Exploration of Wire Tension with Cold Electronics

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BNL

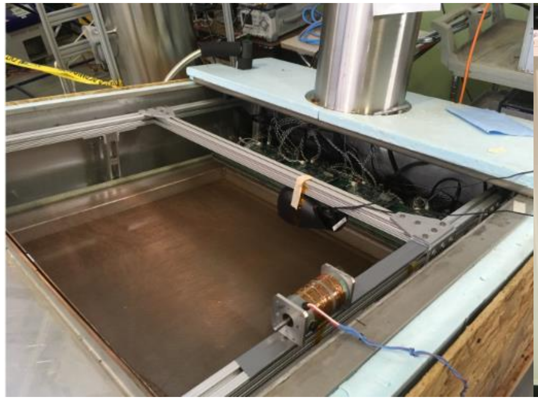
Wire tension measurement

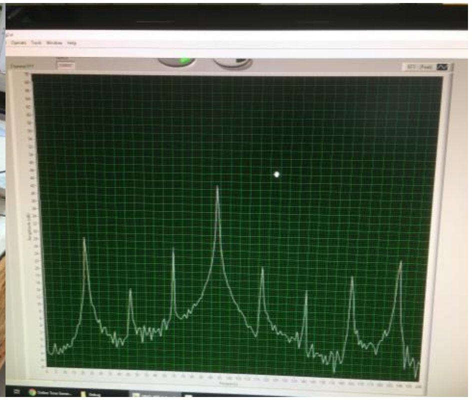
- **$T = 4\mu f^2 L^2$, f: fundamental frequency**
- Laser method[1]
  - Time-consuming expensive, complicated laser positioning system
- Electrical method[2]
  - No mechanical disturbance required
- In-situ method[3]
  - Take all wire data simultaneously
  - Reuse the cold electronics system

[1]: https://www.bnl.gov/isd/documents/95423.pdf
[2]: https://arxiv.org/pdf/1804.05941.pdf
[3]: https://indico.fnal.gov/event/19889/contribution/2/material/slides/0.pdf

Sebastien's previous test on 40% APA

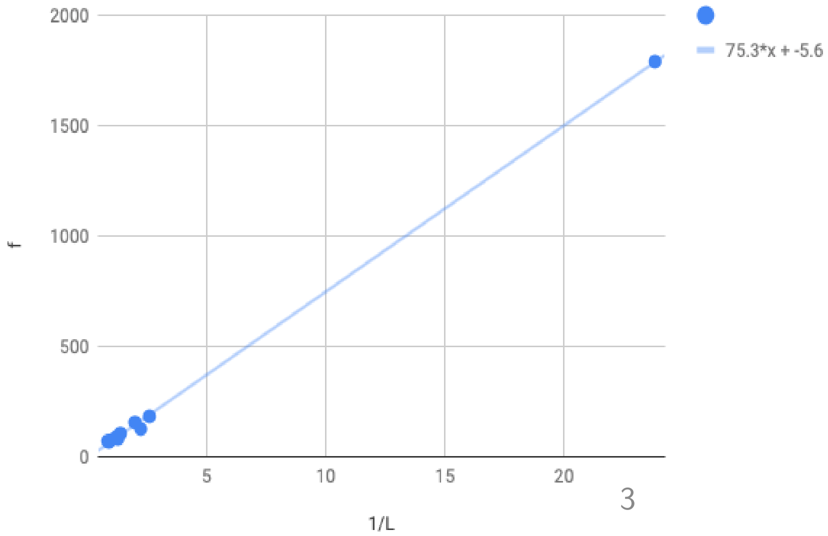
- 40% APA at BNL
  - 2.8m * 1m
  - U & V angle ~ 45 deg
- Vibrate wires at once
  - Acoustic, motor, wood-stick, etc.
  - Some intrinsic frequencies observed from CE
  - Issues
    - Interference from neighboring-wire vibration?
    - Impact of vibration modes from APA frame?





- If only pluck individual wires (however, not the way we want)

$T = 4\mu f^2 L^2$ →



Capacitance for multiple conductors (wires)

Coefficient of capacitance

$$\underbrace{\begin{bmatrix} q_0 \\ q_1 \\ \vdots \\ q_n \end{bmatrix}}_{\mathbf{Q}'} = \underbrace{\begin{bmatrix} \mathscr{C}_{00} & \mathscr{C}_{01} & \cdots & \mathscr{C}_{0n} \\ \mathscr{C}_{10} & \mathscr{C}_{11} & \cdots & \mathscr{C}_{1n} \\ \vdots & \vdots & \ddots & \vdots \\ \mathscr{C}_{n0} & \mathscr{C}_{n1} & \cdots & \mathscr{C}_{nn} \end{bmatrix}}_{\mathscr{C}} \underbrace{\begin{bmatrix} \phi_0 \\ \phi_1 \\ \vdots \\ \phi_n \end{bmatrix}}_{\Phi}$$

- General relation of Q and C,V for a system of multiple conductors

- In our APA system,

$Q_U = \sum C_{UG}\phi_G + \sum C_{UU}\phi_U + \sum C_{UV}\phi_V + \sum C_{UX}\phi_X$,

- Q_U: charge on a U-wire
- C_{Uj}: capacitance coefficient between a U-wire and a j-wire
- ϕ_j: potential on a j-wire

- If a U wire is vibrating, it induces current from its capacitance coupling
  - to adjacent wire plane
  - to adjacent wires in the same plane
- $\phi_V = 0$. ϕ_G, ϕ_U and ϕ_X can be controlled **individually**

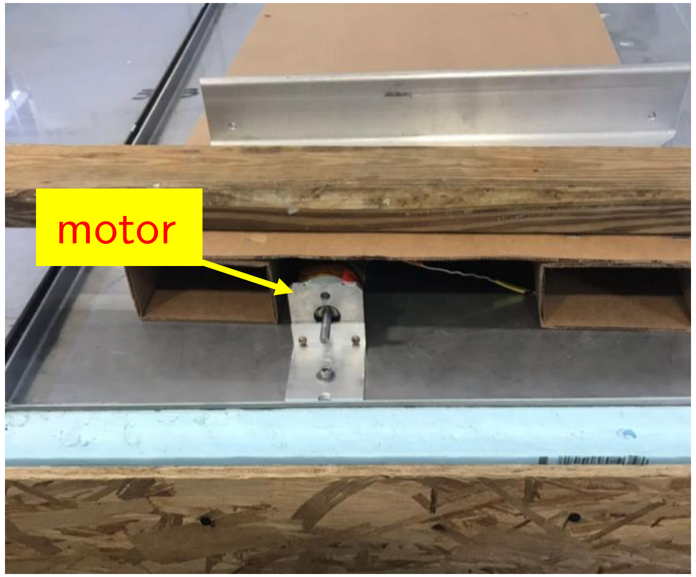
Goals in the new test

- Test 1: demonstrate that capacitance couplings can be controlled by turning on/off the bias voltage

- Test 2: can we observe the intrinsic vibration frequency of a wire by vibrating the entire APA system?
  - Higher harmonic, (environmental, test-induced) background noise, cross talk (to nearby wire planes, to adjacent wires) ...

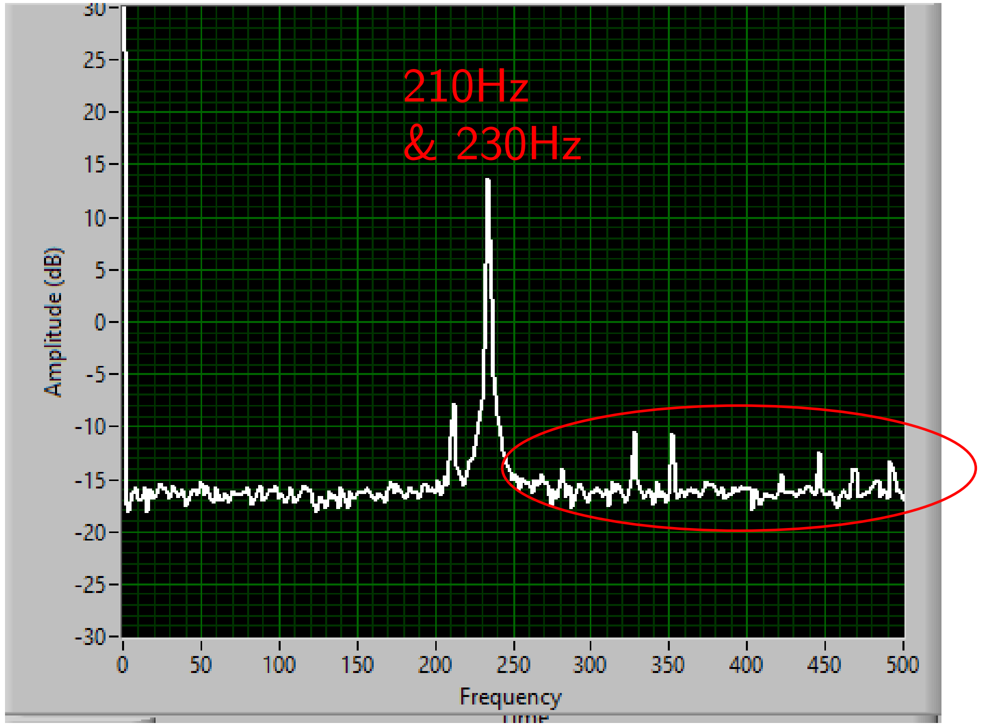
- Our ultimate goal: vibrate the APA frame at once => wire tension info.
  - Or it could be a relative measurement, check the consistency at the factory and at the assembly site

Test 1: Turn on/off U plane

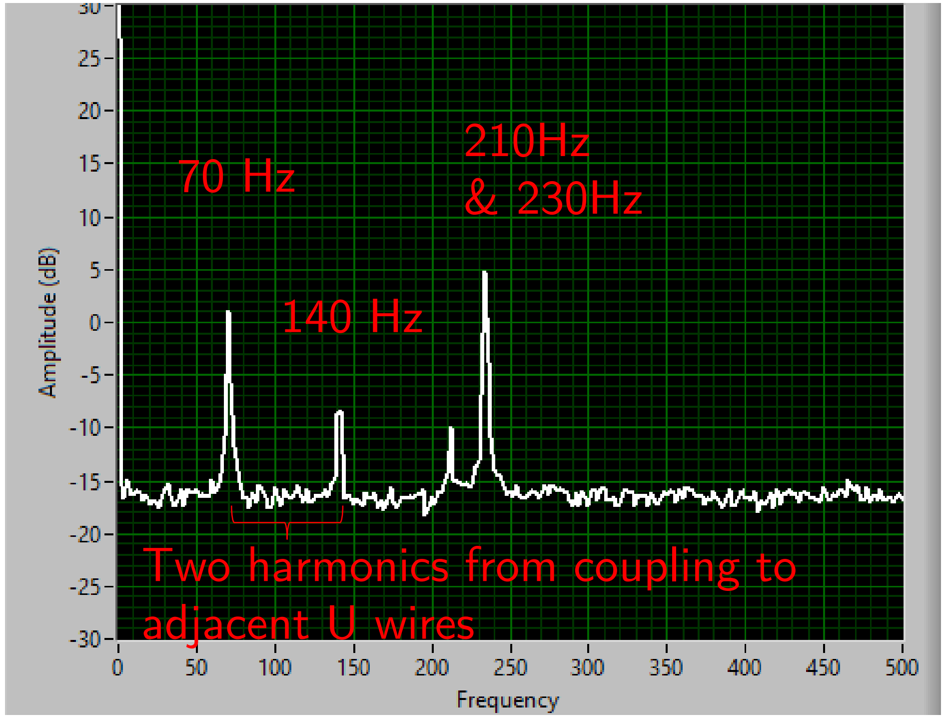


- Vibration with motor continuously
- Take average FFT (wire U-19)

