Quality Control of Carbon Fiber Structures by Acoustic Method

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Introduction

- A need for Quality Testing of Aircraft Components was identified
- Especially for Parts made of **C**arbon **F**iber **R**einforced **P**olymers, **CFRP**
- Efficient and easy to use – by Production personnel
- Focus on structural ***performance*** rather than identifying voids, visible defects
- An additional use of the method is for used parts - to Identify need for Repair, Replace

Existing Non-Destructive Test Methods, and their shortcomings

- Ultrasonic testing
  - Identify Voids and non-homogeneities in the sample
  - Special equipment, trained operator
  - Not necessarily giving reduced ***operating*** performance of the part
- Thermographic inspection
  - Identify Voids and non-homogeneities in the sample
  - Special equipment, trained operator
  - Not necessarily giving reduced ***operating*** performance of the part
- Acoustic emission ["Traditional"]
  - Requires part to be in operation condition
  - Not suitable in production environment
- Experimental Modal analysis
  - Requires vibration Special equipment [Accelerometers, vibrometer, force gauge],
  - And a trained operator

The Strategy

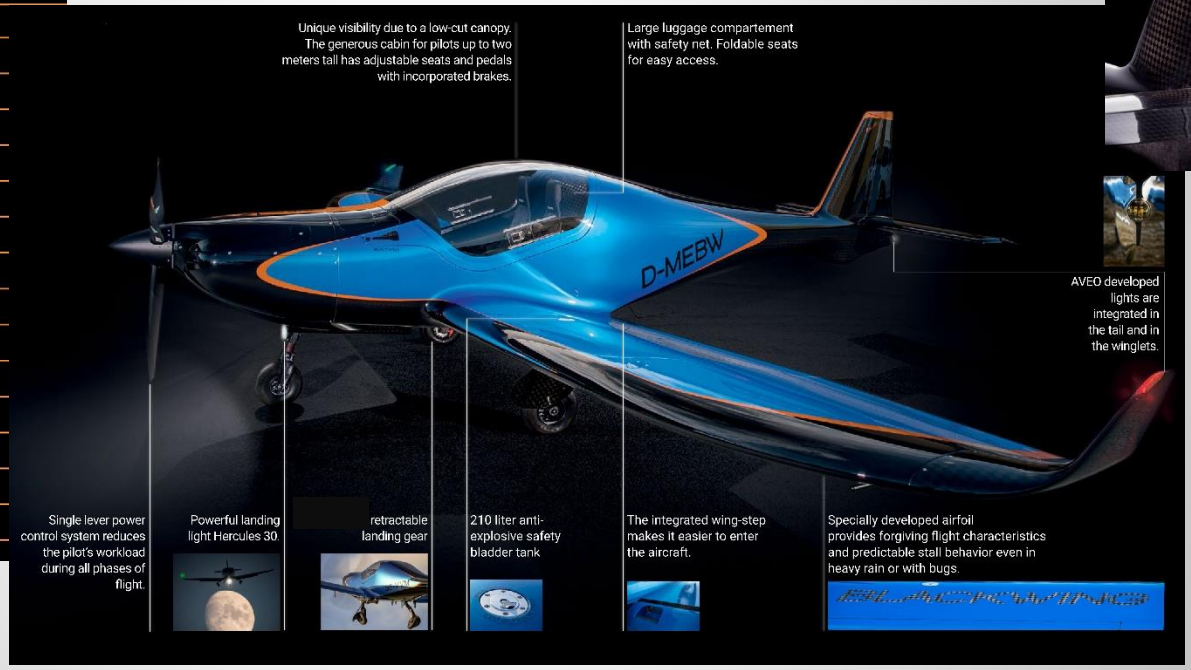
- Tap-test
  - Using Radiated Sound for Structural Eigenmode detection
- Challenges
  - Applicable for the typical components?
  - Test setup in minutes possible?
  - Reliable?

A typical Application
The BLACKWING AIRCRAFT

Performance

BW650RG

ENGINE MAX POWER	160hp
VNE TAS SL	173 knots (320 km/h)
VNE TAS FL95	200 knots (370 km/h)
CRUISE SPEED 65% FL95	190 knots (352 km/h)
STALL SPEED	38 knots (70 km/h)
FUEL TANK	140 liter (5.5h at 65%)
TAKEOFF DISTANCE	100 meter
LANDING DISTANCE	300 meter
CLIMB RATE	2500 ft/min (12.7 m/s)
CABIN WIDTH	1.21 m (47.5")
LUGGAGE	25 kg (300 L)
MAX TOW	600 kg
EMPTY WEIGHT	370 kg
WING SPAN	8.4 m (27.5 ft)
LOAD FACTOR	+ 4.4 / - 2.2 G
ENGINE	Rotax 916 iS



- More than 200 CFRP Parts per Aircraft
- Transition from "Prototype Workshop" to Serial Production Factory
- Production Rate: 12 Aircraft / Year
- Quality is paramount

Physics, theoretical foundation

- Structural Dynamics

$$K_s X(t) + M_s \ddot{X}(t) = F(t) \quad (6)$$

$$X(t) = \hat{X}(\omega) e^{-i\omega t} \quad (7)$$

$$K_s \hat{X}(\omega) - \omega^2 M_s \hat{X}(\omega) = \hat{F}(\omega) \quad (10)$$

