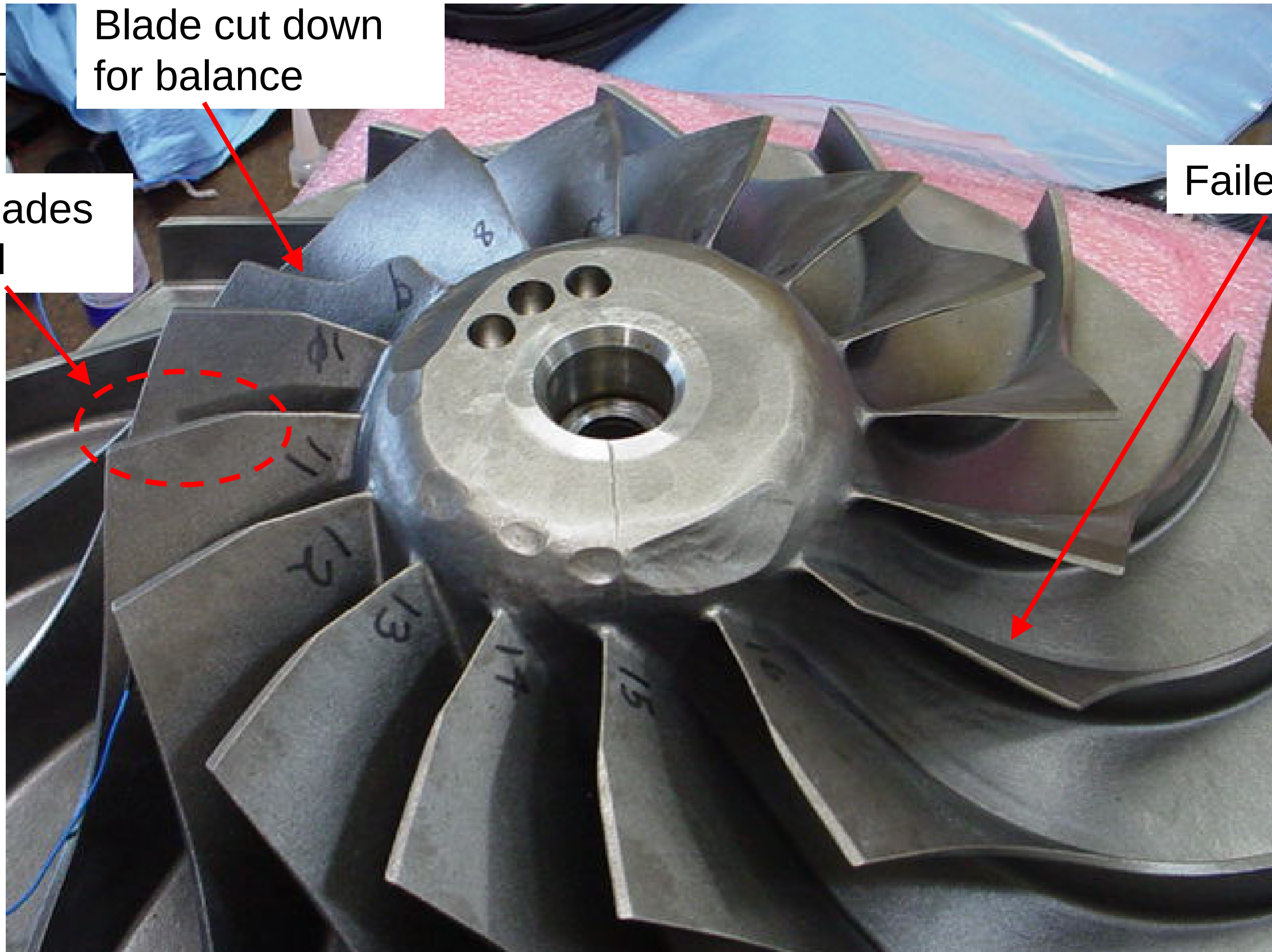
Measurement Techniques

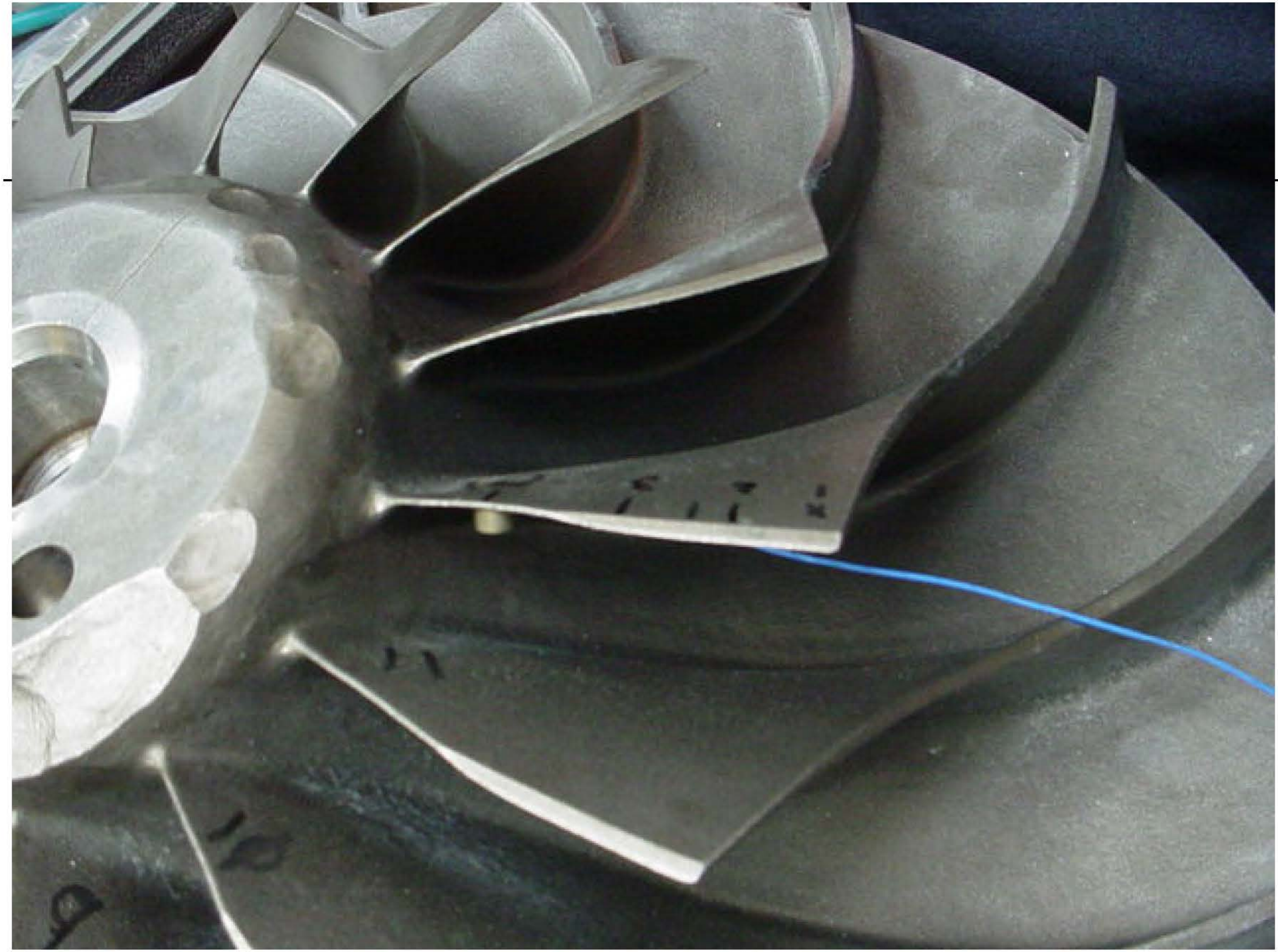
- Used a sub-miniature accelerometer (0.5 gr and 10 mV/g)
- Subminiature impact hammer to excite the blade