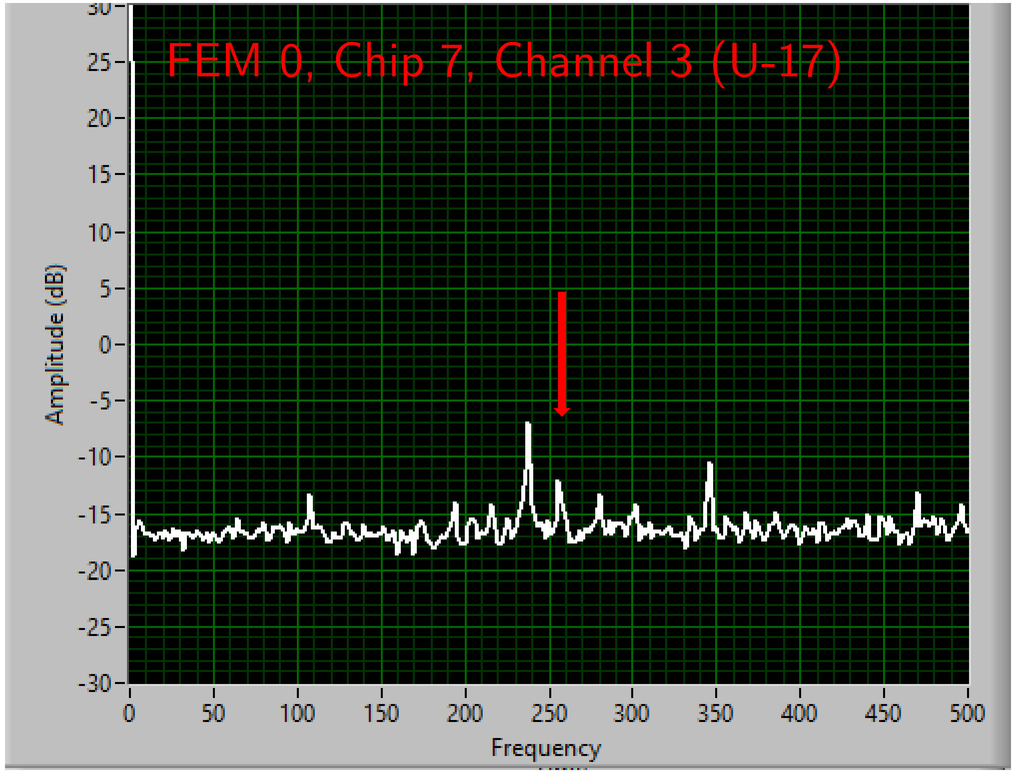
Grid -50V



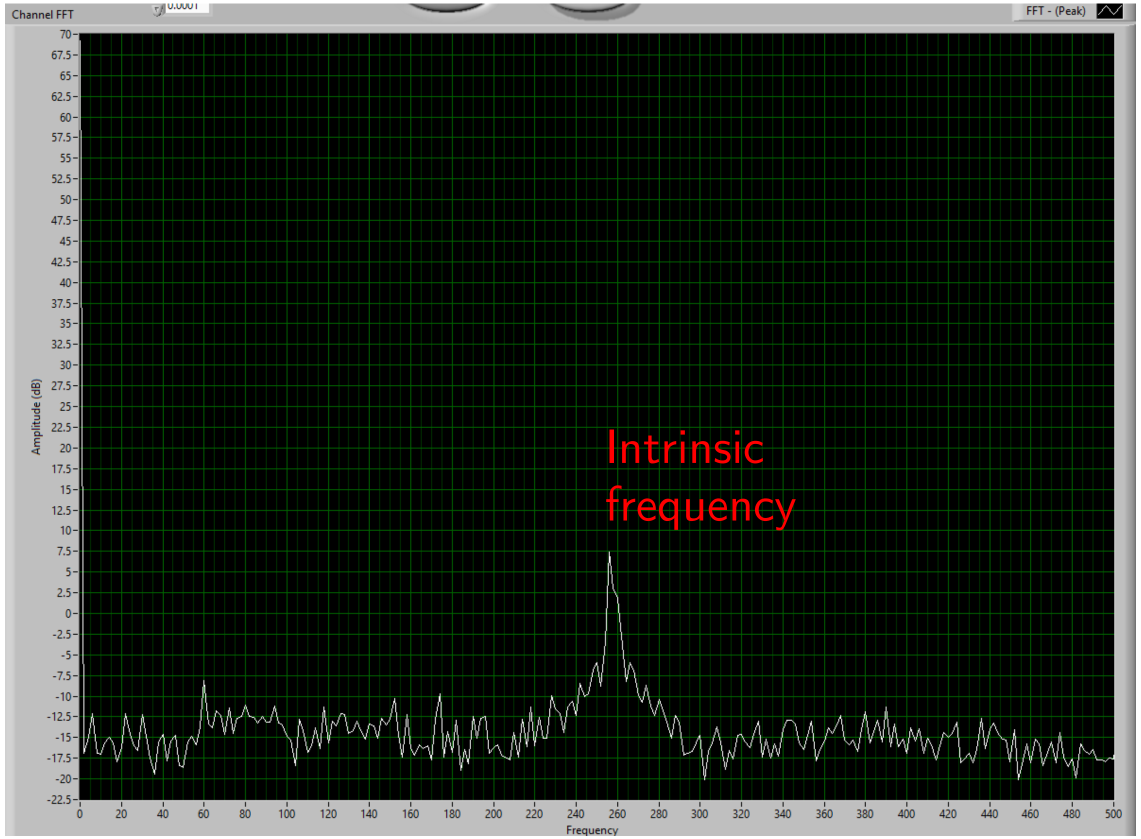
Grid -50V
U -50V



Test 2: intrinsic frequency of U-17 wire



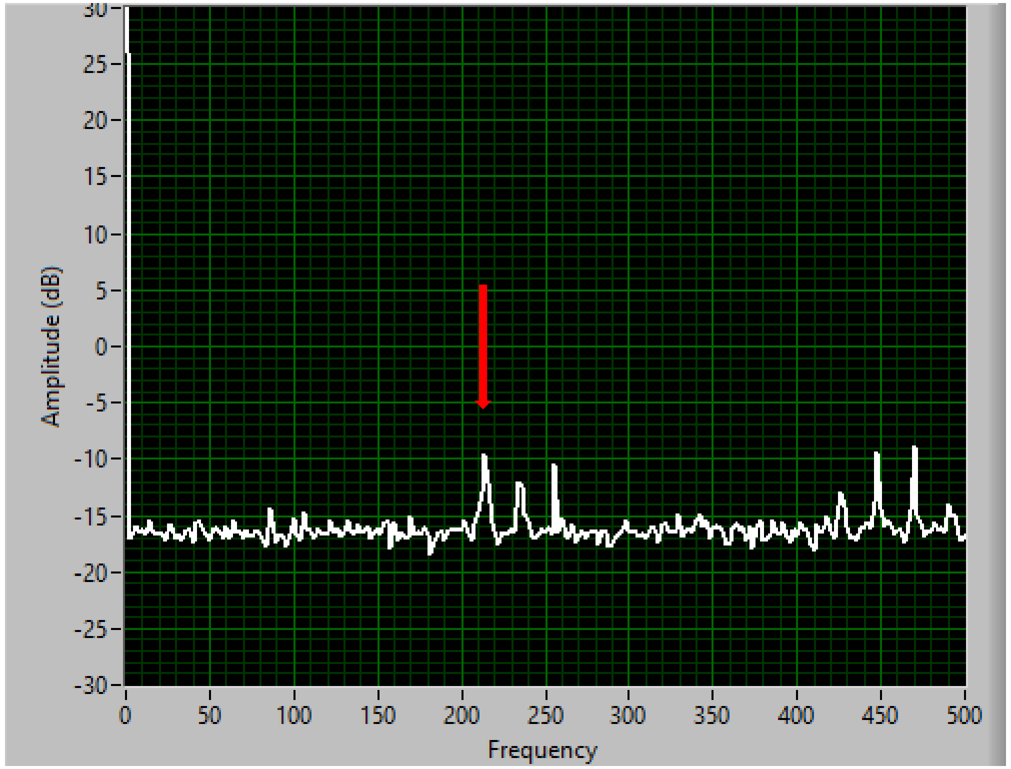
Grid plane with bias voltage only
Motor vibration on



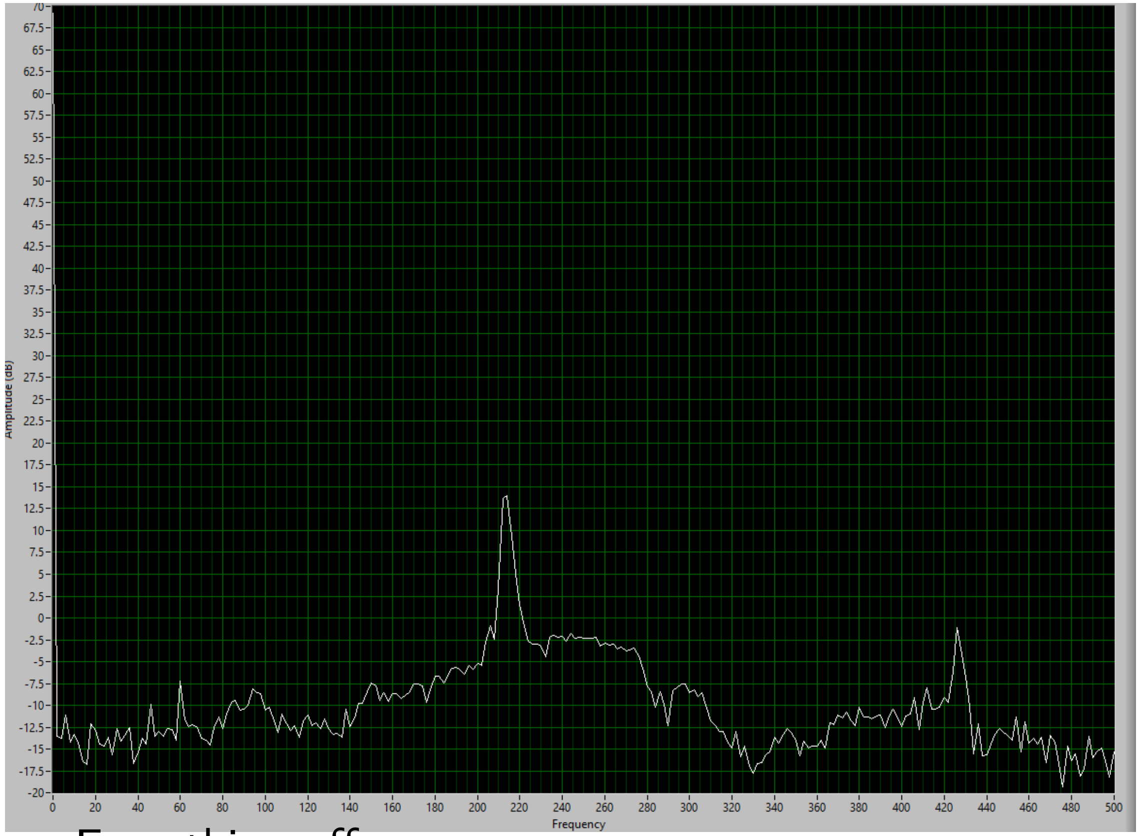
Everything off,
touching this particular wire

These could be the same peak at 250-260 Hz in both cases...