- Acoustics

$$\frac{\partial^2 P}{\partial t^2} - c^2 \nabla^2 P = Q \quad (11)$$

- Vibro-Acoustics

$$Q_{sf}(t) = c^2 \rho \int_A N_s N_f \, \vec{n} \ddot{X}(t) dA \quad (18)$$

$$\left(\begin{bmatrix} K_s & K_{sf} \\ 0 & K_f \end{bmatrix} - \omega^2 \begin{bmatrix} M_s & 0 \\ M_{fs} & M_f \end{bmatrix} \right) \begin{bmatrix} \hat{X}(\omega) \\ \hat{P}(\omega) \end{bmatrix} = \begin{bmatrix} \hat{F}(\omega) \\ \hat{Q}(\omega) \end{bmatrix} \quad (19)$$

Experimental Characterization of CFRP, and Radiation Efficiency

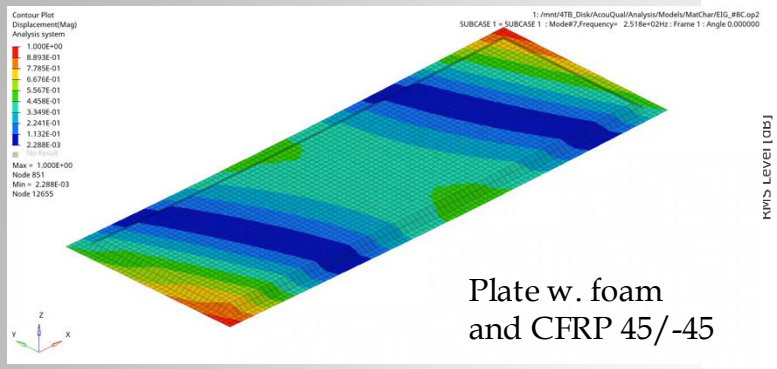
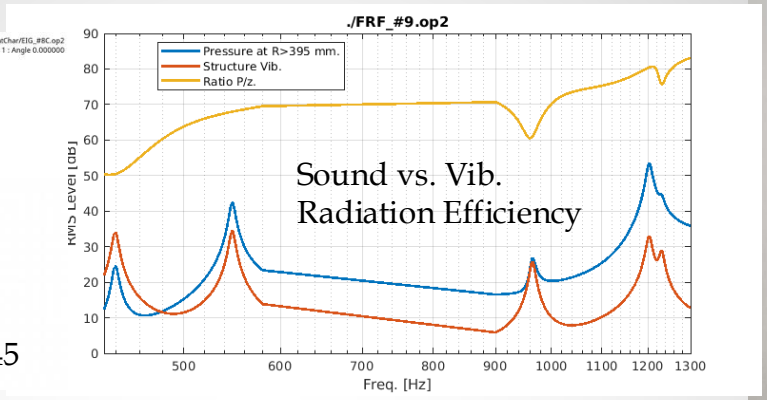
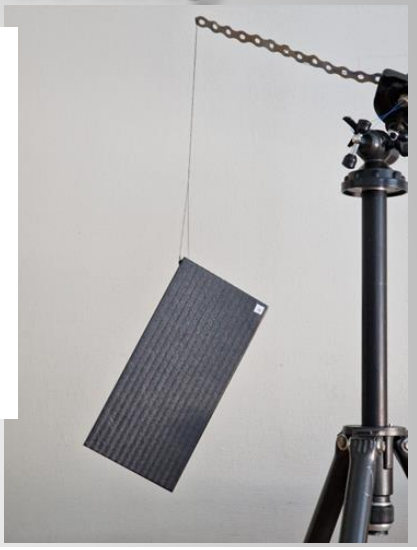


Plate w. foam
and CFRP 45/-45





Material, "CFRP A"

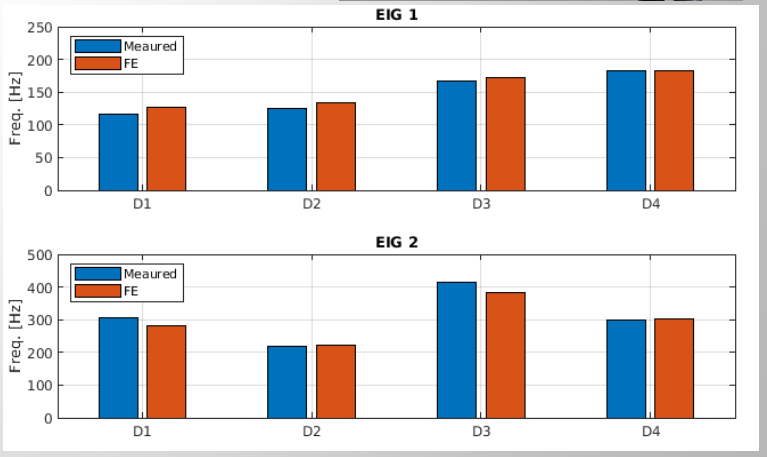
MAT8, Orthotropic

E1: 110 GPa, E2: 10 GPa, ν : 0.05

G12: 5.0 GPa, G1,Z: 5.0 GPa, G2,Z: 5.0 GPa

Density : 1450 kg*m^{-3}

	D1 45/-45	D2 0/90	D3 45/-45	D4 0/90
Tot	2.2	2.2	3.0	3.0
NPly	7	7	5	5
Ply	0.314	0.314	0.6	0.6
Mass	95 g	95 g	130 g	130 g
Density [kg/m^3]	1450	1450	1450	1450