Measurement Techniques



Measurement on first cast impeller



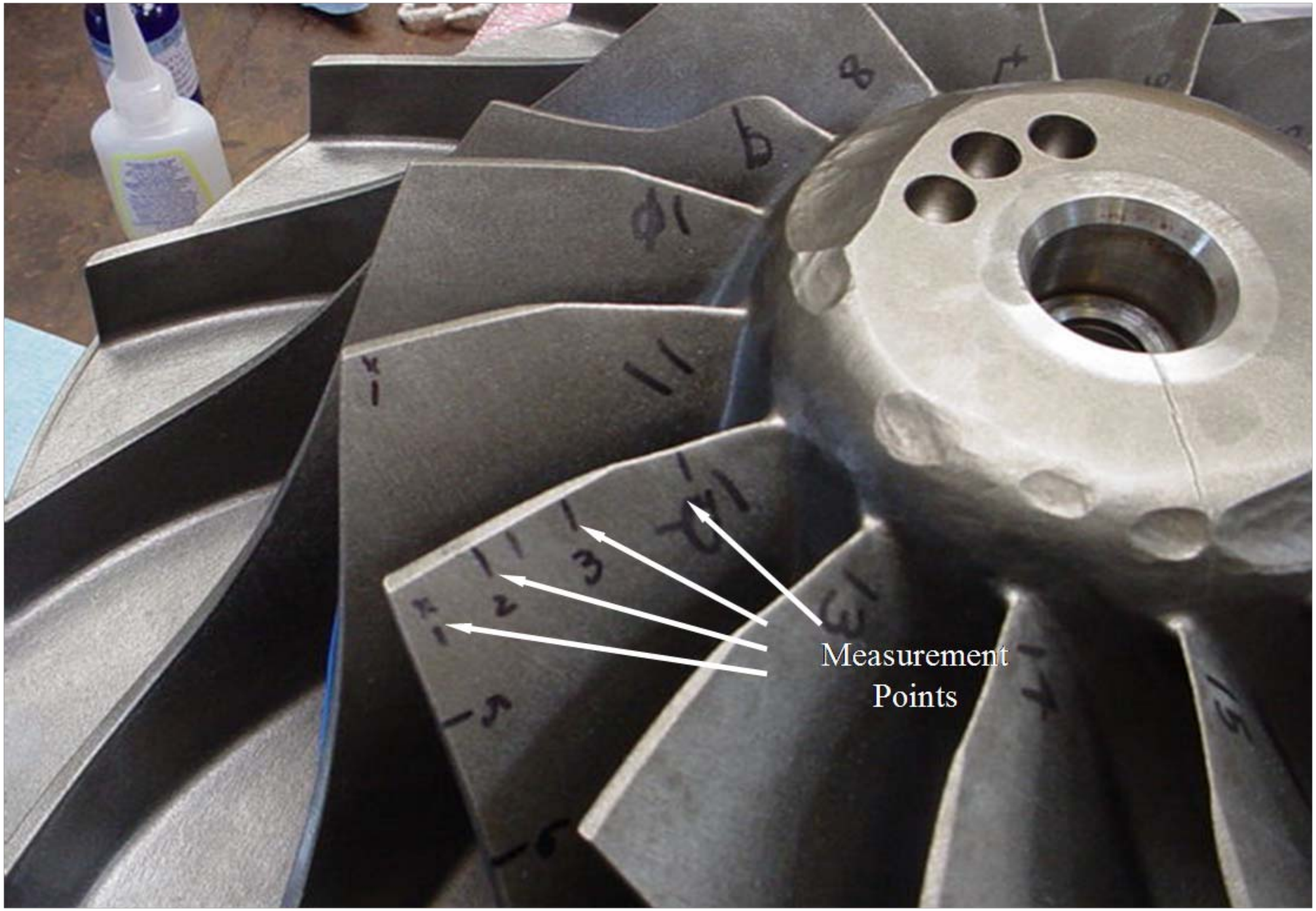


Mass Loading Effect

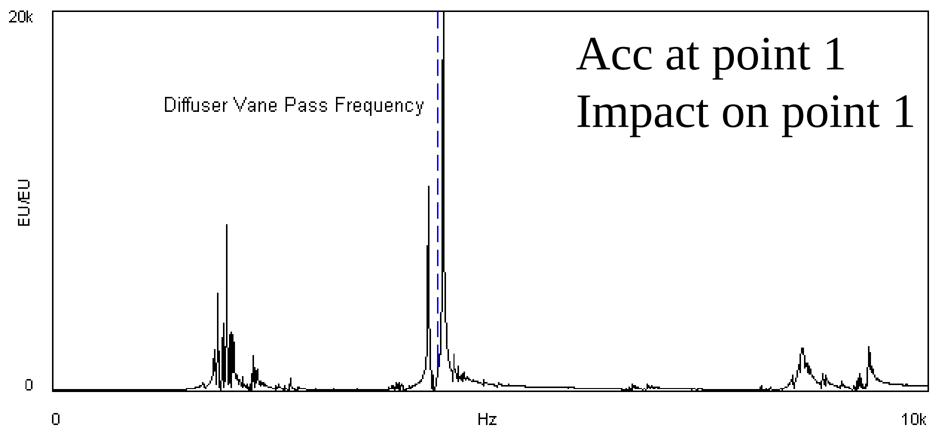
- One of the draw backs of the technique used in this impeller is that the mass of the accelerometer affects the measurements
- This results in measured frequencies lower than in reality
- This effect is normally referred as

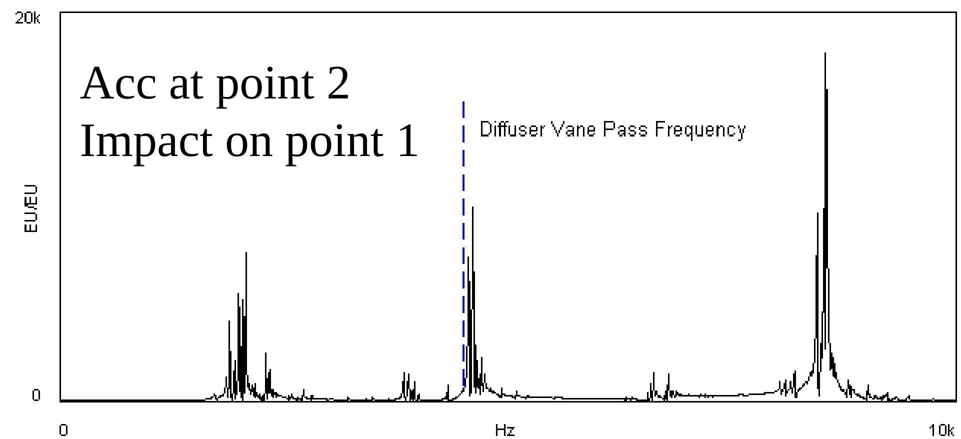
mass-loading

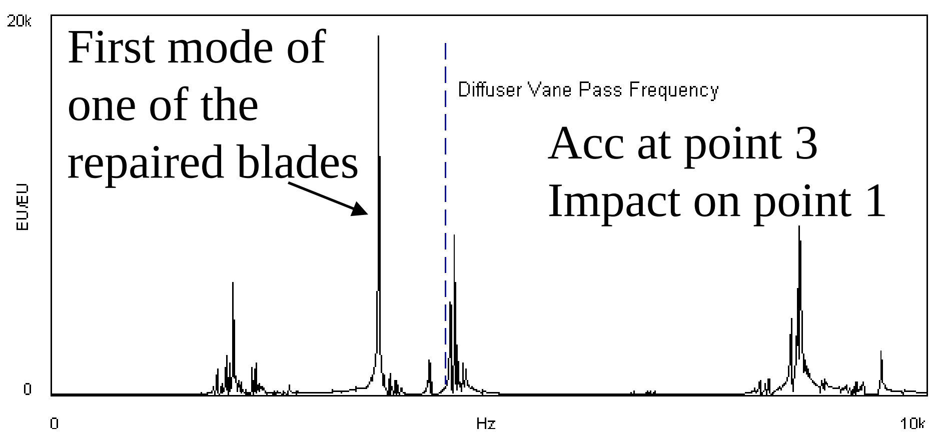
Use multiple points to verify mass loading and estimate effect

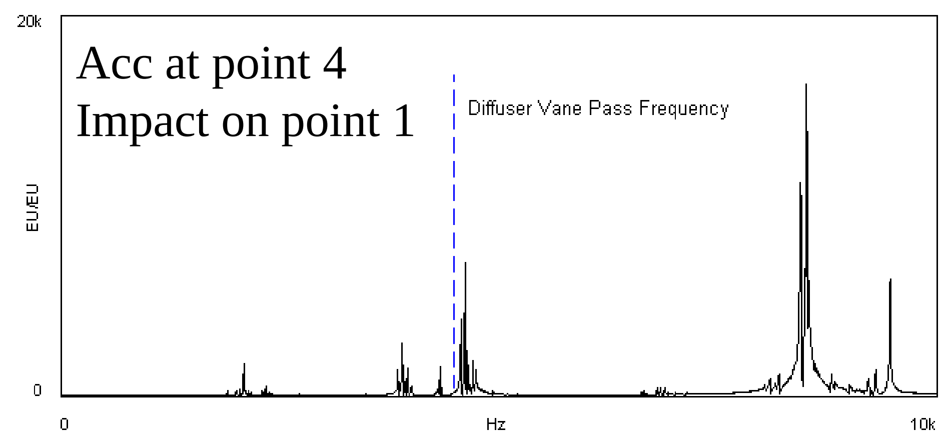


Use multiple points to verify mass loading and estimate effect





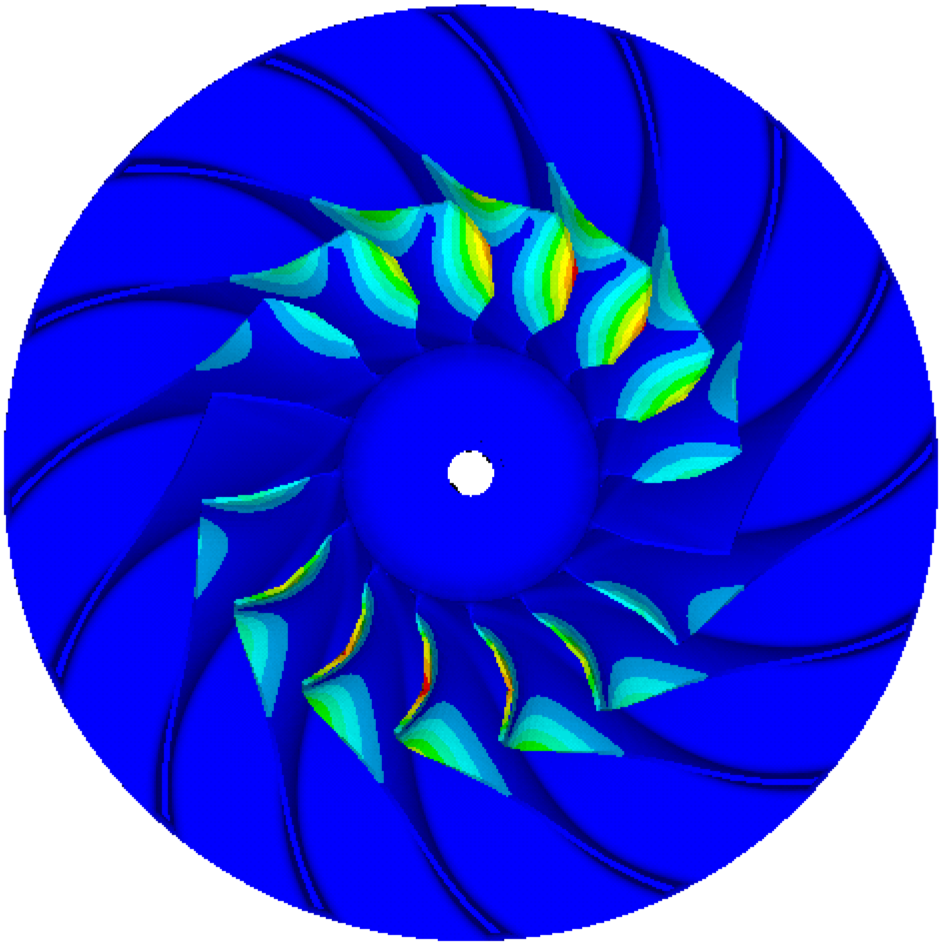




Mass Loading

- By moving the accelerometer to different locations it is possible to estimate the effect of the accelerometer mass and subtract it from the measurements.
- One has to be aware that the resonances from other blades also show up on the measurements.
- The challenge is to figure out which frequency corresponds to each blade