FEM 0, Chip 7, Channel 1 (U-18)



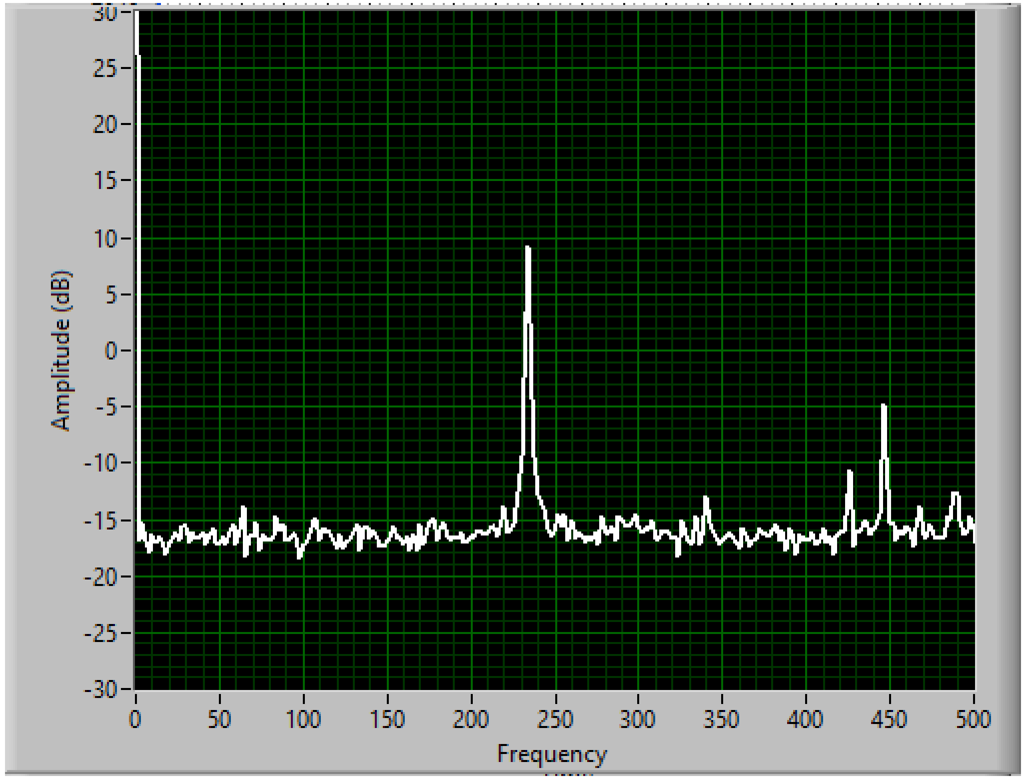
Grid plane with bias voltage only
Motor on

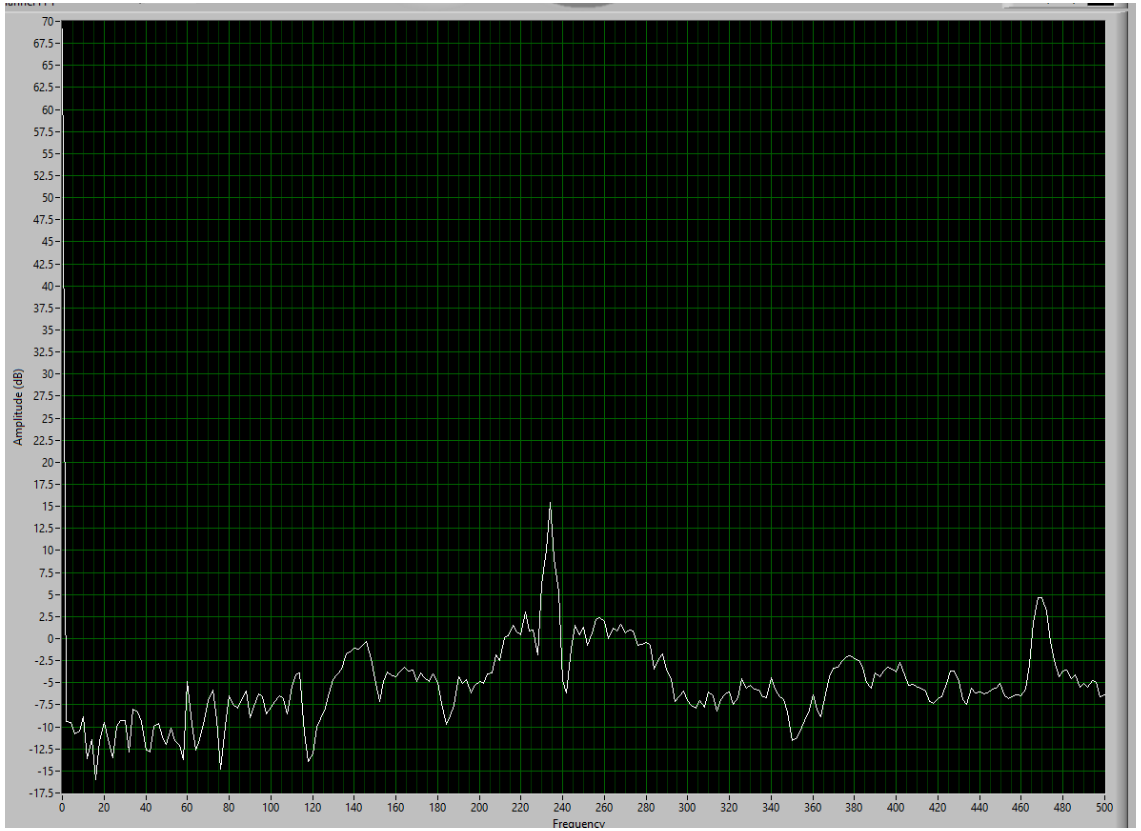


Everything off,
touching this particular wire

These could be the same peak at 210-220 Hz in both cases...

FEM 0, Chip 3, Channel 15 (U19)



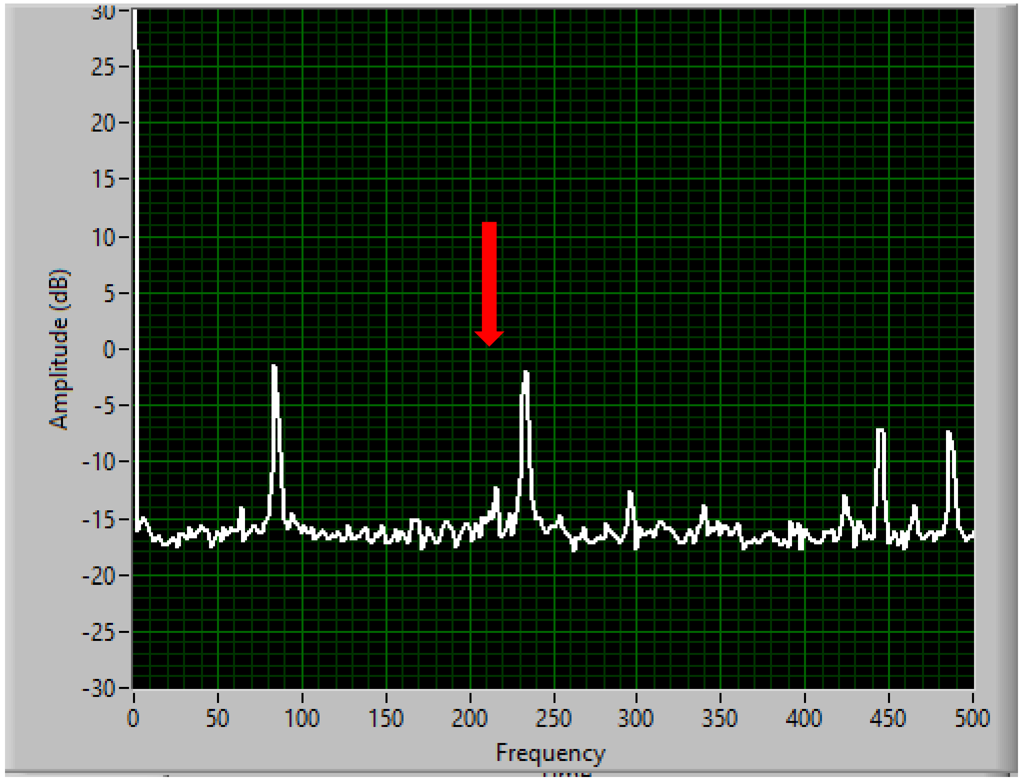


Grid plane with bias voltage only
Motor on

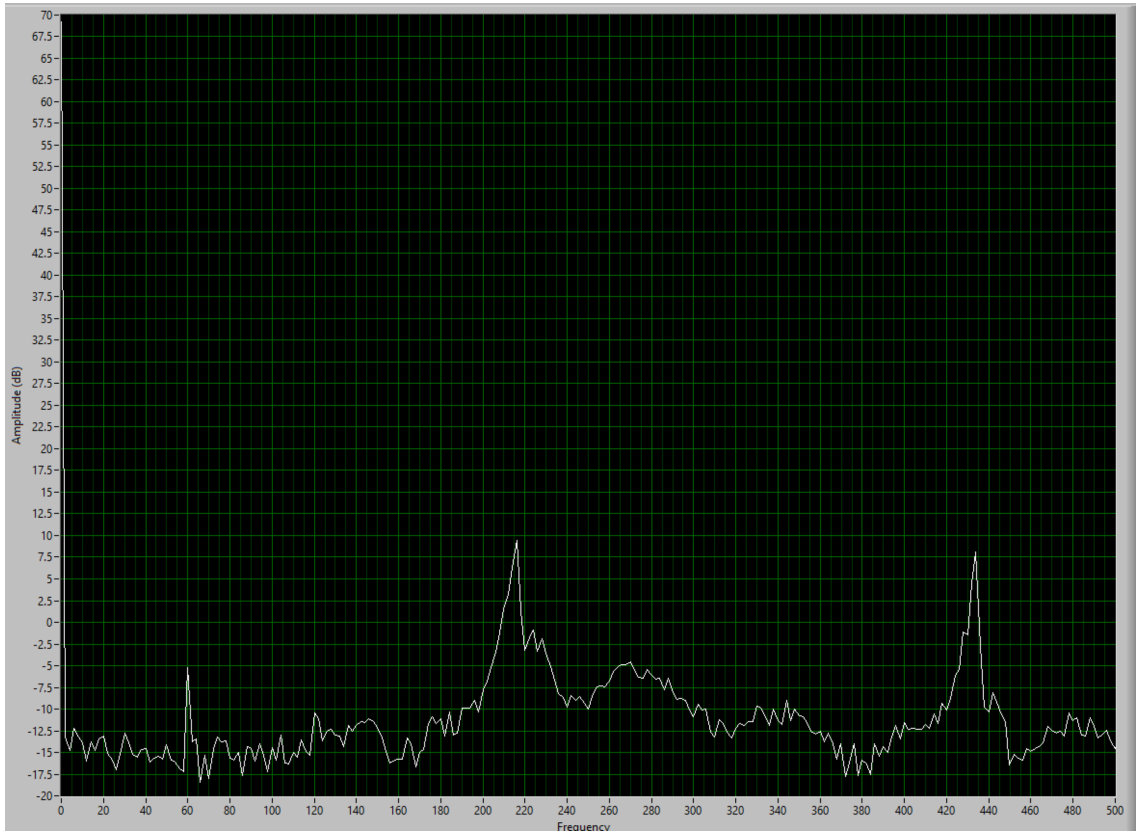
Everything off,
touching this particular wire

Same frequencies show up in both cases

FEM 0, CHIP 3, Channel 13 (U20)



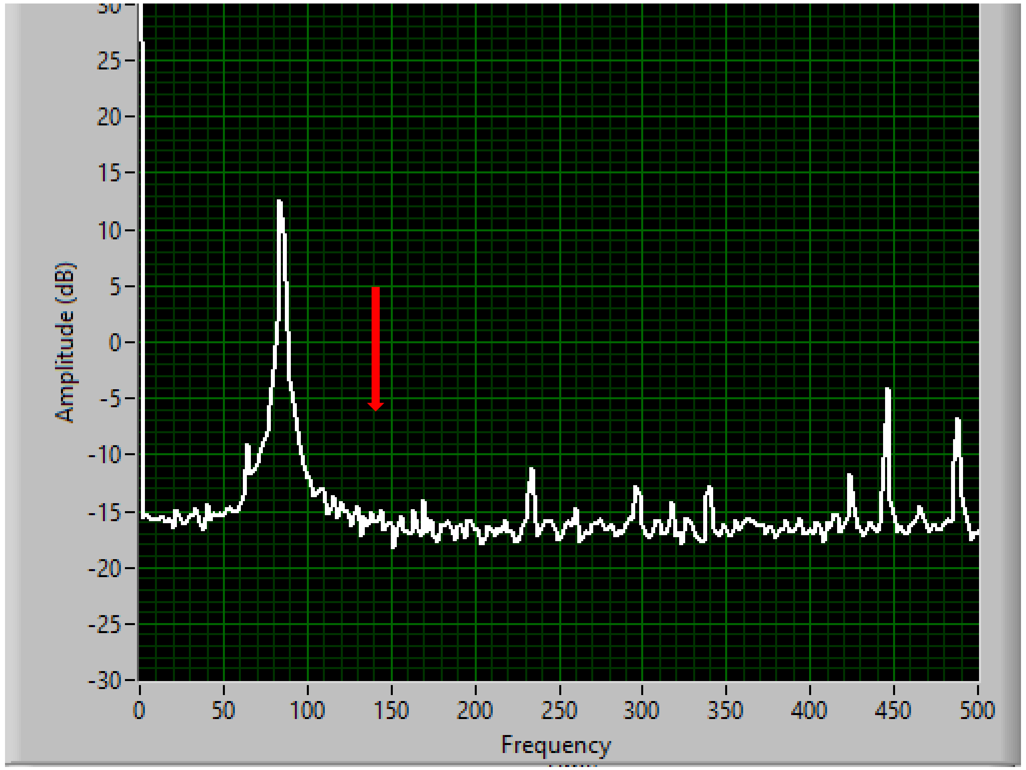
Grid plane with bias voltage only
Motor on