The effect of Vibro-Acoustic Coupling

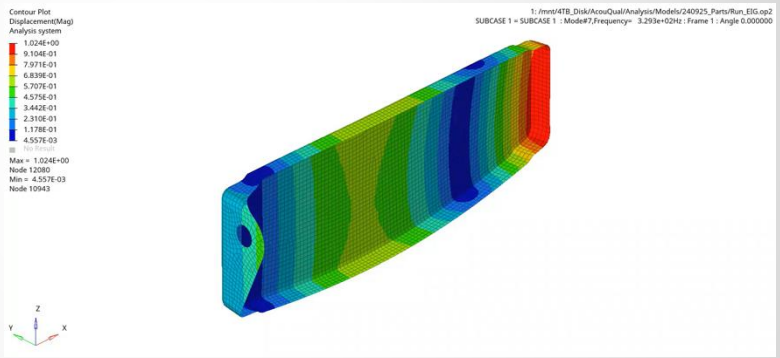
- Essentially:
  - The Vibro-Acoustic coupling is low from a structural point of view
  - The effect of the Acoustic Environment is negligible
  - Test results can be compared with FEMA in terms of radiation efficiency and directivity
- Noticed:
  - A. The plies are over-sized; requirement on **overlap** - can be more [hard to model]
  - B. Groove or not at the flange - effect on Eigenmodes

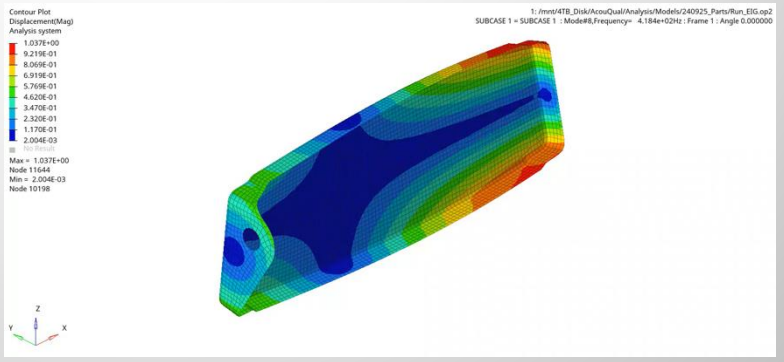
Table 1: Eigenfrequencies - Structure Only.

Eigen Mode	1	2	3	4
Freq. [Hz]	370.4	410.5	957.0	1027.5

Table 2: Eigenfrequencies - Structure in Air.

Eigen Mode	1	2	3	4
Freq. [Hz]	364.3	408.3	949.0	1009.5
df [Hz]	- 6.1	-2.2	-8.0	-18.0
df [%]	-1.6	-0.5	-0.8	-1.8





Parts Tested

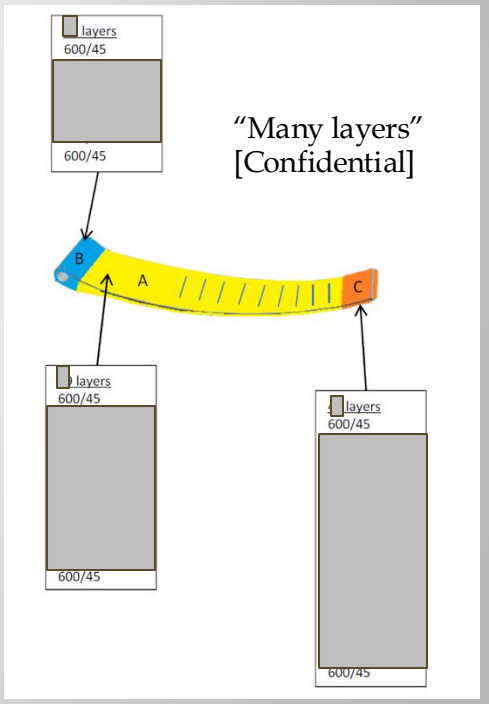
- Database with Production part testing *Vcomb_Sept10*
- Additional "Development Test"
  - Landing Gear
  - Small area parts (e.g. WID 022/023)

Database Vcomb_Sept10 (cont.)

CSA102S: 4 Tested Parts.
CSD085S: 2 Tested Parts.
CSD085M: 1 Tested Parts.
CSD086S: 4 Tested Parts.
CSD086M: 3 Tested Parts.
CSD090S: 2 Tested Parts.
CSD091S: 2 Tested Parts.
FUD017S: 2 Tested Parts.
HTD009S: 4 Tested Parts.
HTD009M: 1 Tested Parts.
HTD020S: 1 Tested Parts.
HTD021S: 1 Tested Parts.
HTD023S: 1 Tested Parts.
HTD030S: 1 Tested Parts.
HTD030M: 1 Tested Parts.
HTD031S: 1 Tested Parts.
HTD031M: 1 Tested Parts.
MGD001S: 6 Tested Parts +1.
MGD001M: 6 Tested Parts +1.
NGD030S: 4 Tested Parts.
NGD032S: 4 Tested Parts.
WID020S: 1 Tested Parts.
WID021S: 1 Tested Parts.
WID022S: 5 Tested Parts.
WID023S: 5 Tested Parts.
WID024S: 1 Tested Parts.
WID024M: 1 Tested Parts.
WID026S: 1 Tested Parts.
WID026M: 4 Tested Parts.
WID027M: 2 Tested Parts.
WID033M: 1 Tested Parts.
WID037M: 1 Tested Parts.
WID038M: 1 Tested Parts.
WID039M: 2 Tested Parts.