Use FEA to calculate stiffening effect due to centrifugal force and scarfing

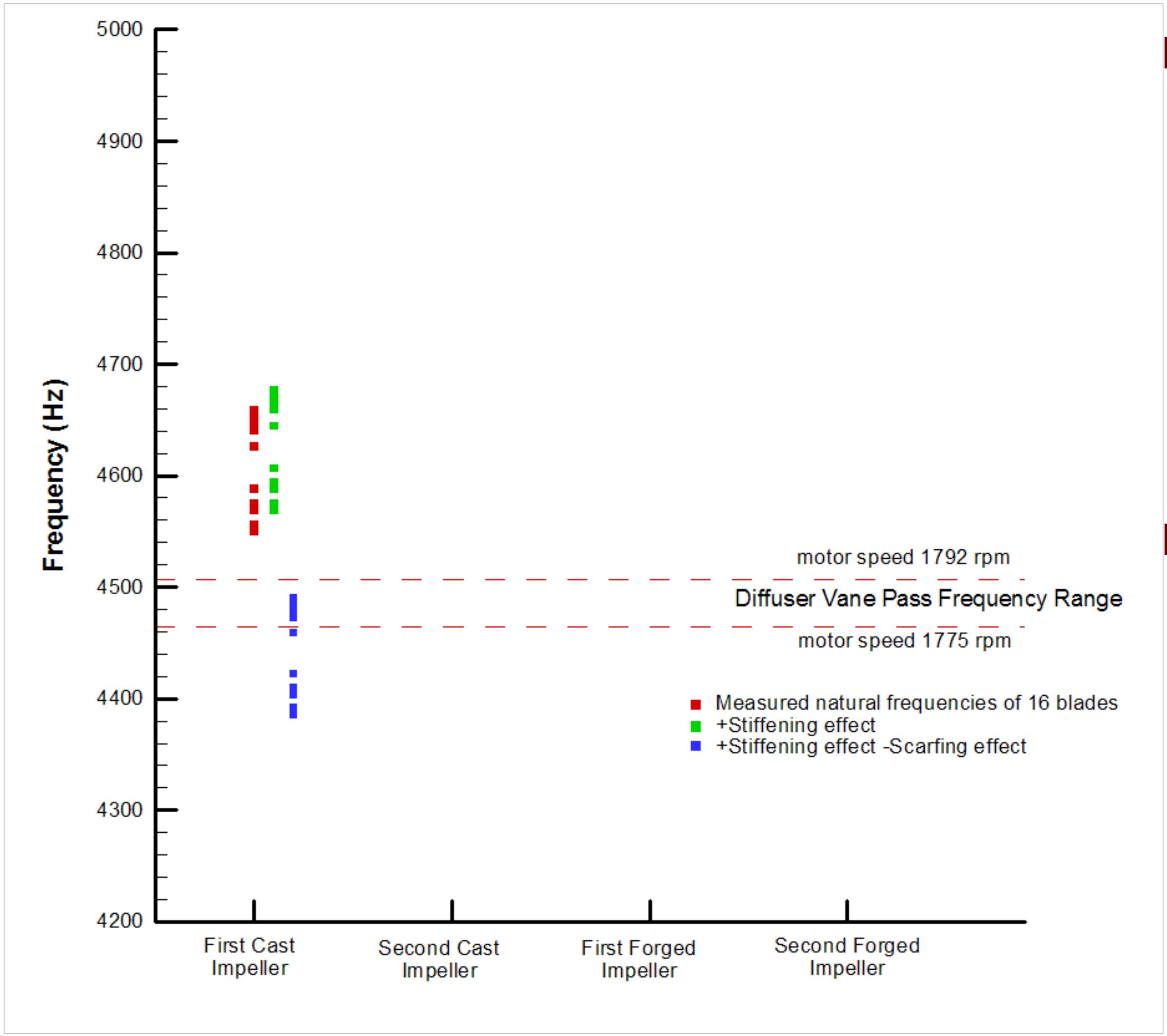


- When the impeller rotates, the centrifugal force stretches the blades, increasing their natural frequency
- Cutting the blade down (scarfing) reduces the mass of the blade and increases its natural frequencies

Use FEA to calculate stiffening effect due to centrifugal force and scarfing

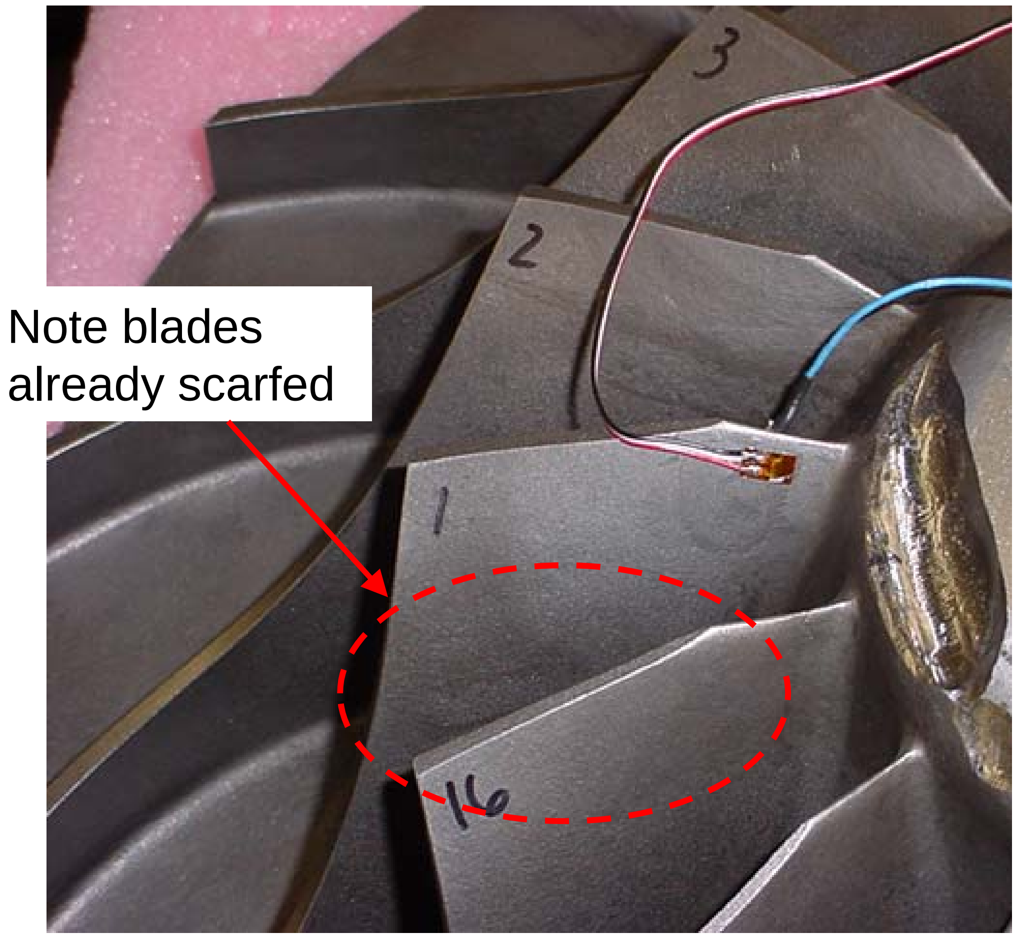
- From FEA model of the impeller it was calculated that scarfing increased the natural frequencies of the blades by 4%. Remember that at the time of the tests the blades were already scarfed so we had no way to test the original blades.
- The centrifugal stiffening for this impeller was calculated at 0.4 %