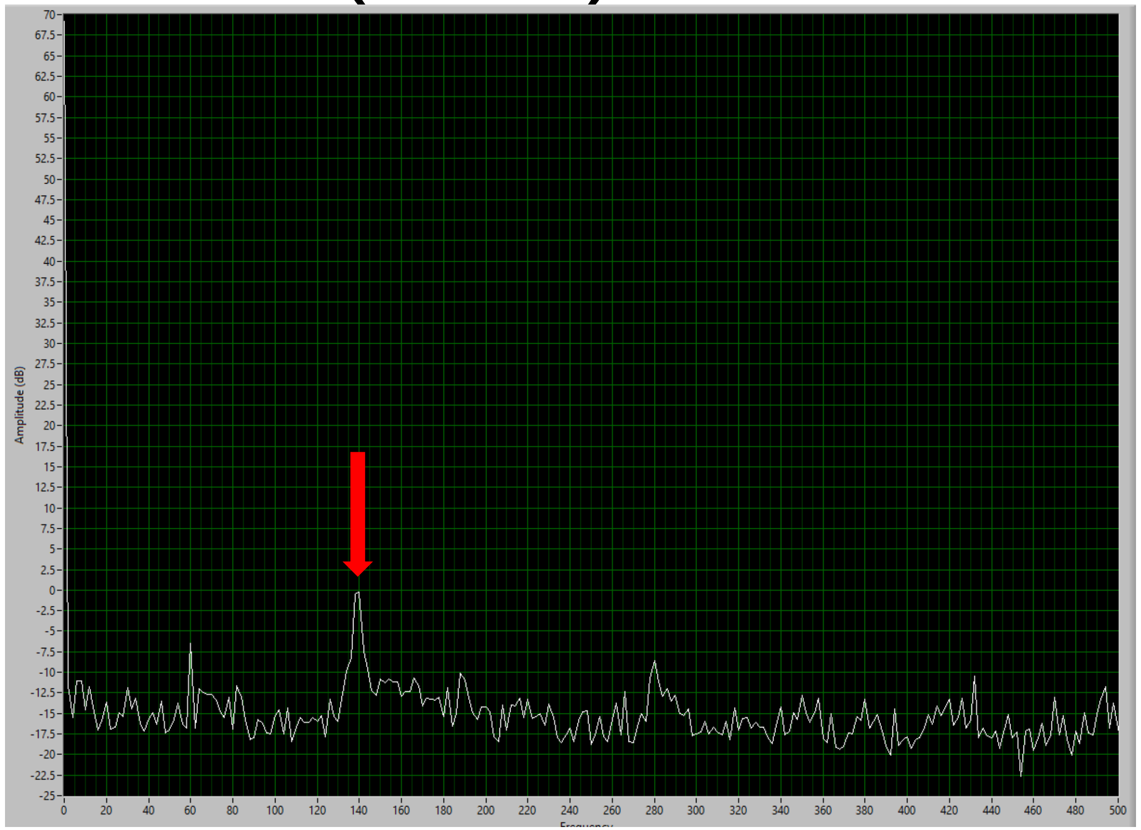
Everything off,
touching this particular wire

There are signs of a small peak at 215 Hz ...

FEM 0, CHIP 3, Channel 11 (U21)



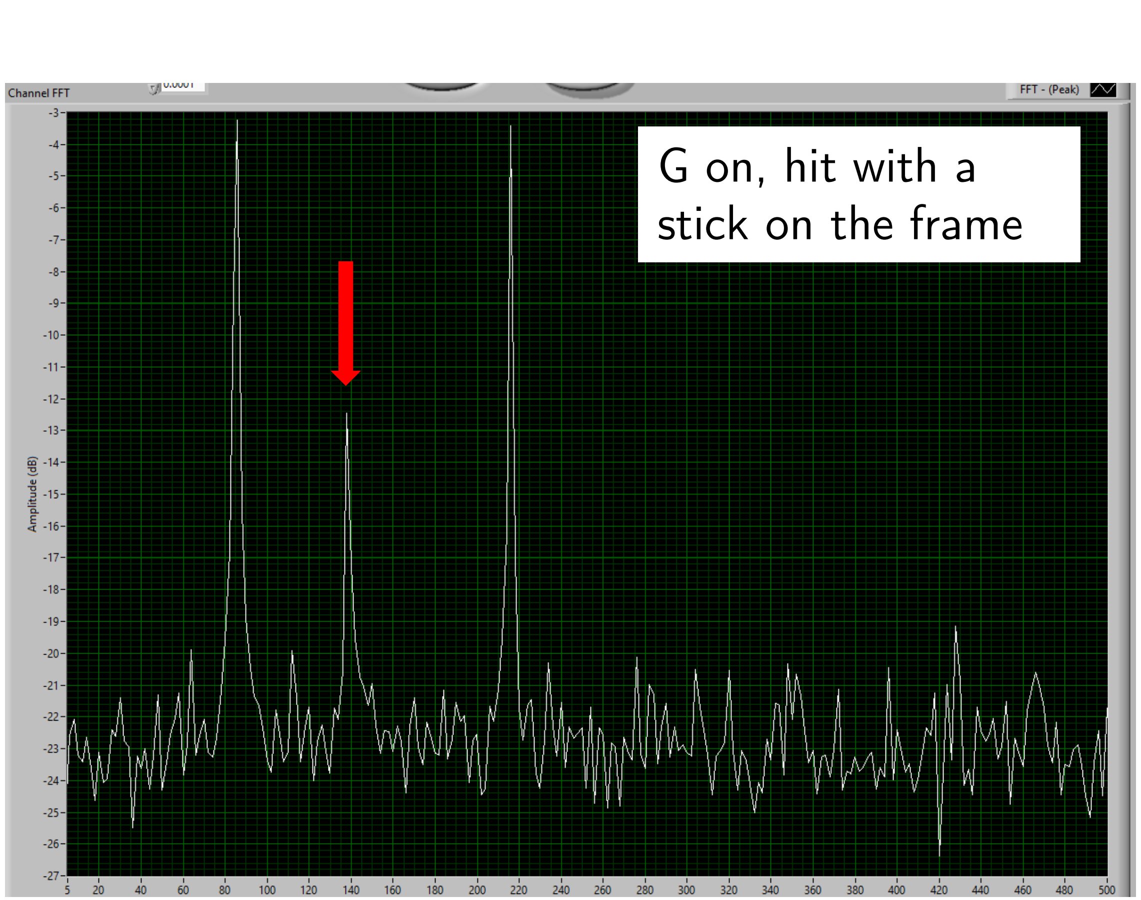
Grid plane with bias voltage only
Motor on

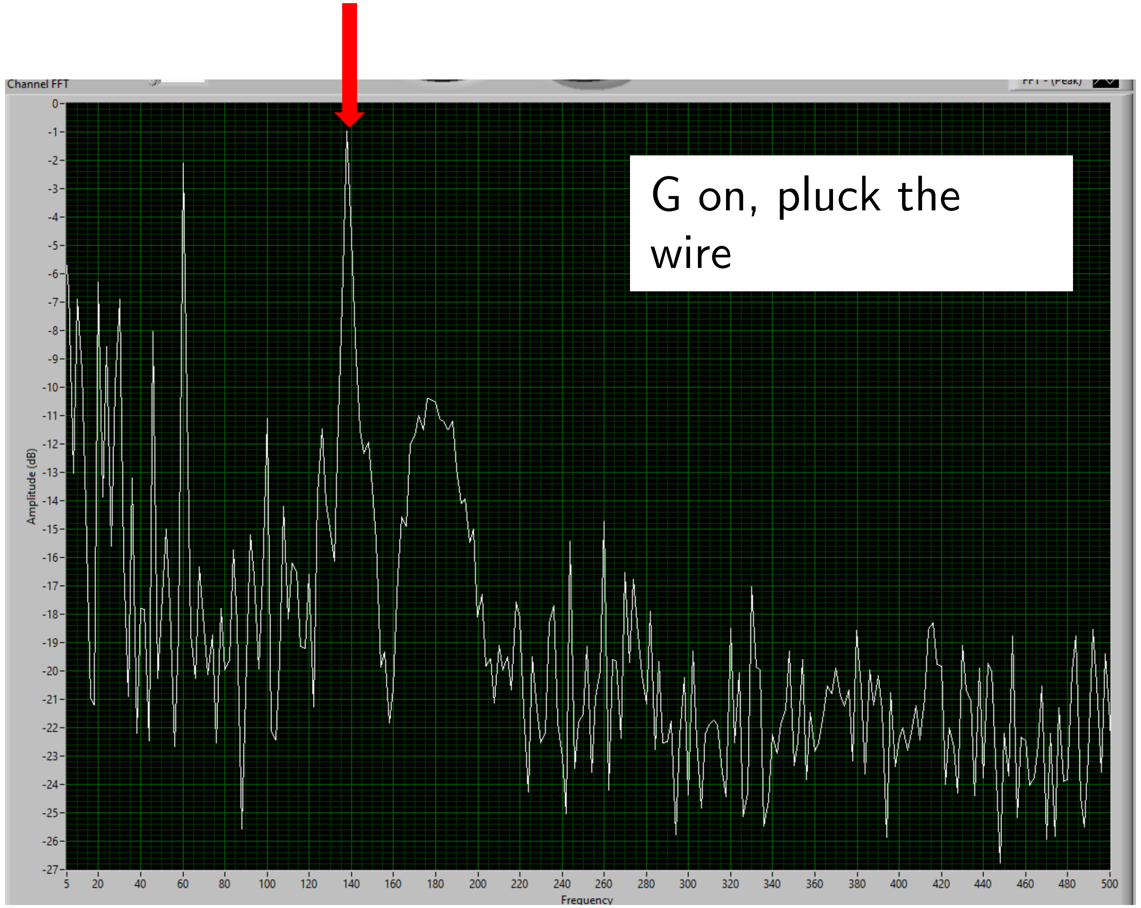


Everything off,
touching this particular wire

There is no peak at 140 Hz ...