A Critical Part: The Main Landing Gear

- Laminate of CFRP and Fiber glass

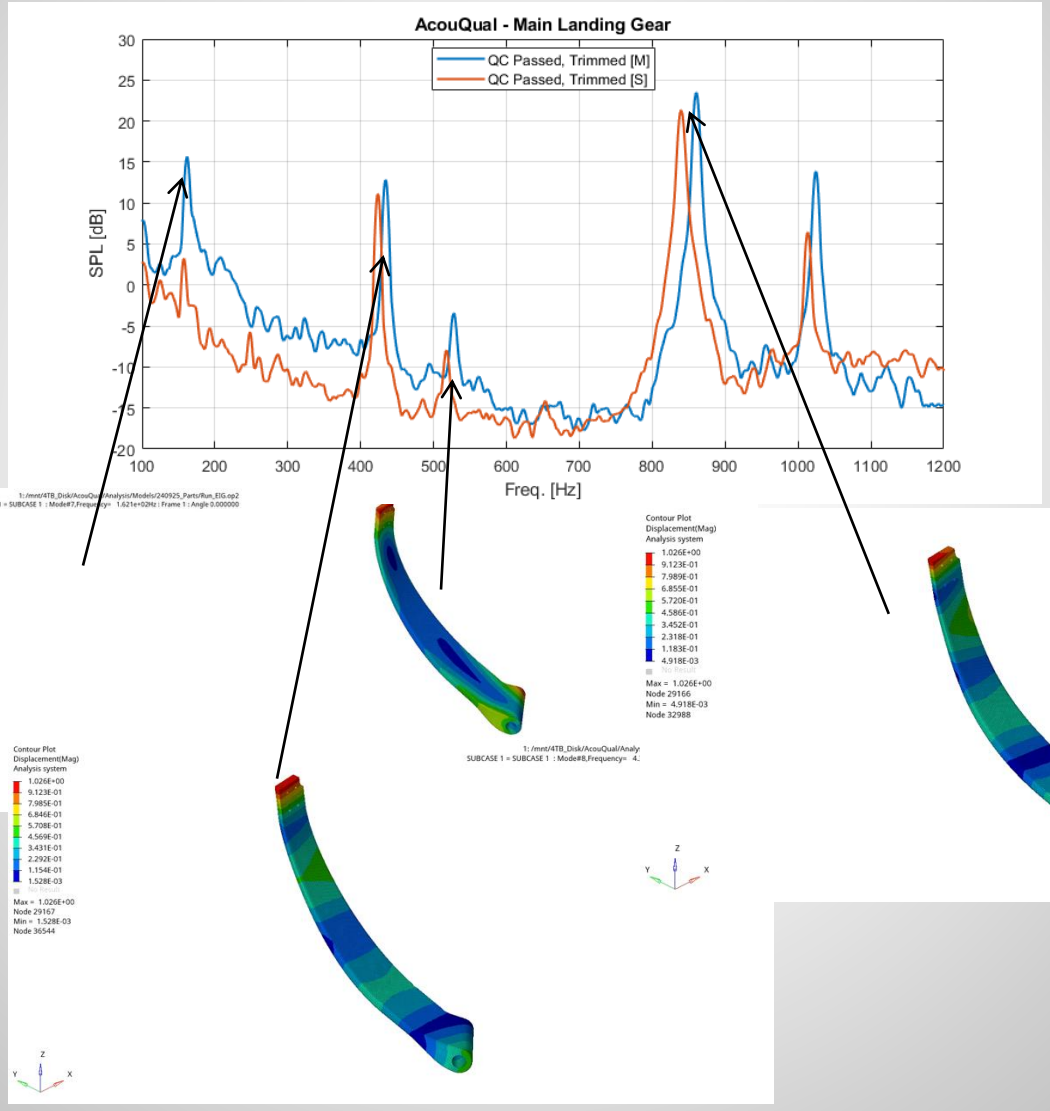


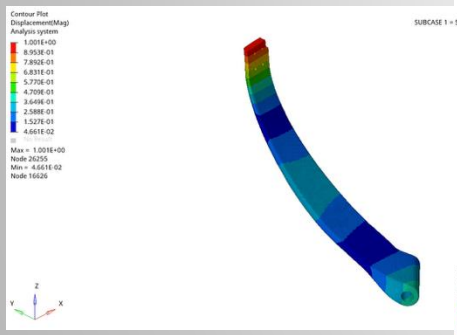
The making of parts

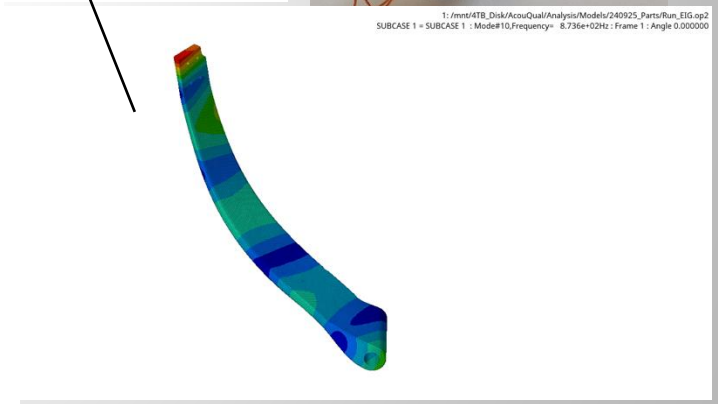
- Forming in Mold (typically aluminum Molds)
- Vacuum bagging
- Cure in autoclave [Pressure 5 Bar, Heat]