Summary for first cast impeller



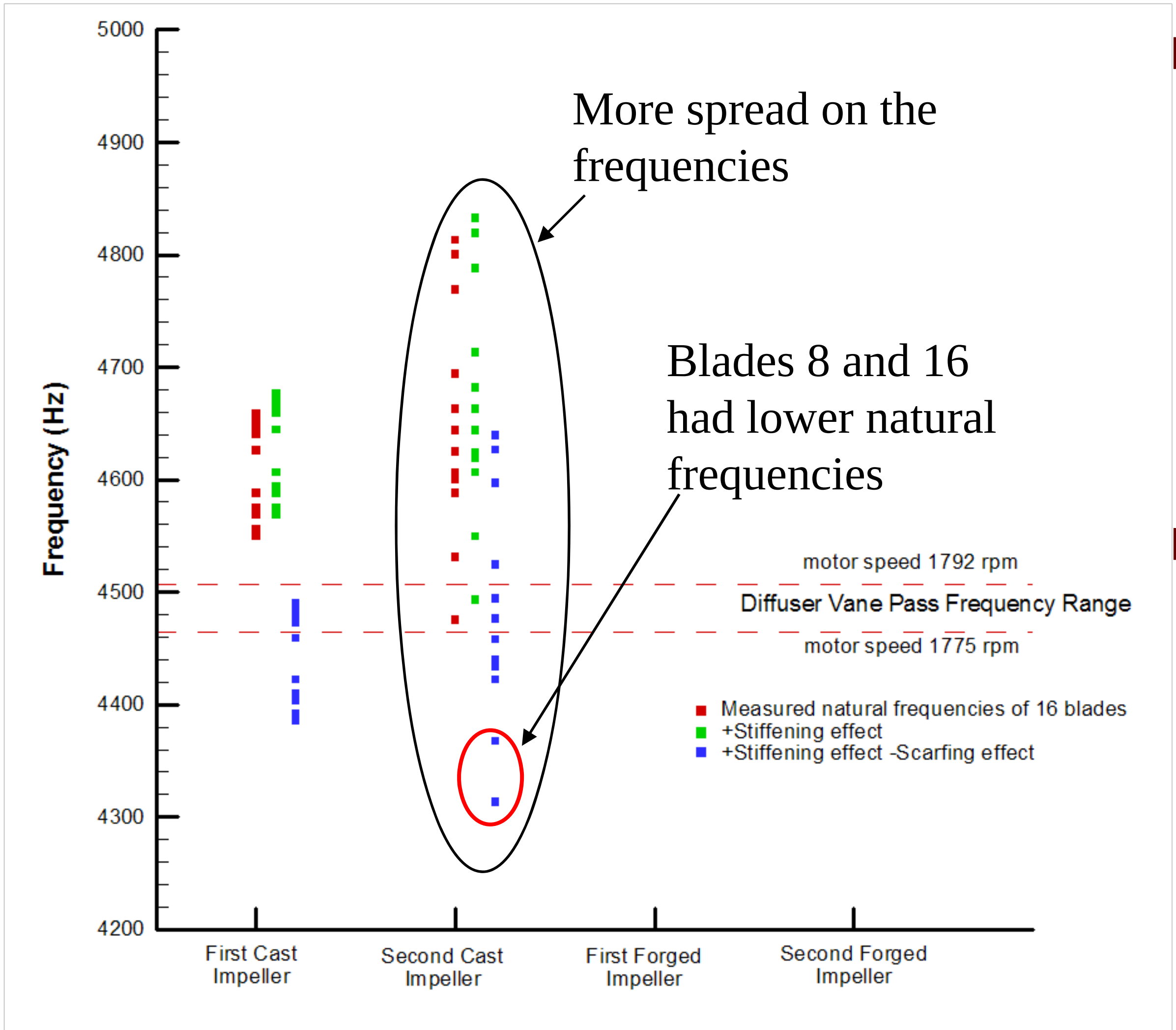
- Used the measured frequencies and calculated effects to estimate the original natural frequencies of the blades
- The natural frequencies of the blades were right at blade pass frequency

Measurements on the second cast impeller



- Cast impeller
- Tried using a strain gage to measure the response
- Kept the accelerometer to prove the method
- Used a similar technique as on the first cast impeller

Summary for second cast impeller

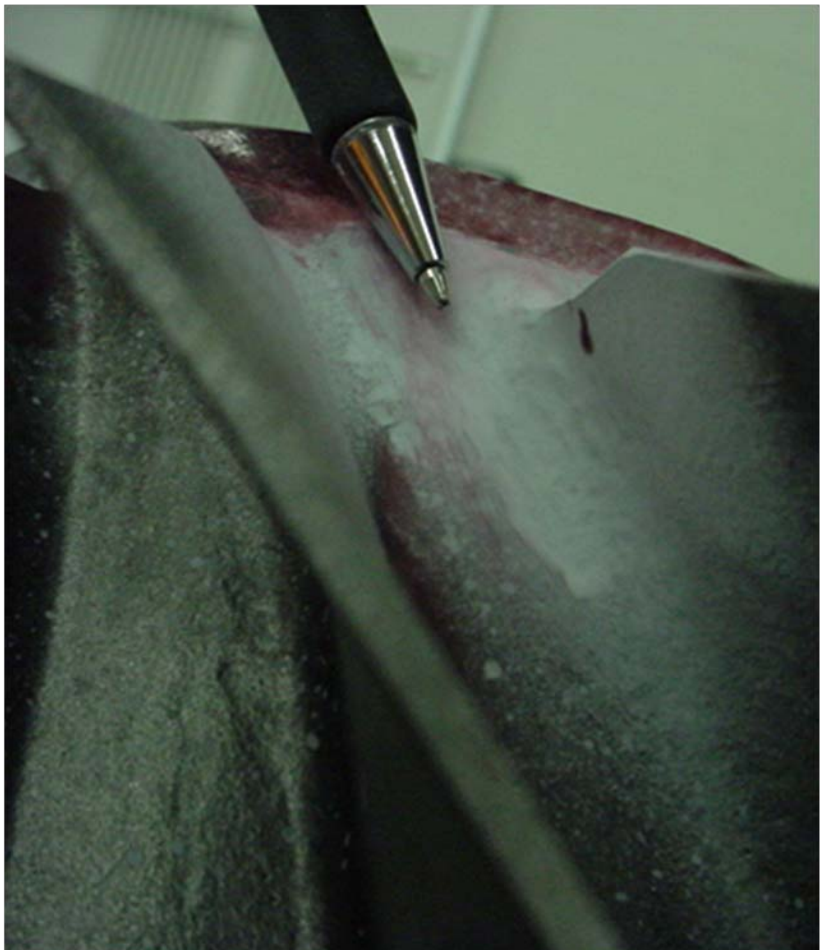


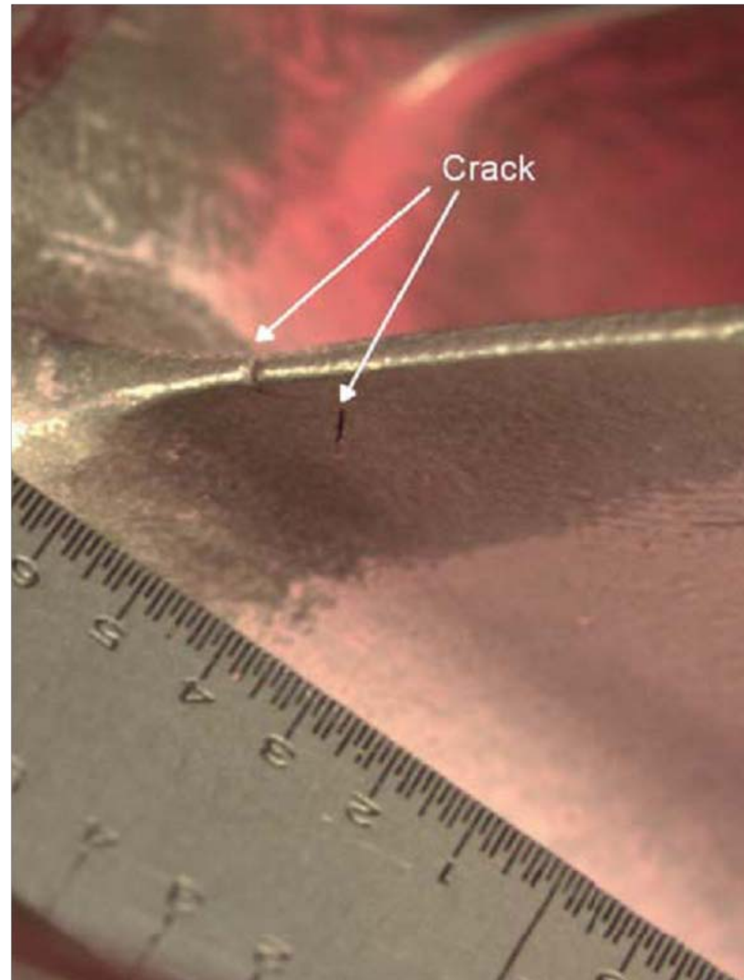
- Used the measured frequencies and calculated effects to estimate the original natural frequencies of the blades
- Without the scarf, the blade natural frequencies would have been right at blade pass frequency

Summary of second cast impeller

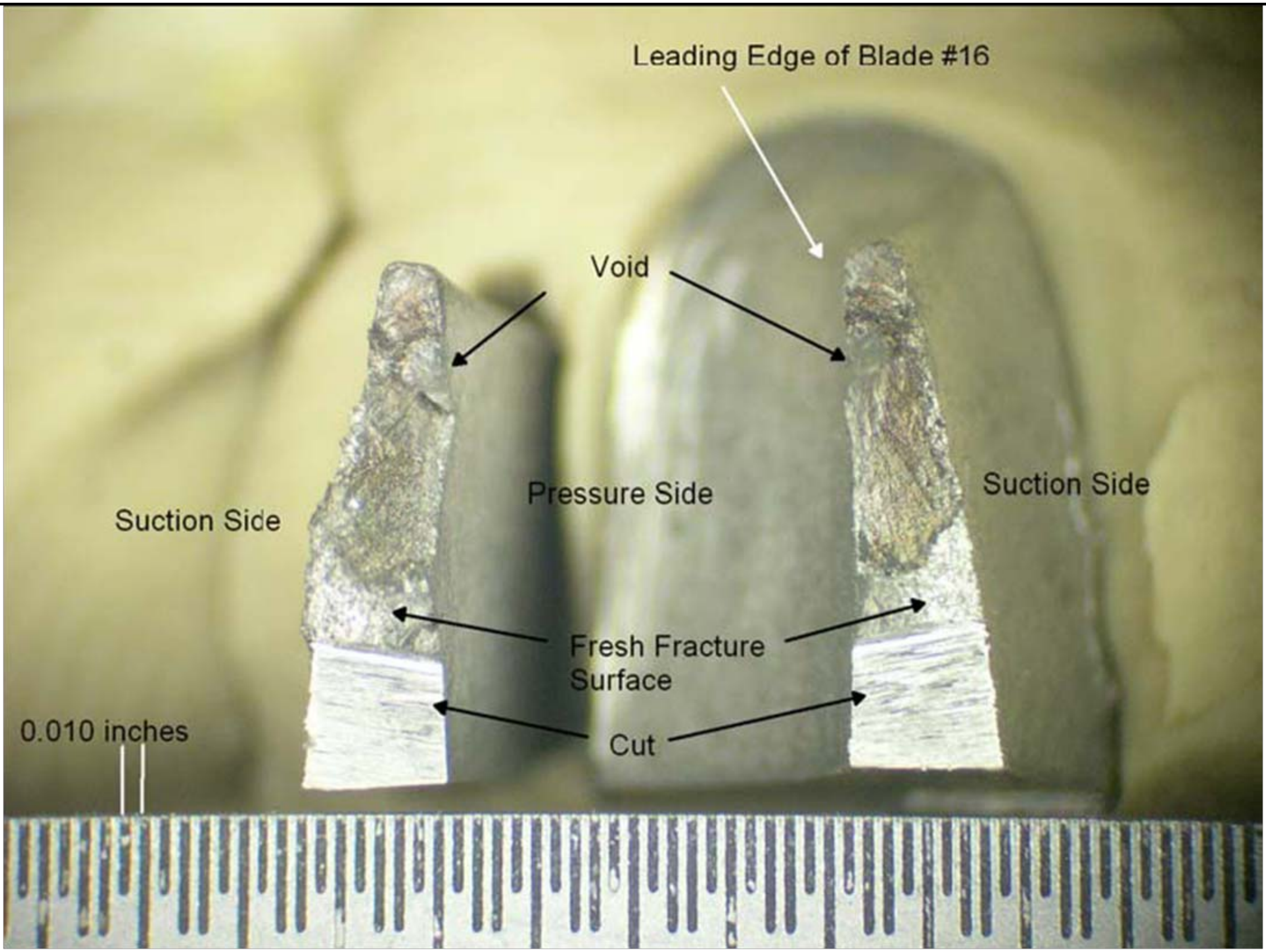
- Impeller was rejected after inspection based on crack found on blade 16
- NDT did not identify any obvious defects on blade 8. There was a small surface defect but not enough to account for the difference in frequency.
- The OEM sent the impeller for analysis. Blades 8 and 16 were cut for inspection and analysis
- Casting defects were found on both blades giving additional reasoning for going to forged impellers.