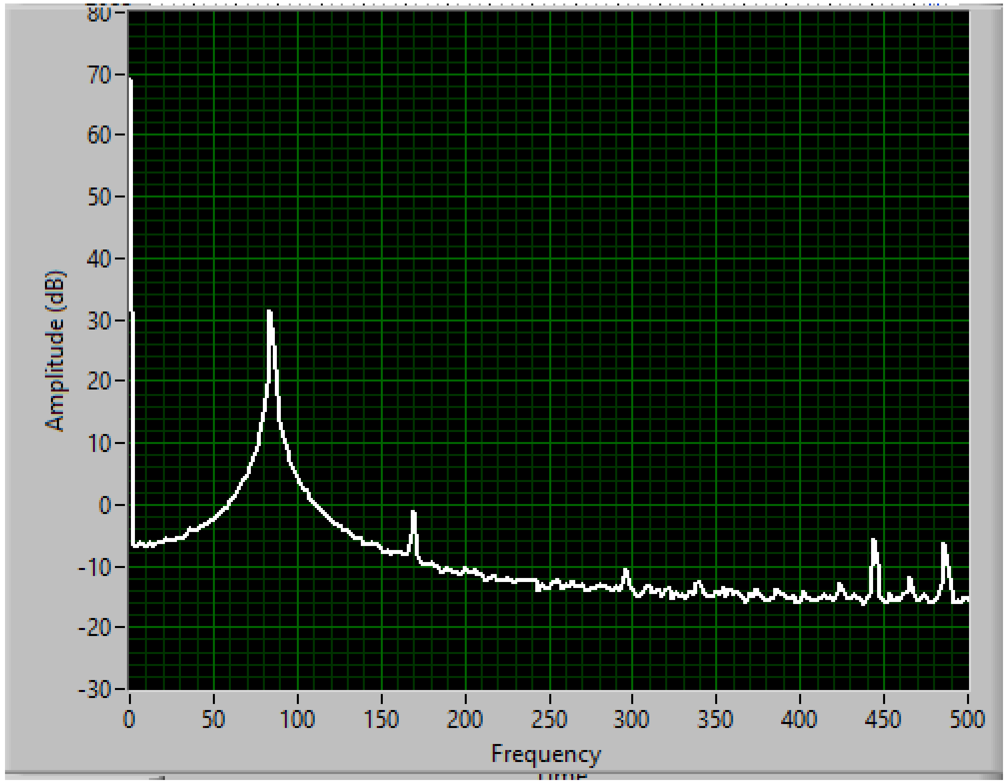
FEM 0, CHIP 3, Channel 11 (U21)



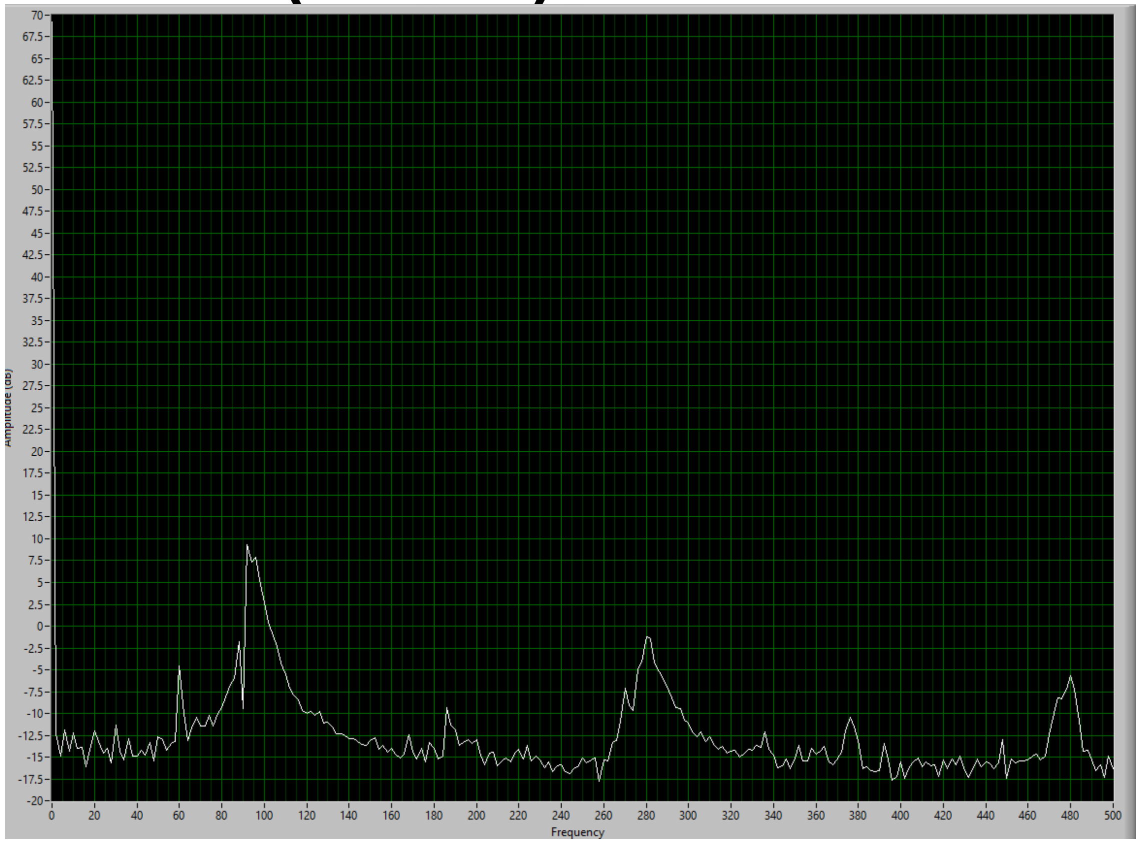


Although we cannot excite the intrinsic frequency with motor vibration, we can do it by hitting the frame with a wood stick

FEM 0, CHIP 3, Channel 9 (U22)



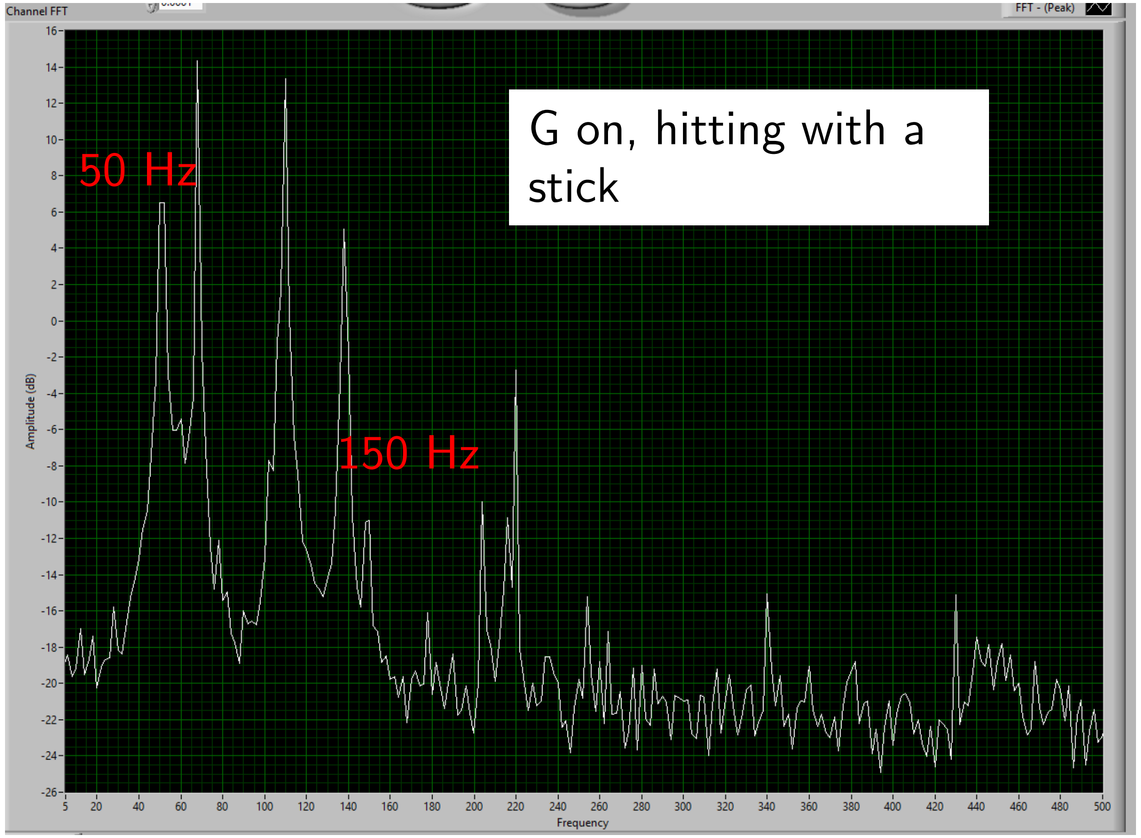
Grid plane with bias voltage only
Motor on

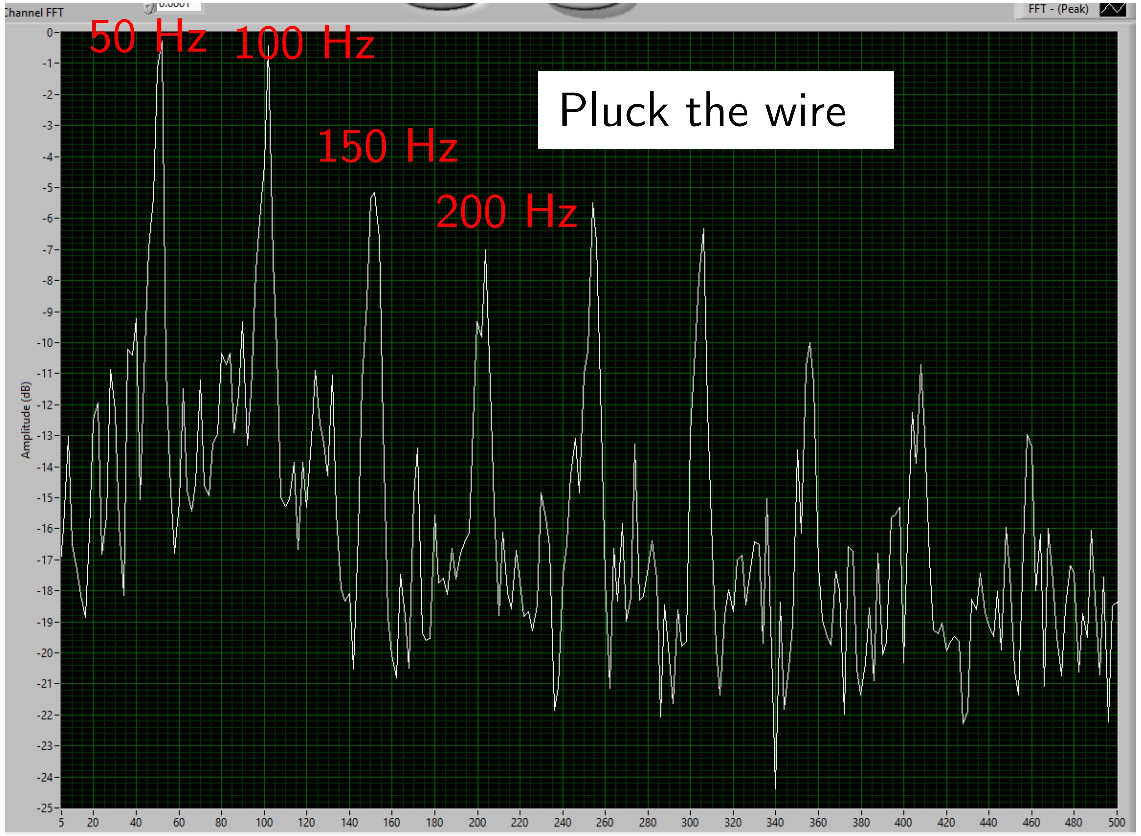


Everything off,
touching this particular wire

These could be the same peak at 80-90 Hz in both cases…

FEMB3, CHIP4, CH5, long U wire (tension confirmation)





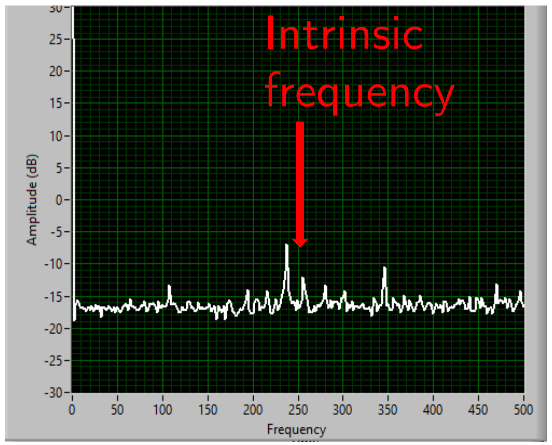
Wire is about 1.4 m long, assuming 5 N, we have about ~60 Hz intrinsic frequency
Measured to be about 50 Hz, good enough

Discussions

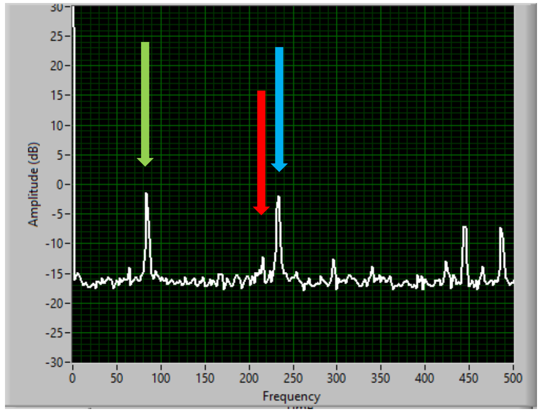
- There are 3 cases, where the intrinsic frequencies can be identified in both cases
  - Another 1 case may be good
- There is 1 case, where the excitation with motor is weak
- There is 1 case, where we can not see the excitation with motor at all

- Certain modes may not be able to be excited with motor
  - We should try other ways to excite (e.g. hitting the frame with a wood stick), confirm the finding on the U wire, extend to wires that we cannot touch (V and W wires?)