Main Landing Gear – Analysis, Test Results

- Vital Component
- Structural and Visual
- Third EigenMode is torsion, with low sound radiation

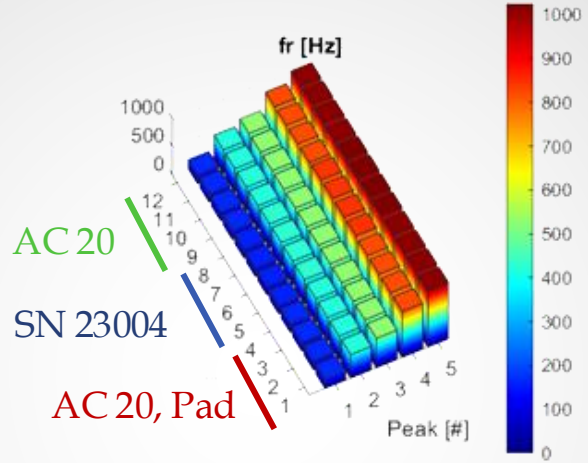


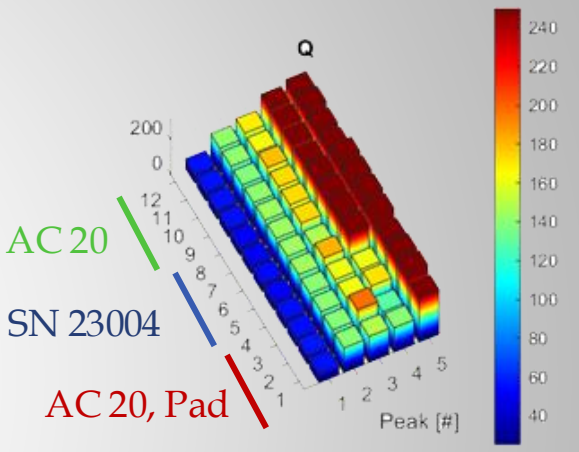




MGD 001- Main Landing Gear
A Vital Structural Part

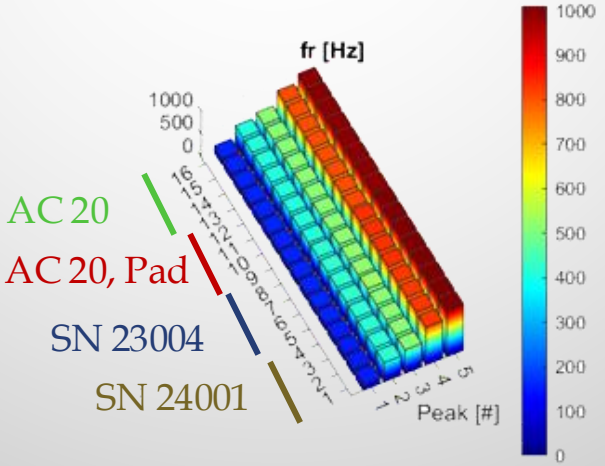
- Measurements for
  - MGD001M07E, AC 20, and SN 23004
  - "Mirror" Right Hand Side
  - Three impact locations; Test 1-3, 5-7, 9-11
  - 4, 8 and 12 are Average spectrum