Blade 16 of the second cast impeller had a crack

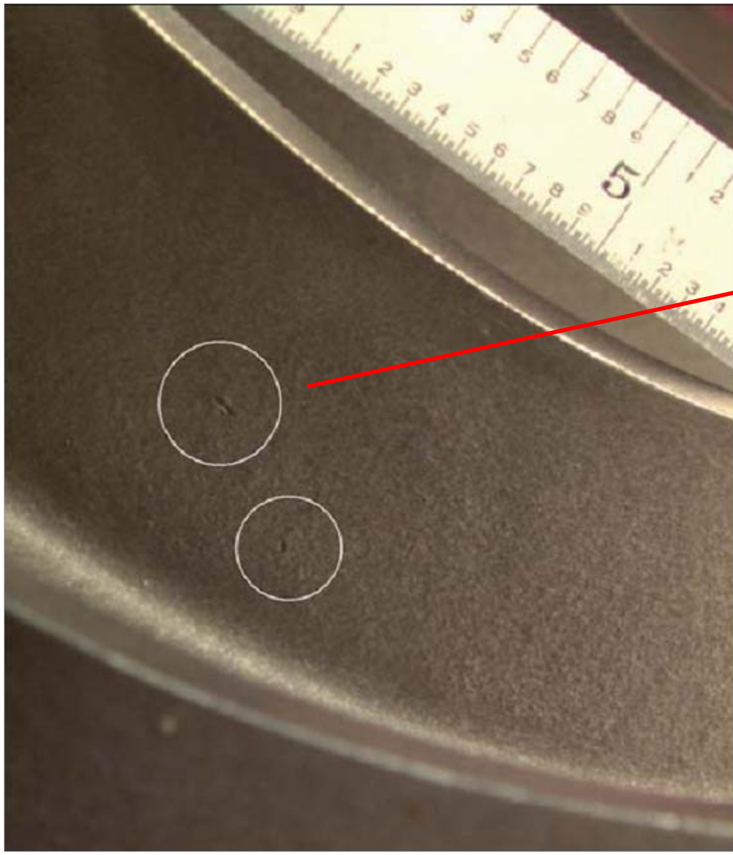


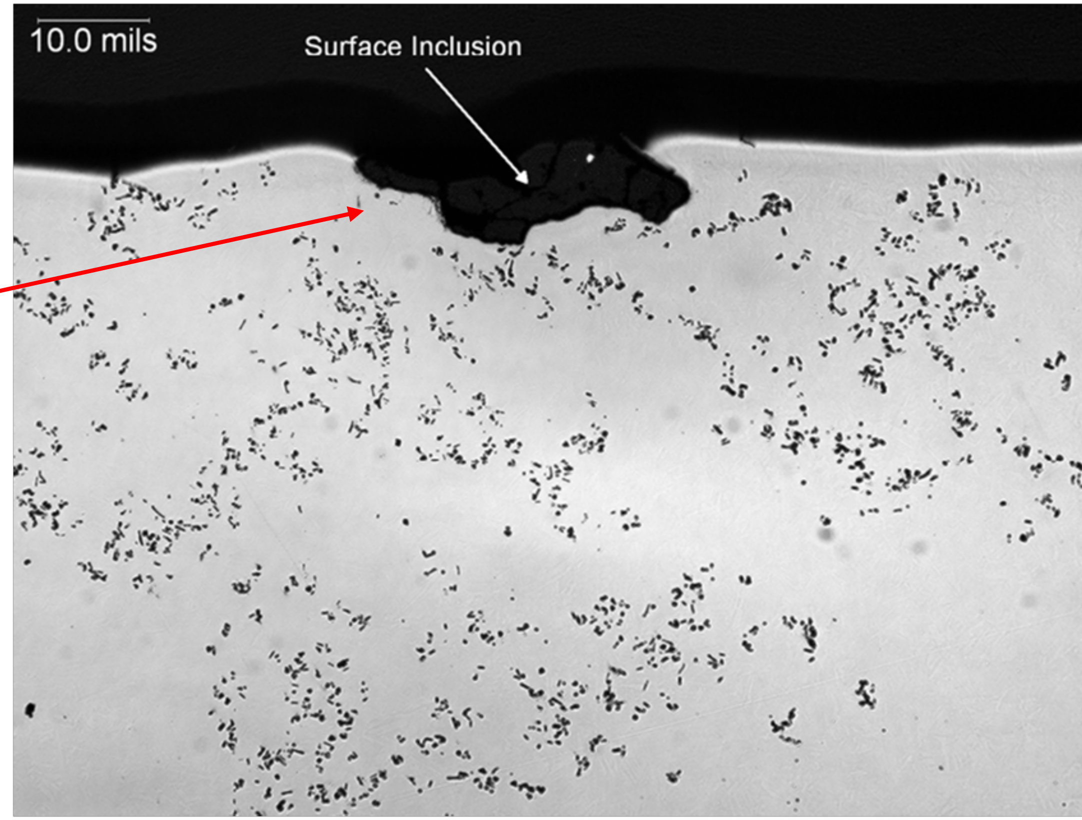


Blade 16 of the second cast impeller had a crack



Blade 8 of the second cast impeller had inclusions caused by casting defect



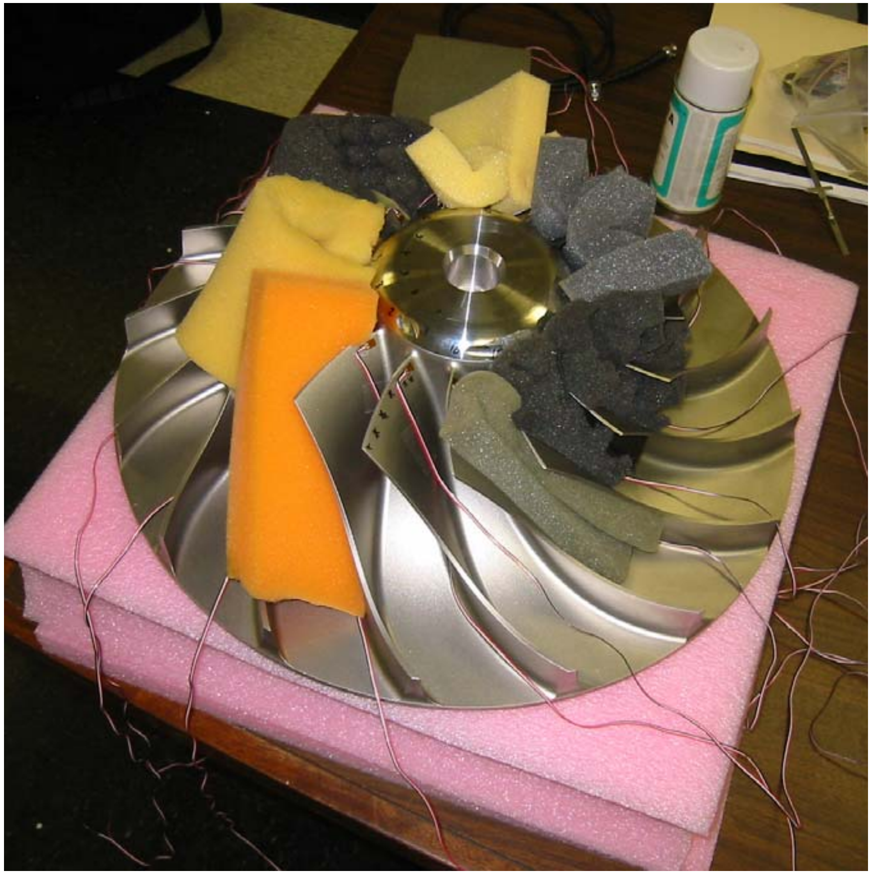


Sub-surface inclusions probably caused by a defect on the casting process

Measurements on the first forged impeller

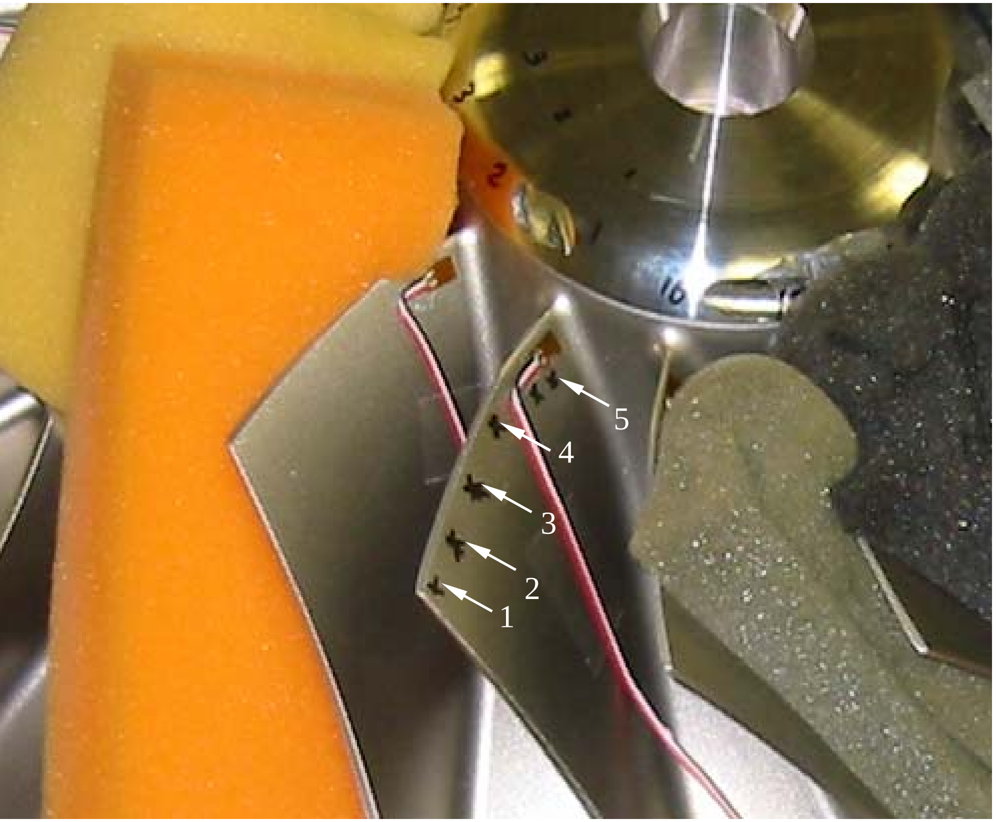
- Used strain gages for vibration measurements
- Eliminated the effect of mass loading of the accelerometer

Measurements on the first forged impeller



- The foam is used to damp the response of the blades that are not under test
- Dampening the response of other blades simplifies the measurements

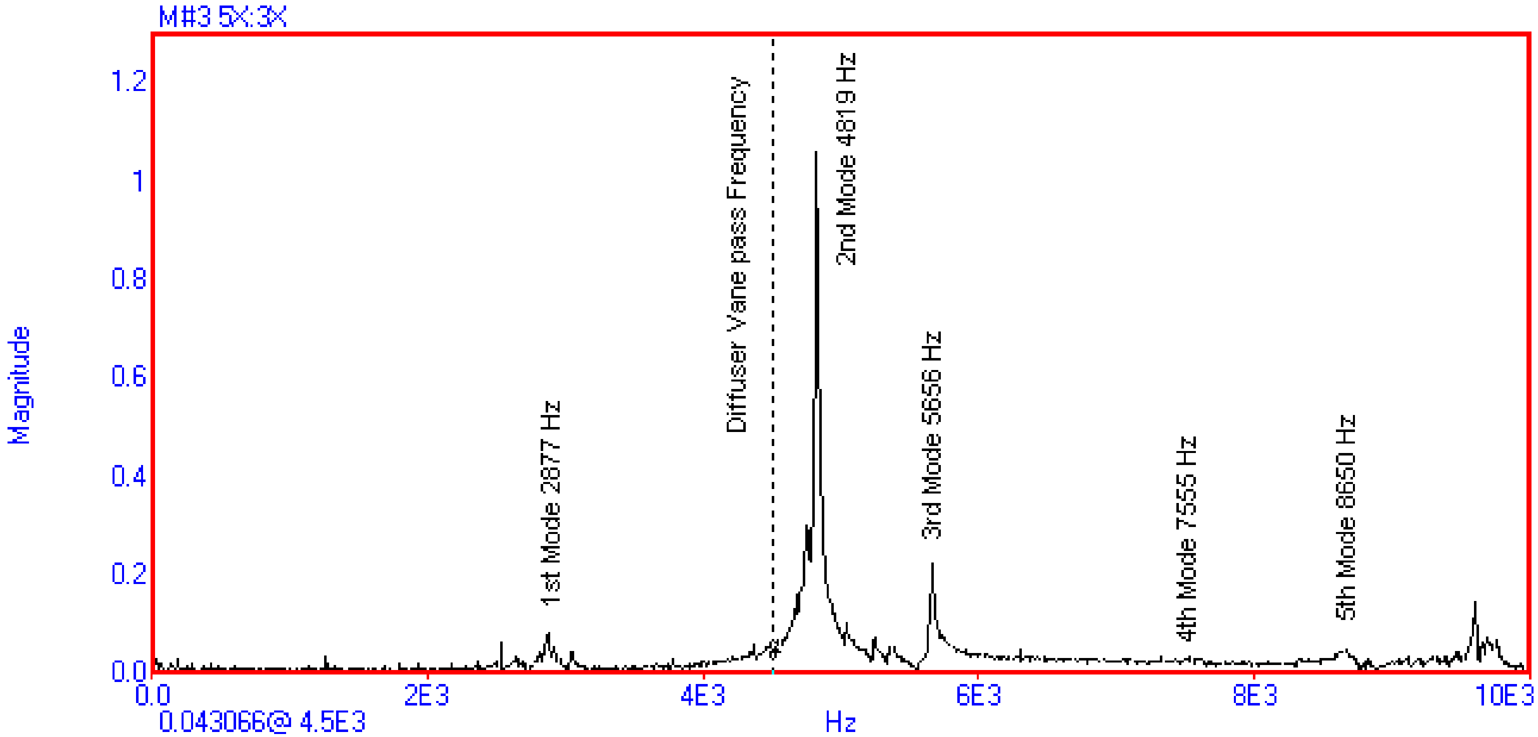
Measurements on the first forged impeller



- Before, we impacted in one location and moved the accelerometer
- For this kind of test the impact location is moved from one to position to the next