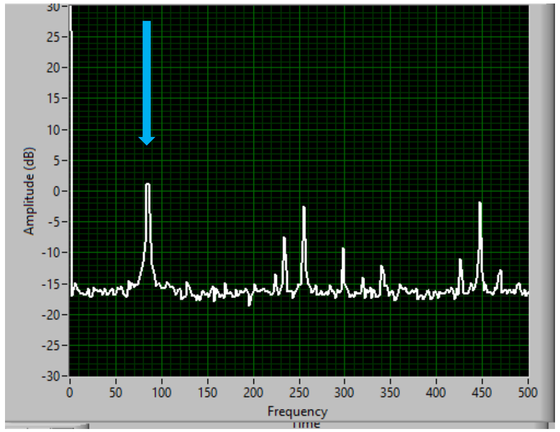
U17



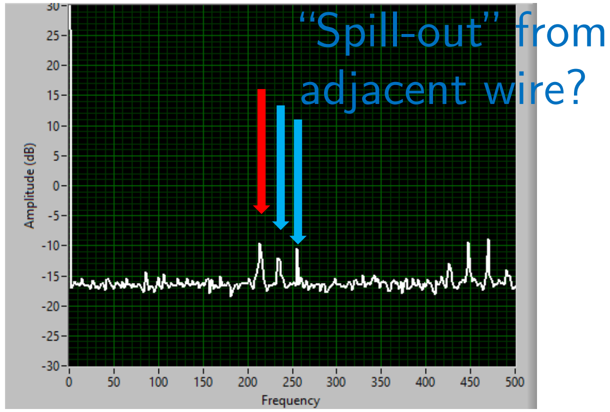
U20



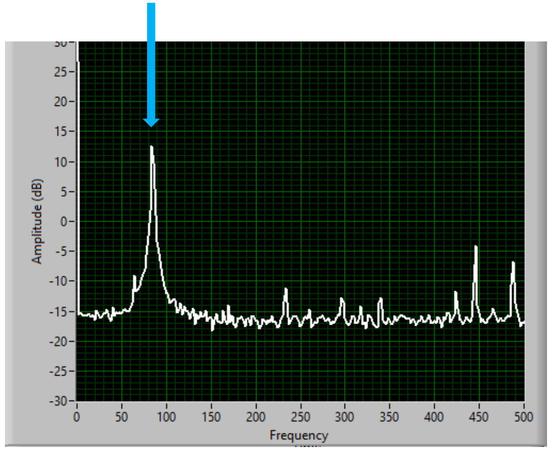
U23



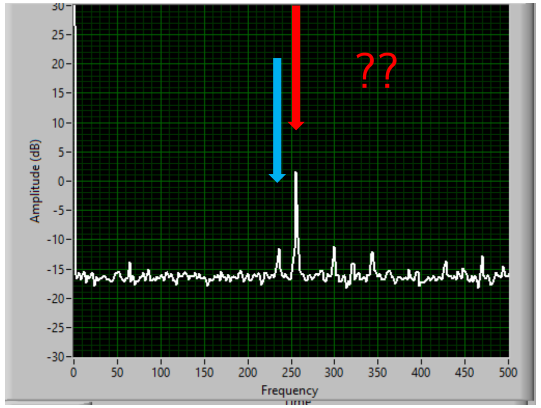
U18



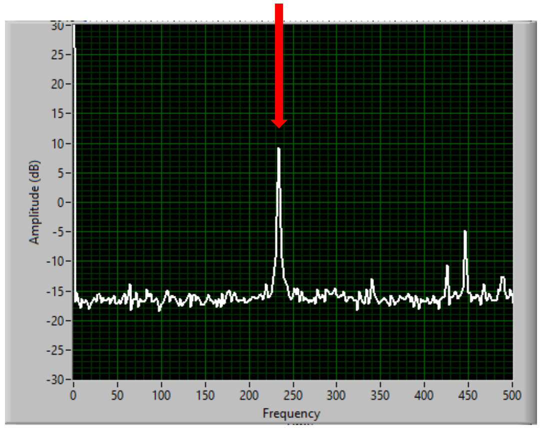
U21



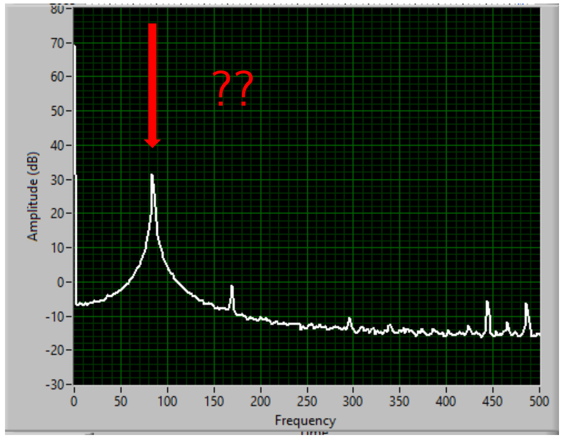
U24



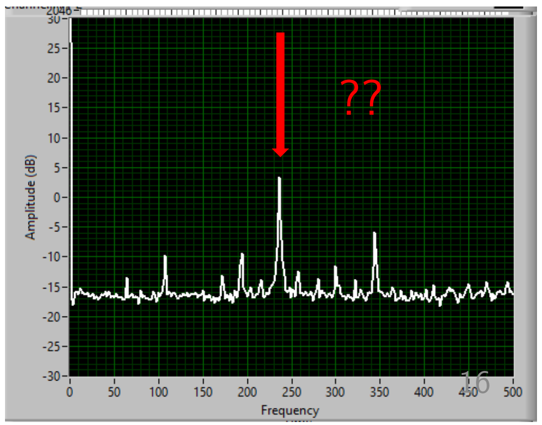
U19



U22



U25



Discussions

- When the grid plane voltage is on, it seems that we can excite some intrinsic frequencies of the wires
  - Not all cases though …
- There is a spill-out effect, the adjacent wires may pick up the same frequencies, but usually at a much lower amplitude, but the reduction is not clear enough …
- Need to understand better the situation of "spill out", when we can take all data simultaneously …
  - Is there any pattern in the reduction in magnitude? Similar to the problem of field response in signal processing
  - See next slide for a model prediction

Basic Model: Wires above Ground Plane

- Construction of the Induction matrix “L”, we can then deduced capacitance matrix

$$\mathbf{C} = \mu\varepsilon\,\mathbf{L}^{-1}$$

$$L_{ii} = \frac{\mu}{2\pi}\ln\left(\frac{2h_i}{r_{wi}}\right)$$

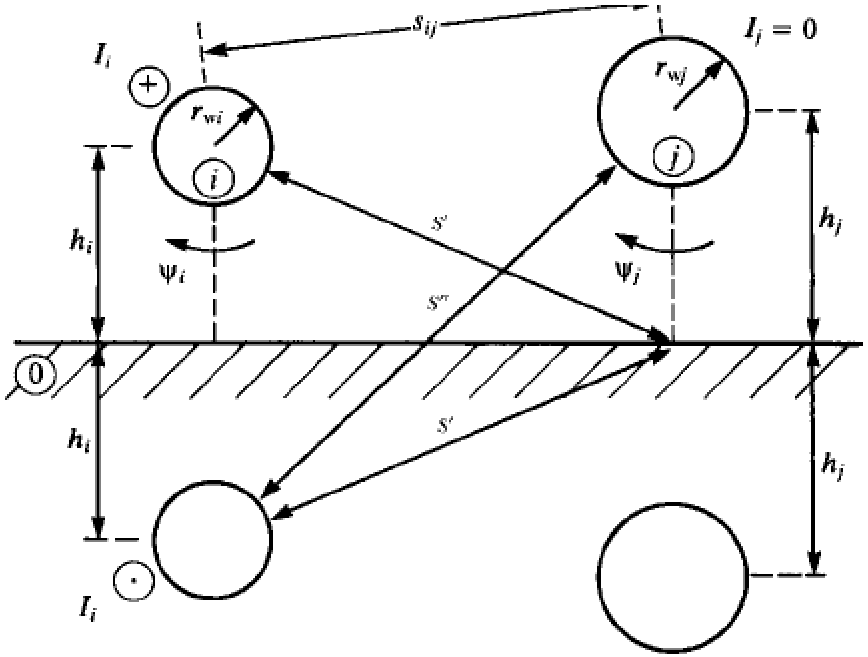
$$L_{ij} = \frac{\mu}{4\pi}\ln\left[1+\frac{4h_i h_j}{s_{ij}^2}\right] \qquad i \neq j$$

$Q = C \cdot V$

Q: (vector) charge on wires

C: (matrix) capacitance matrix

V: (vector) potential on wires

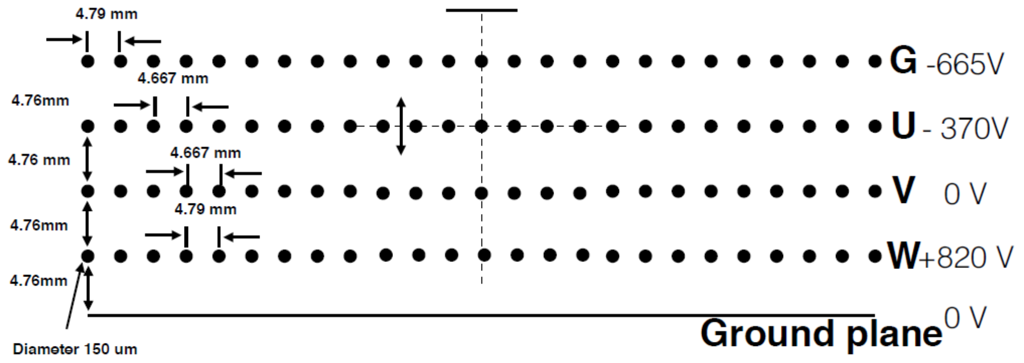


When the wire is vibrating, essentially, some components of induction matrix change, which further leads to change in capacitance matrix. With fixed voltage on electrode, the change in capacitance leads to induced current on wires

Model Construction

- 4 wire planes (G, U, V, X) above a (ground) mesh plane
- Using 40% APA geometry:
  - Wire pitch 4.5 mm for G and X
  - Wire pitch 4.89 mm for U and V
  - Wire plane gap 4.76 mm