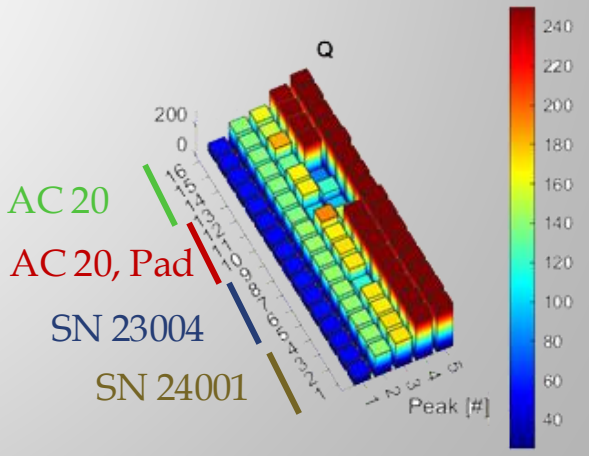




Note the Pad influence on Q

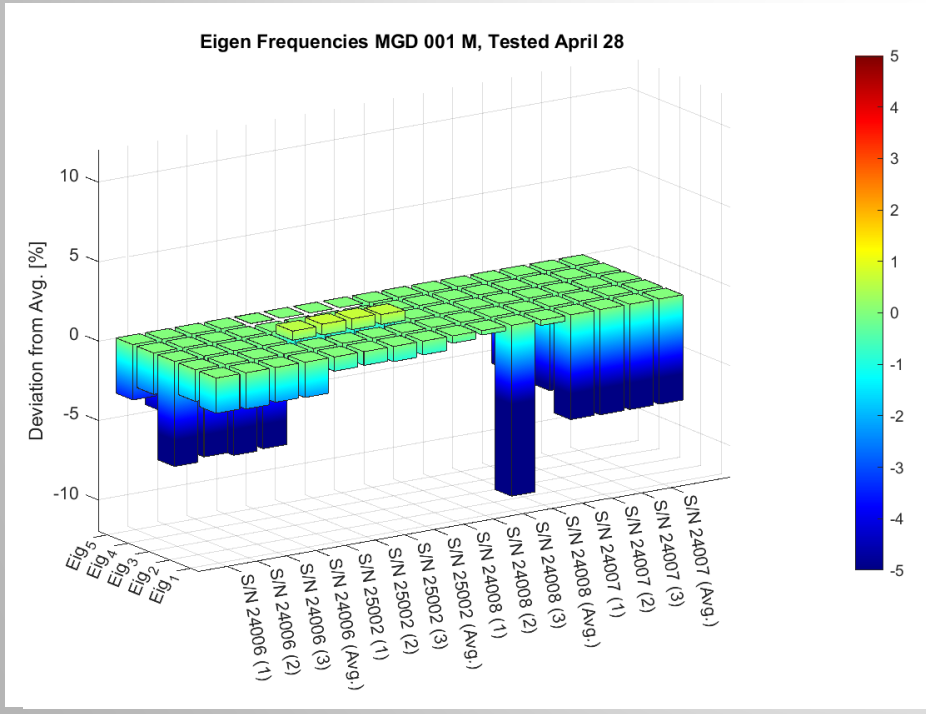
- Measurements for
  - MGD001S07E, AC 20, SN 23004, and SN 24001
  - Left Hand Side
  - Three impact locations; Test 1-3, 5-7, 9-11, 13-15
  - 4, 8 and 12 are Average spectrum

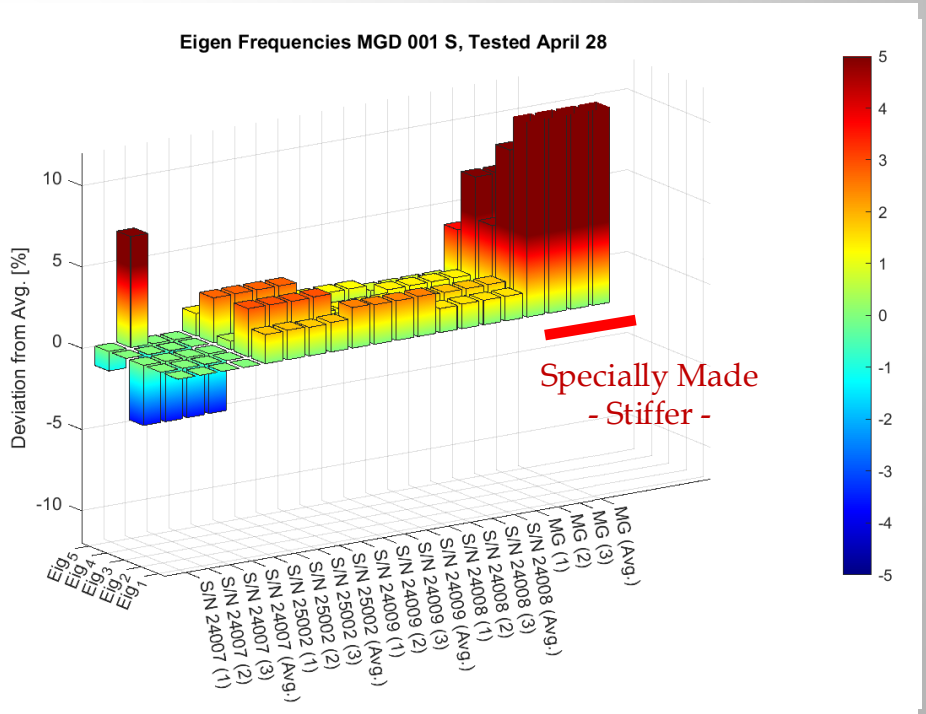




Alternative Graphic Format, a different selection of data, and a *specially made part*

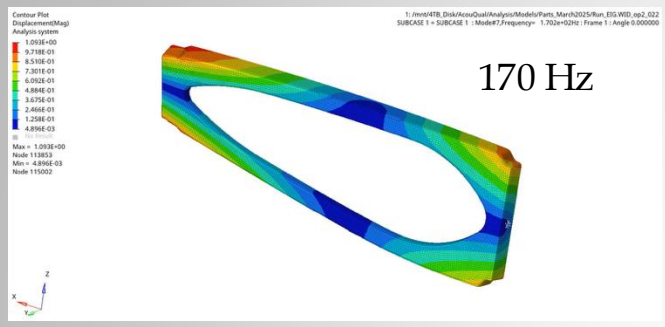
- Show Deviation in Resonance Frequency
- LHS generally stiffer
- RHS, S/N 24007 exceptionally low
- The Specially Made piece stands out stiff