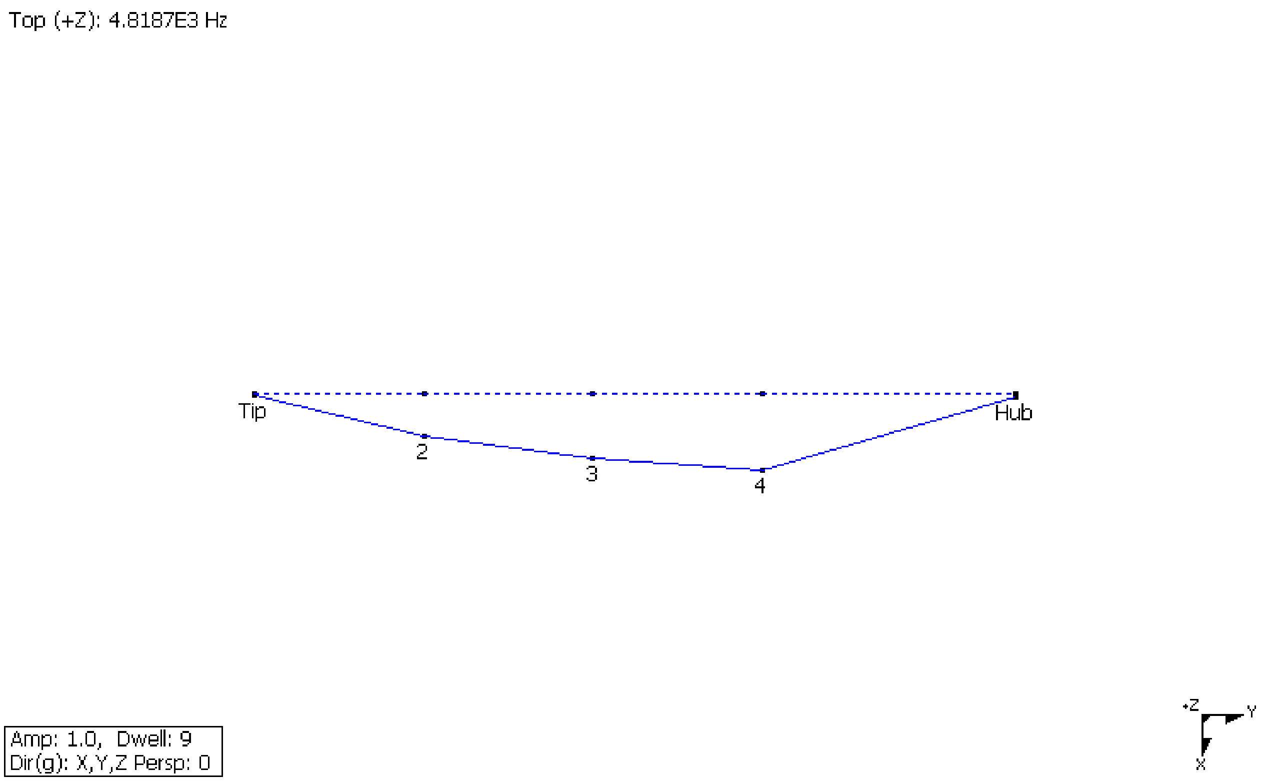
Sample of some measurement results

- Response at the root of the blade (strain) due to impact on location 3

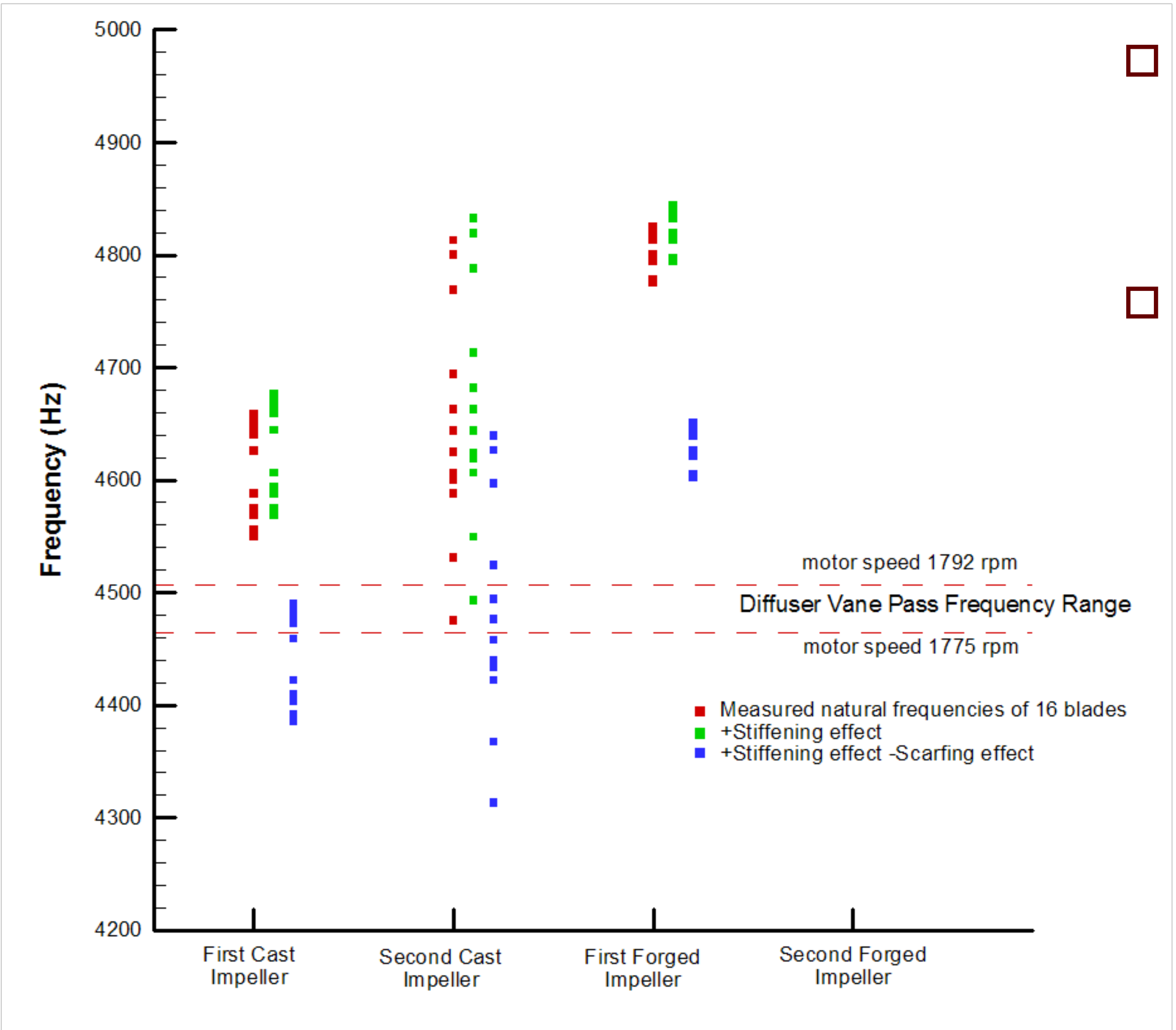


Measurements on the first forged impeller

- Modeshape of the second blade natural frequency.
- The line represents the inductor edge of the blade



Summary for first forged impeller