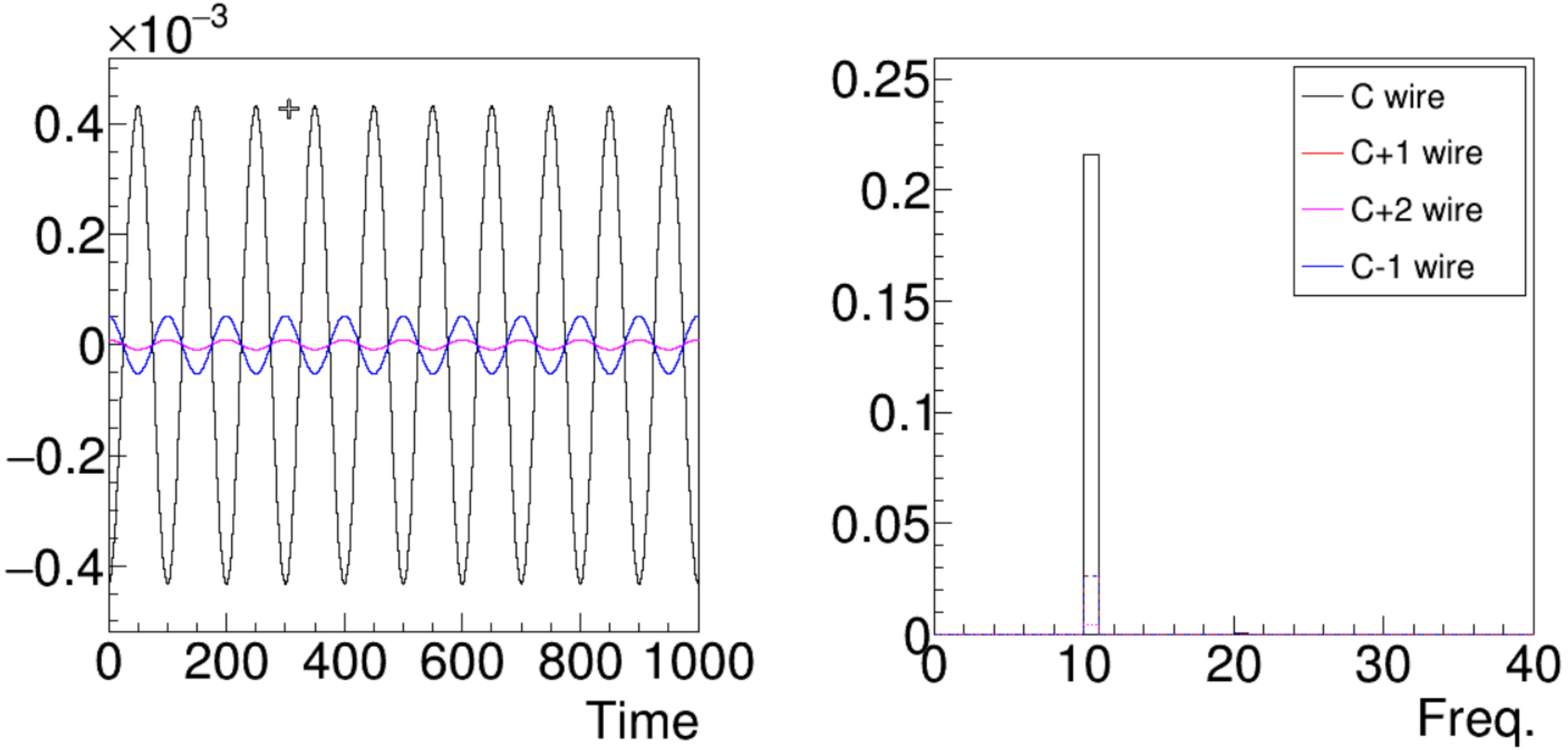
- 2D geometry: parallel wires
  - 11 wires in all four wire planes



ProtoDUNE geometry

Result I: Vertical Vibration of Central U wire

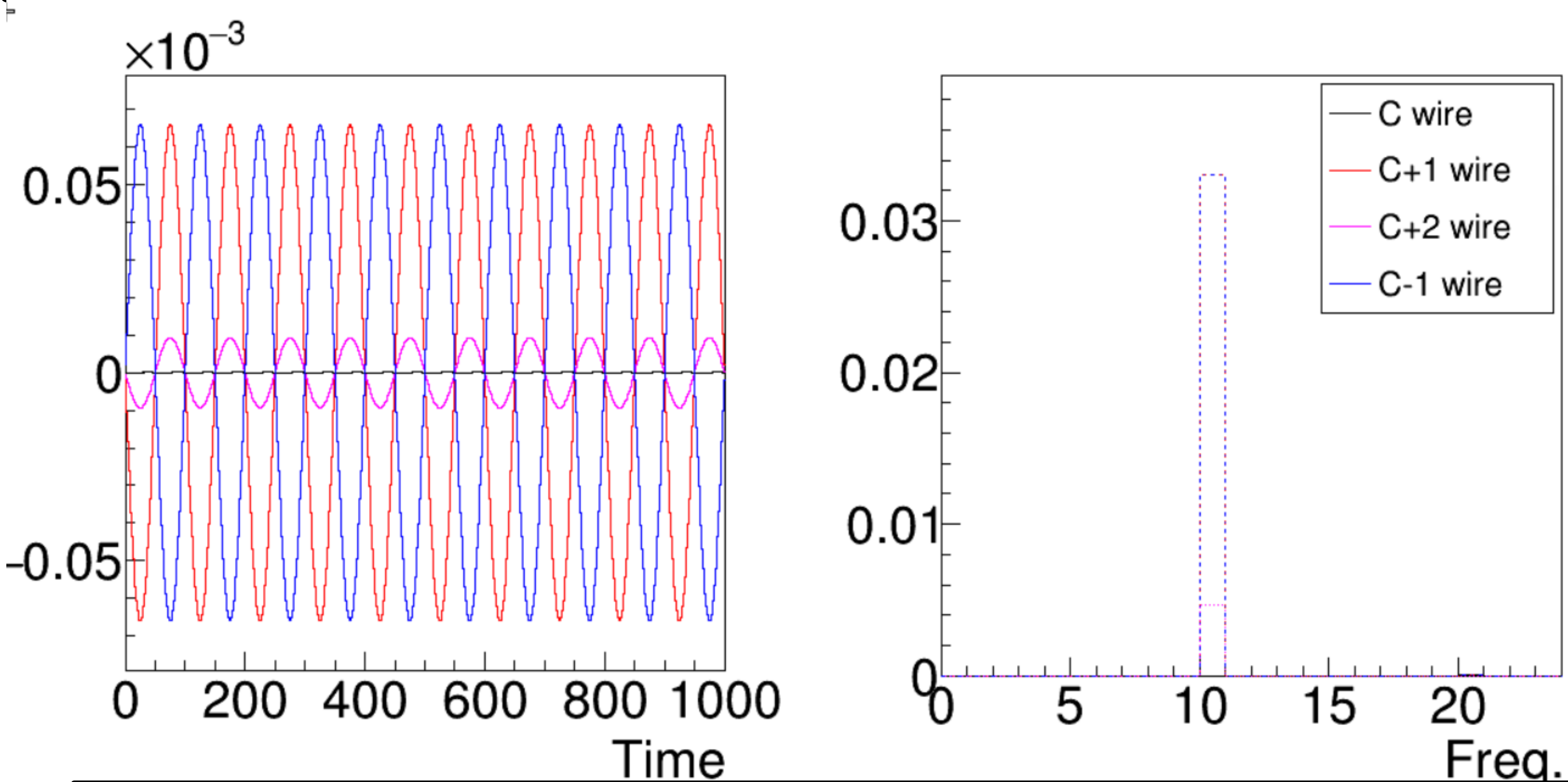
- Assuming vibration is a "sin" wave, G plane at -40 V, rest at zero



Central Wire has the largest signal, adjacent wires have an amplitude suppression of ~8

Result II: Horizontal Vibration of Central Wire

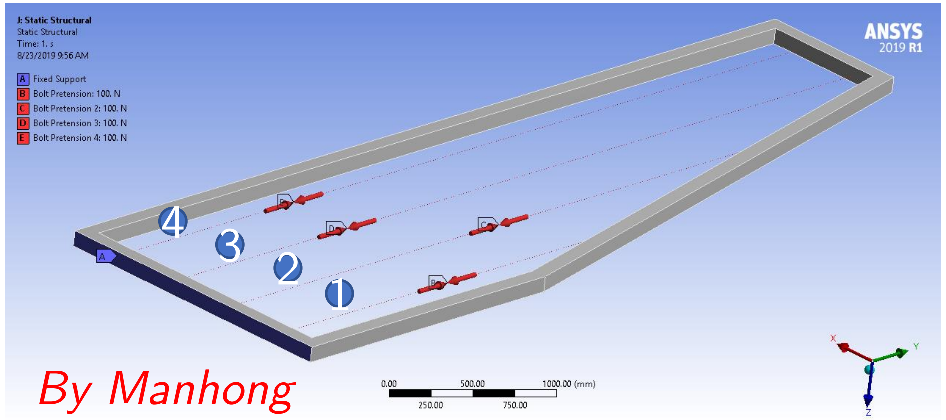
- Assuming vibration is a “sin” wave, G plane at -40 V, rest at zero

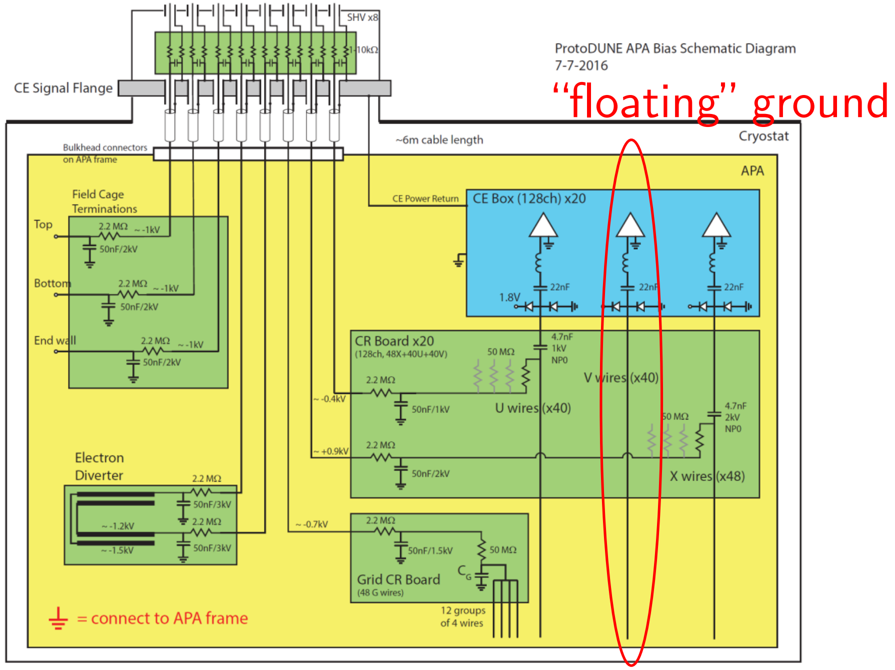


Central wire has almost no signal, sizable induced signal in adjacent wires (similar magnitude as previous case)

Ongoing efforts and plans

- Upgrade the DAQ system for simultaneous data taking
  - Currently, measure one channel (wire) at one time with a LabView GUI
- Understand V plane "weak" grounding and its impact
- Understand the mechanical system through simulation (by Manhong, BNL)





Summary

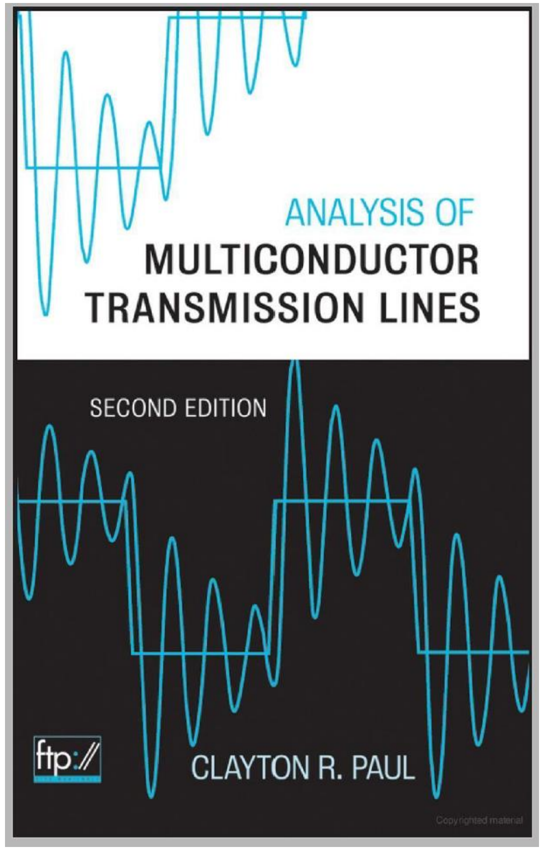
- The capacitance coupling between a wire and adjacent wires/planes has been demonstrated
- By only turning on Grid bias voltage and vibrating the entire APA frame, some intrinsic frequencies are observed
- The "spill-out" from adjacent wires are also observed
  - The pattern can be quantitatively compared with the model prediction once we can take the wire data simultaneously
- Some ongoing efforts to improve this measurement