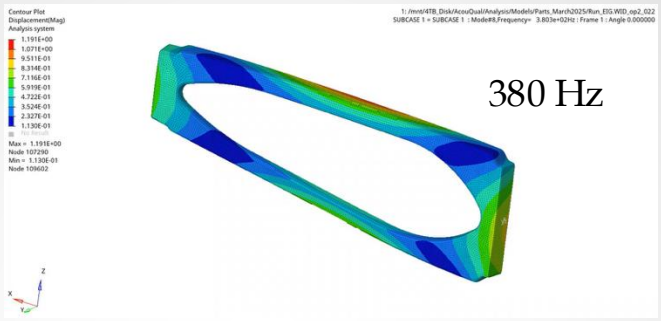


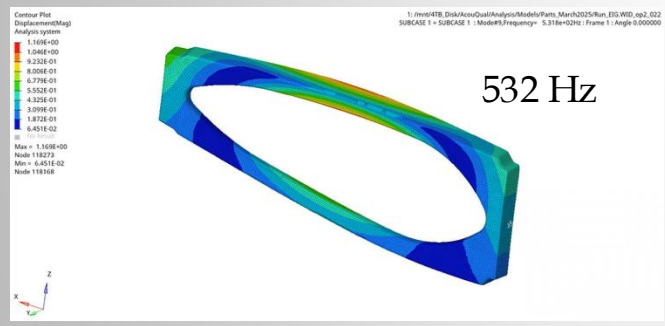


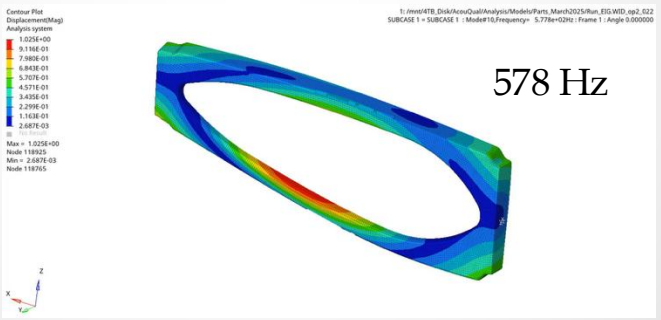
WID 022

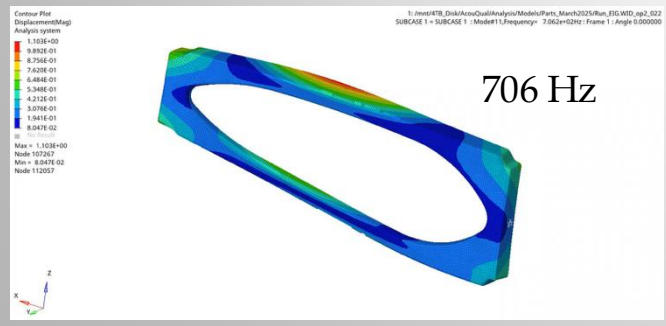
- Vital Component
- Structural, not Visual
- Several EigenModes, small dimensions, potentially giving poor sound radiation