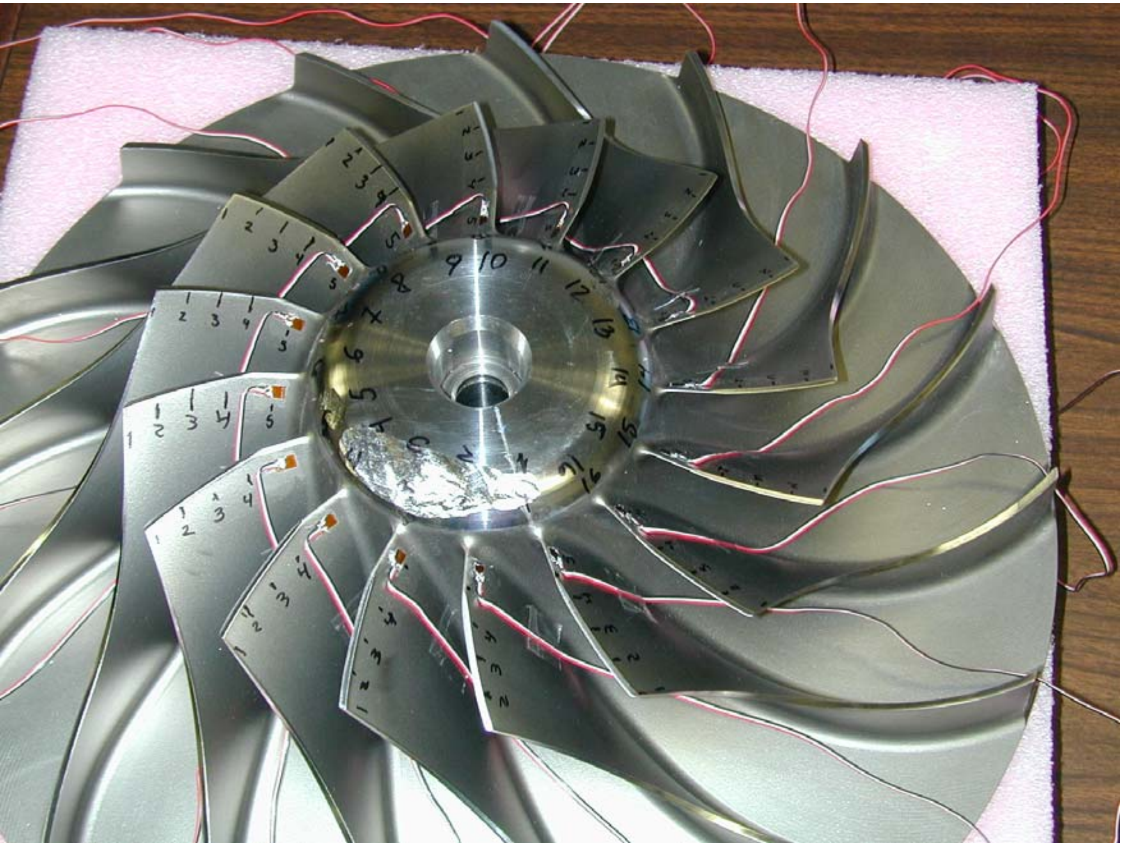


- In this case the natural frequencies are closer together
- Repeatable frequencies indicate that the manufacturing process produce more consistent results

Measurements on first forged impeller

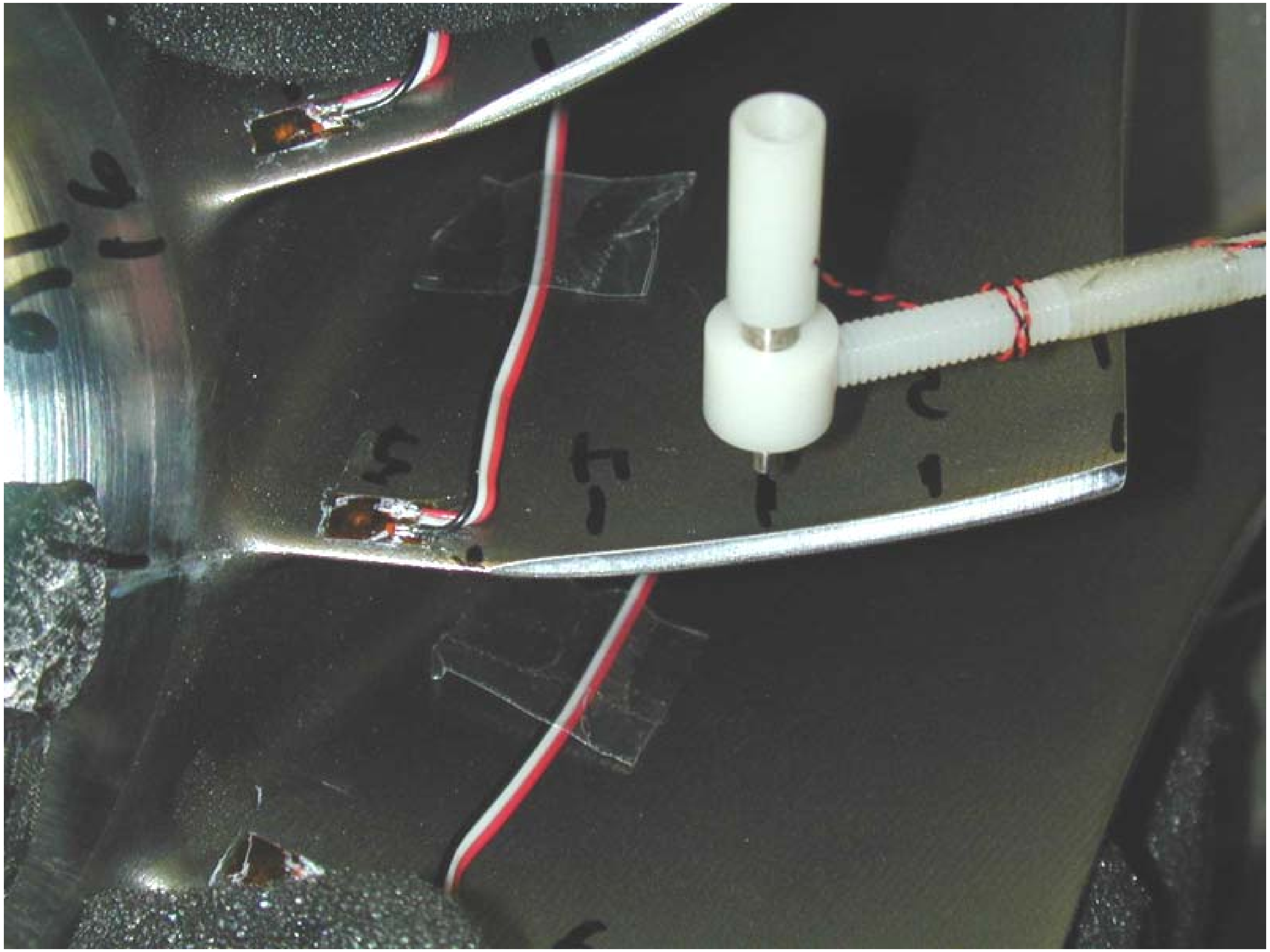
- This impeller was installed in the compressor at the end of 2005.
- It has been working without problem since that time.