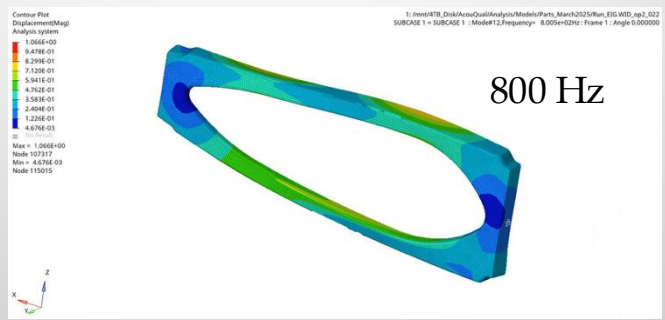


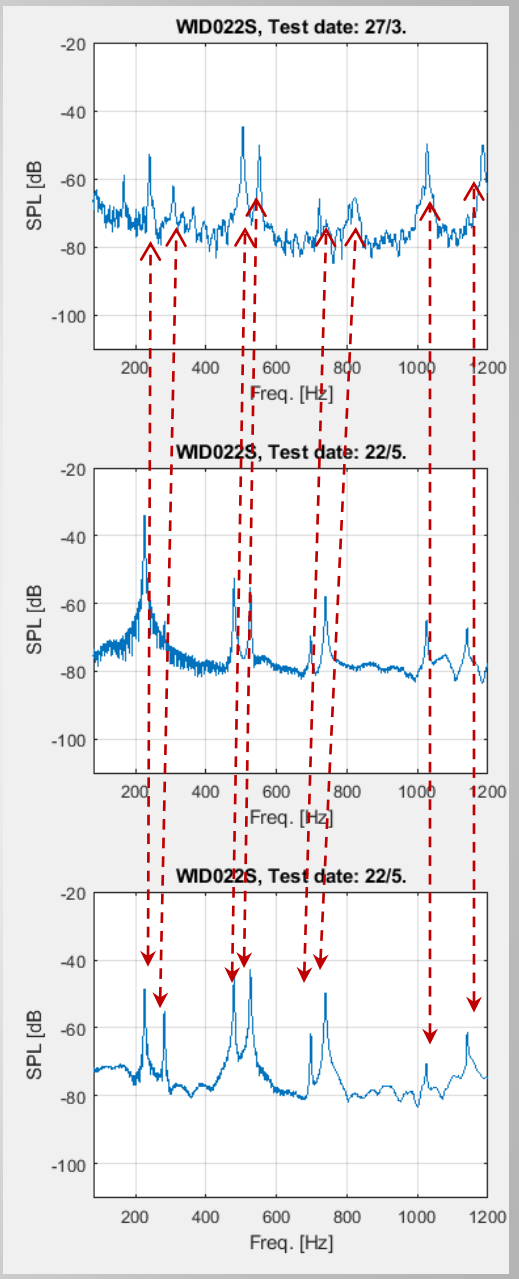




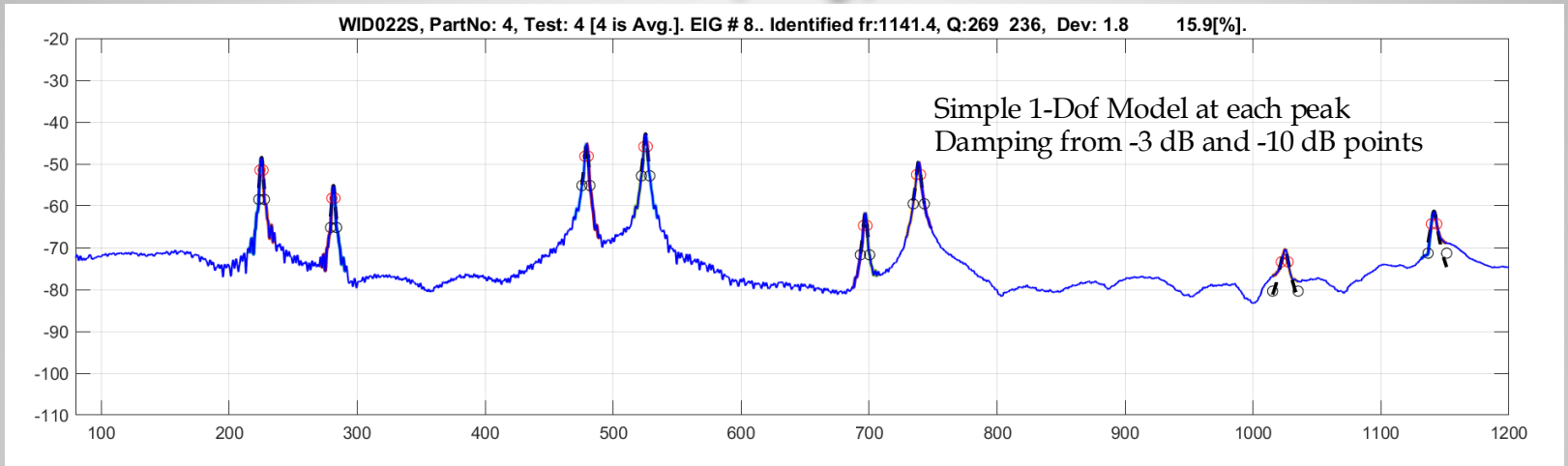




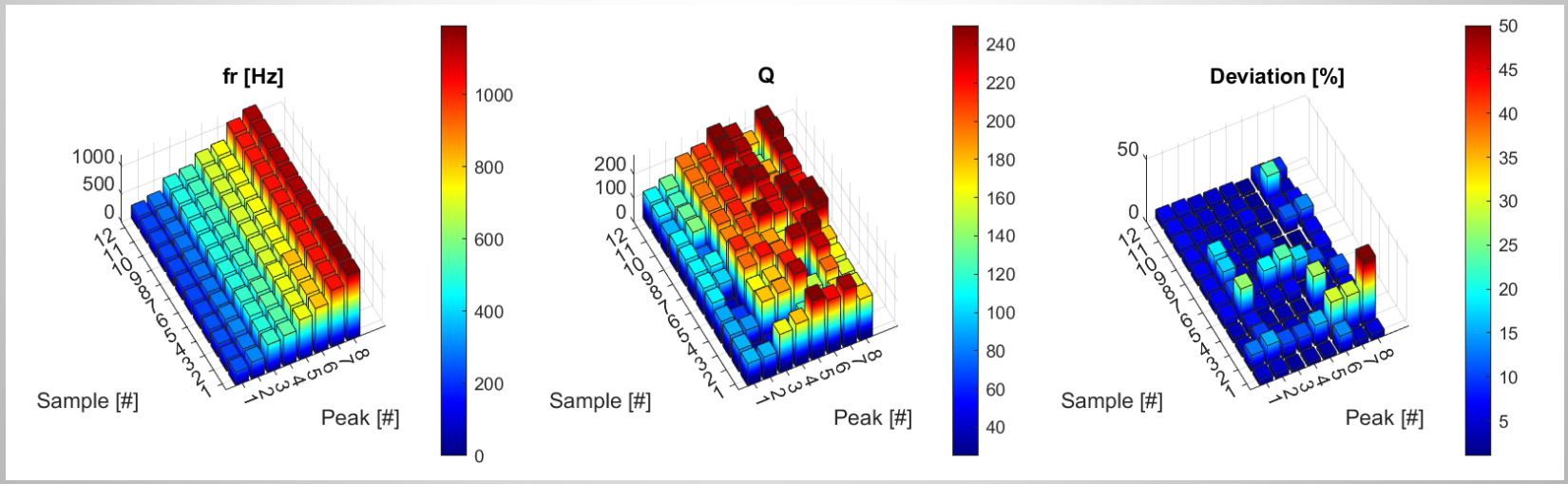




Automatic Peak finder and evaluator f, Q, Deviation



Three (3) impacts, every 4th is average of the three prev.



Way forward

- Introduce in Production line
  - Expand database
  - Further develop quality validation criteria
  - Consider changing from MATLAB environment to Python Software
- Potential extension
  - Apply on Assemblies, with the ultimate goal of testing on complete Aircraft

Acknowledgement

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For the financial support [50% of the project budget]

- End of Presentation -

Research Project
AcouQual
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