Measurements on the second forged impeller



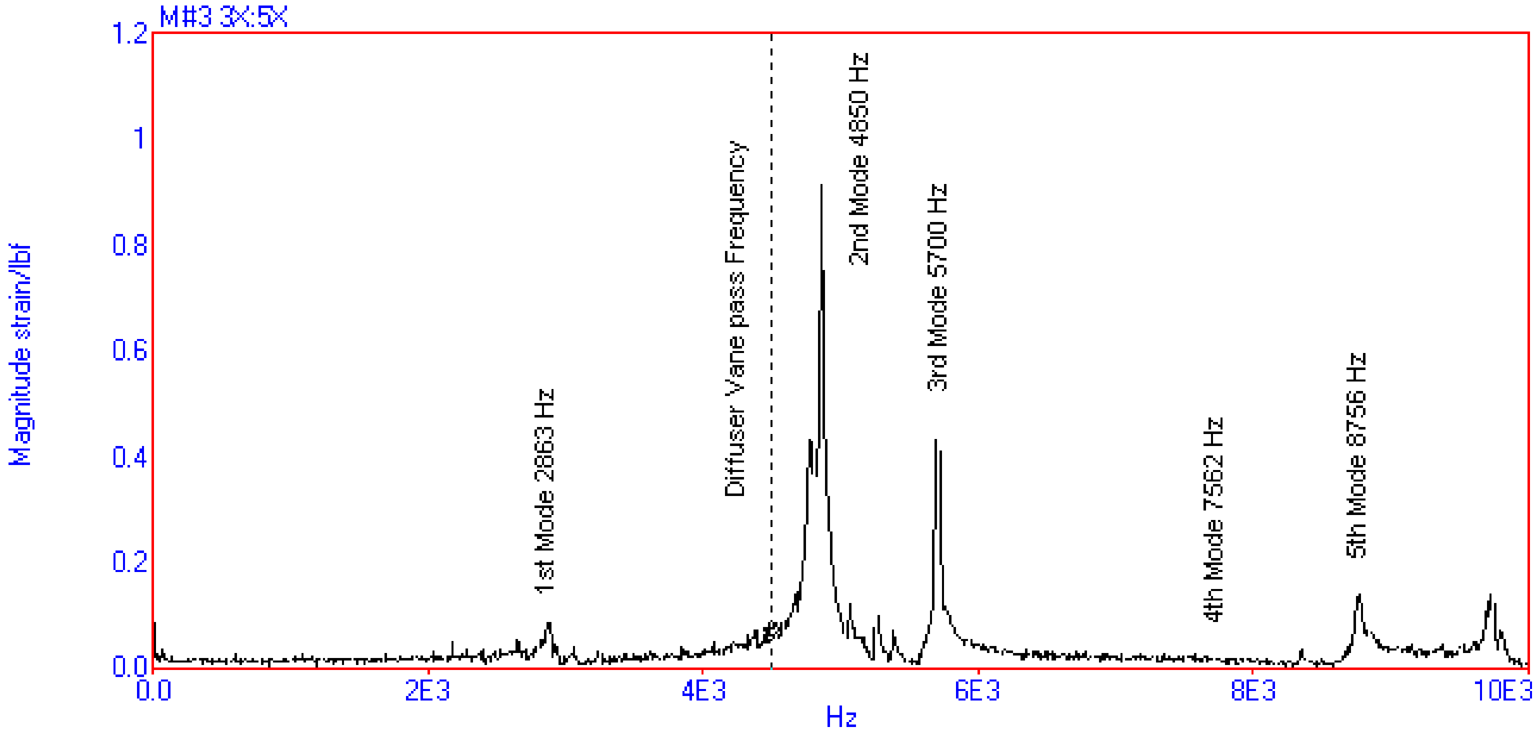
- As in the case of the first forged impeller, we used strain gages to measure the vibration frequencies

Testing of the second forged impeller

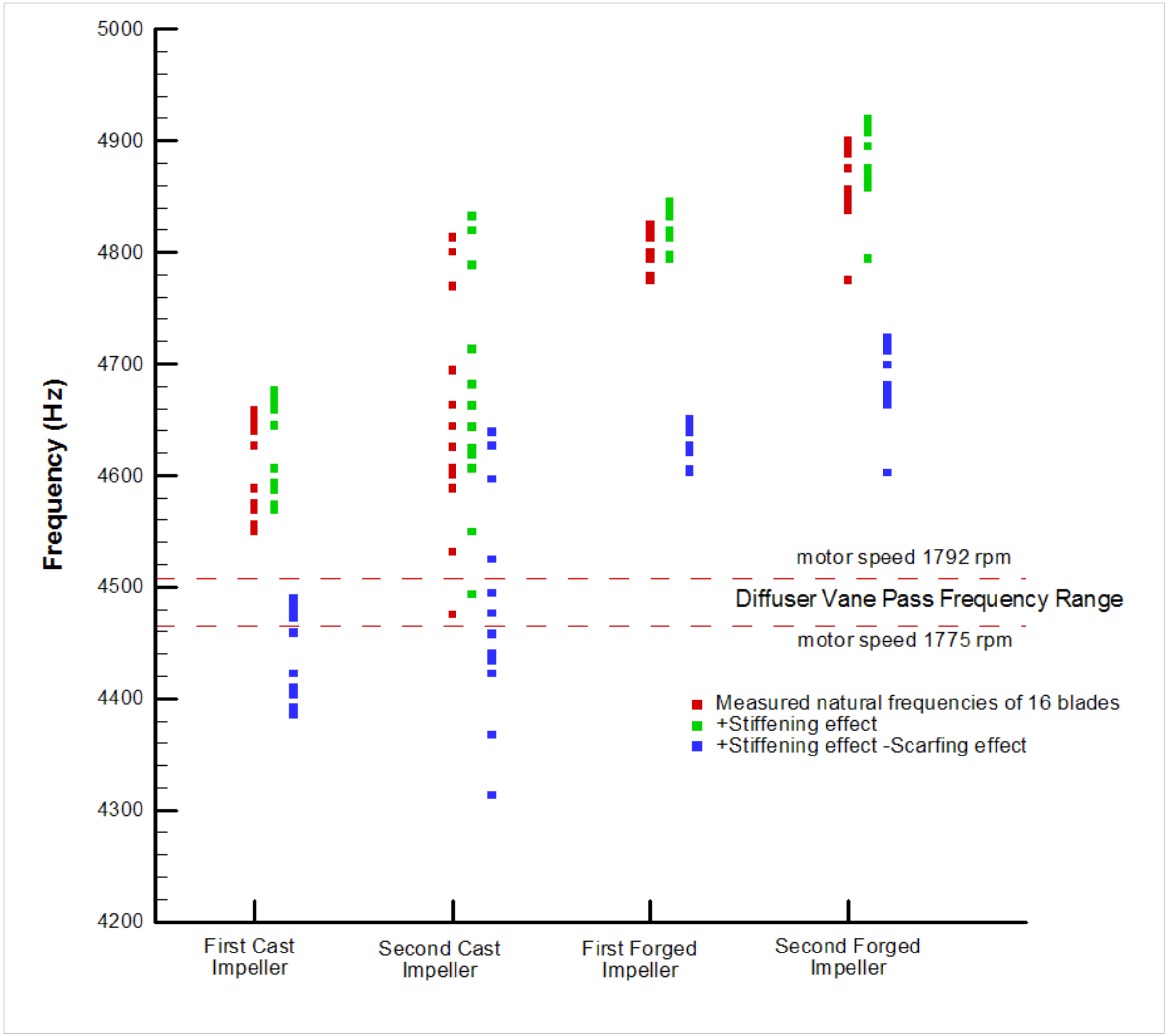


Sample of some measurement results

- Response at the root of the blade (strain) due to impact on location 3



Summary for all impellers



Summary and Conclusions

- Several measurement techniques were presented to measure blade natural frequencies
- Using strain gages at the root of the blades produce the best results since they do not introduce mass loading on the measurements
- Natural frequency measurements identified defects on the blades of the second cast impeller

Summary and Conclusions

- We were able to identify the blade natural frequencies using experimental techniques
- With the addition of Finite Element Analyses we were to back-calculate what would have been the blade natural frequencies on the original blade design without the scarf.

Summary and Conclusions

- Impellers manufactured by 5-axis machining of a forged billet had higher natural frequencies than impellers manufactured by casting
- The 5-axis machining process produced more consistent results on blade to blade, therefore the natural frequencies of the blades were closer together.
- The first forged impeller has been in operation since the end of 2005 without problems.

Summary and Conclusions

- OEM implemented corrective actions:
  - For this application, the correction was to switch to an impeller machined from a forging.
  - Added a second magnetic particle inspection (after shotpeening) for all impeller castings. Since 2005 the OEM has not experienced a repeat inclusion or failure of an impeller due to inclusions.
  - The impeller foundry identified the skimming procedure of the molten pot as the process needing correction and reinforced this process.

Summary and Conclusions

- This work showed a good example of collaboration between users and OEM to resolve problems quickly
- The engineering department of the user appreciates the help of the OEM engineering department on the solution of this problem and their participation in this case study.

Thank you for attending this presentation.

Questions?