Backup slides

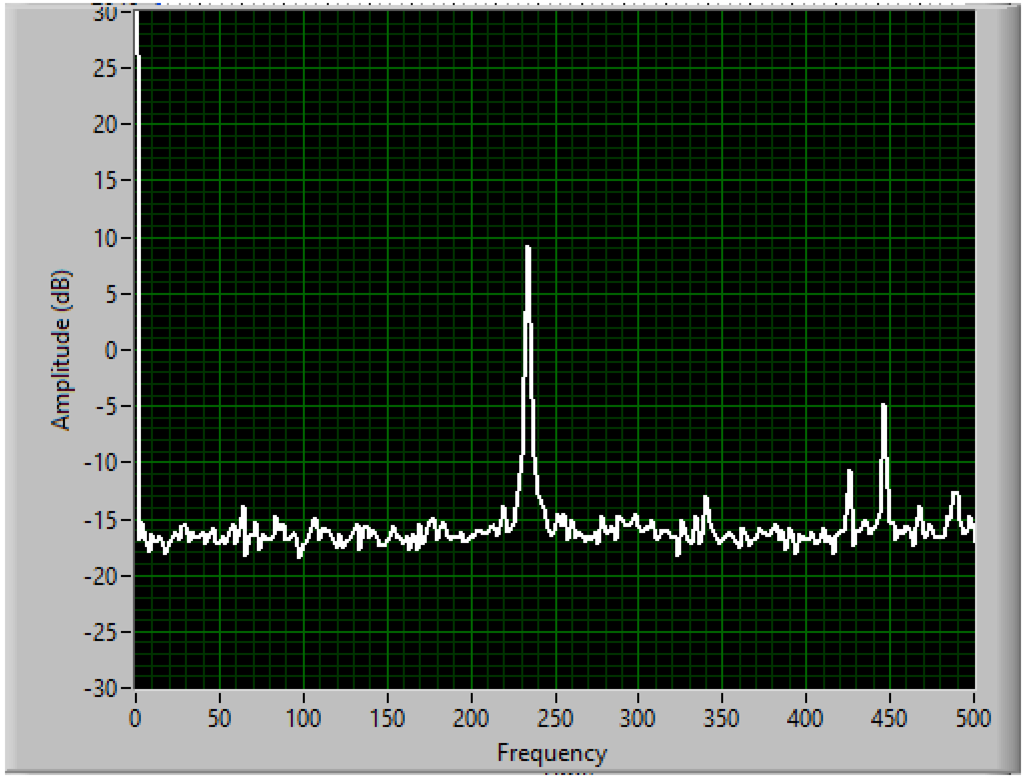
References

- "Analysis of Multiconductor Transmission Lines", second edition, Clayton R. Paul

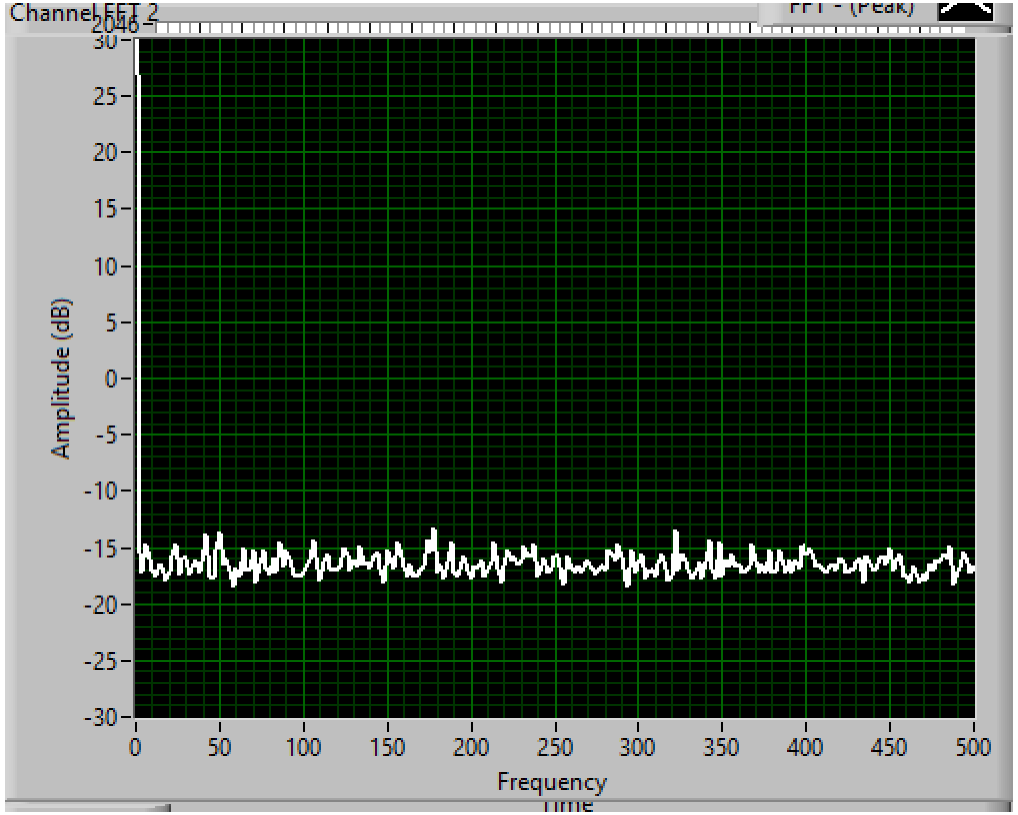
- Code available at github:
  - https://github.com/lastgeorge/wire_tension_simulation



Test of Motor ...



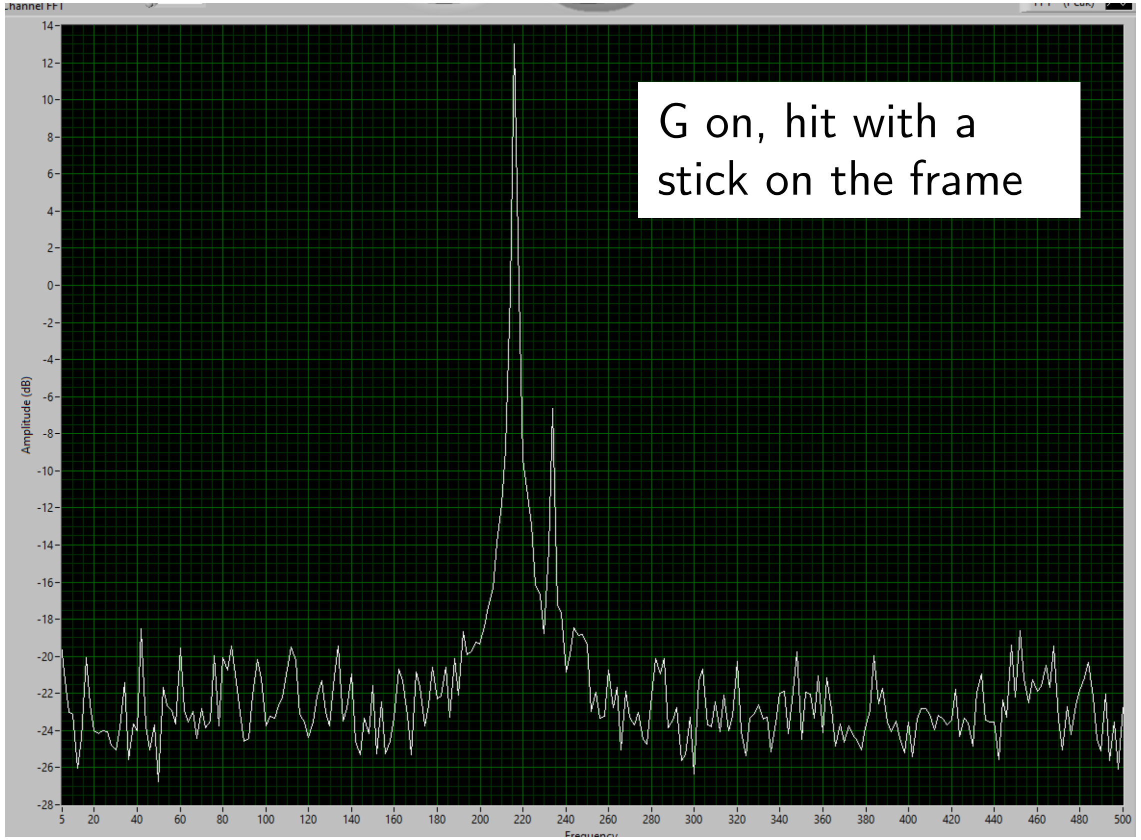
G voltage is on

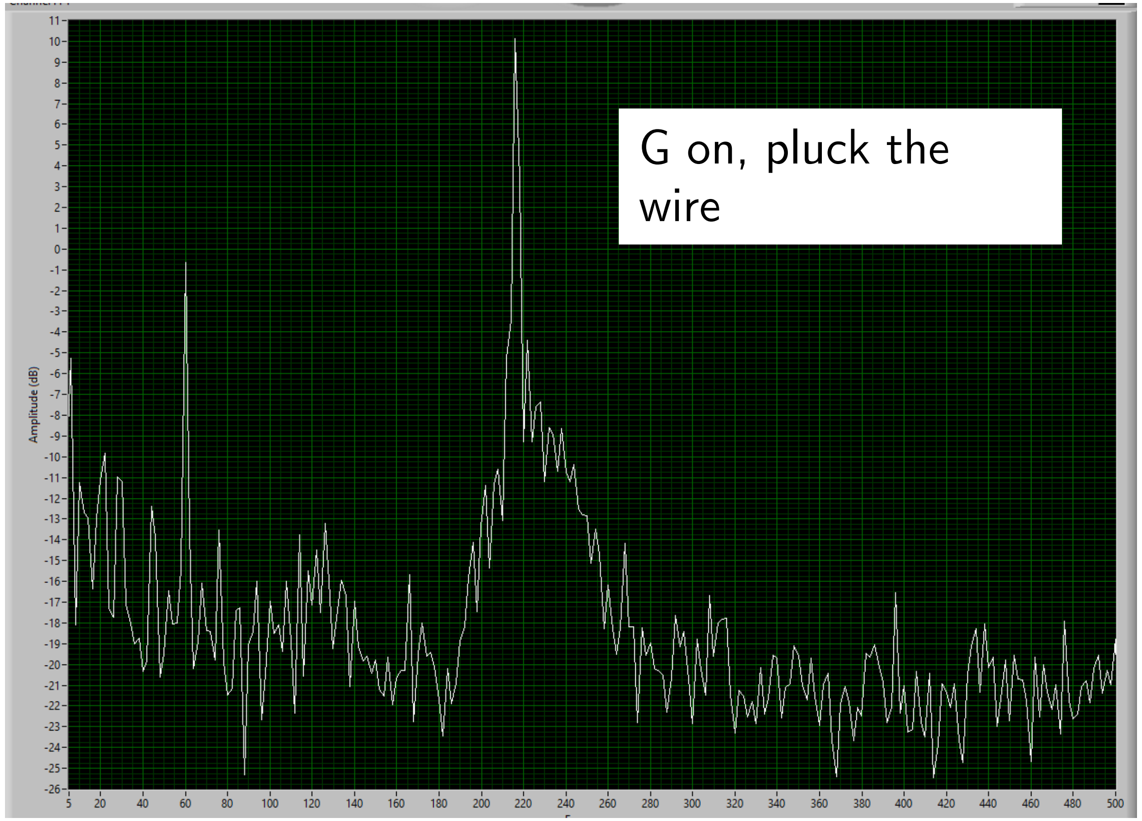


G voltage is off

Without the G voltage on, we cannot see anything on this U19 wire ...

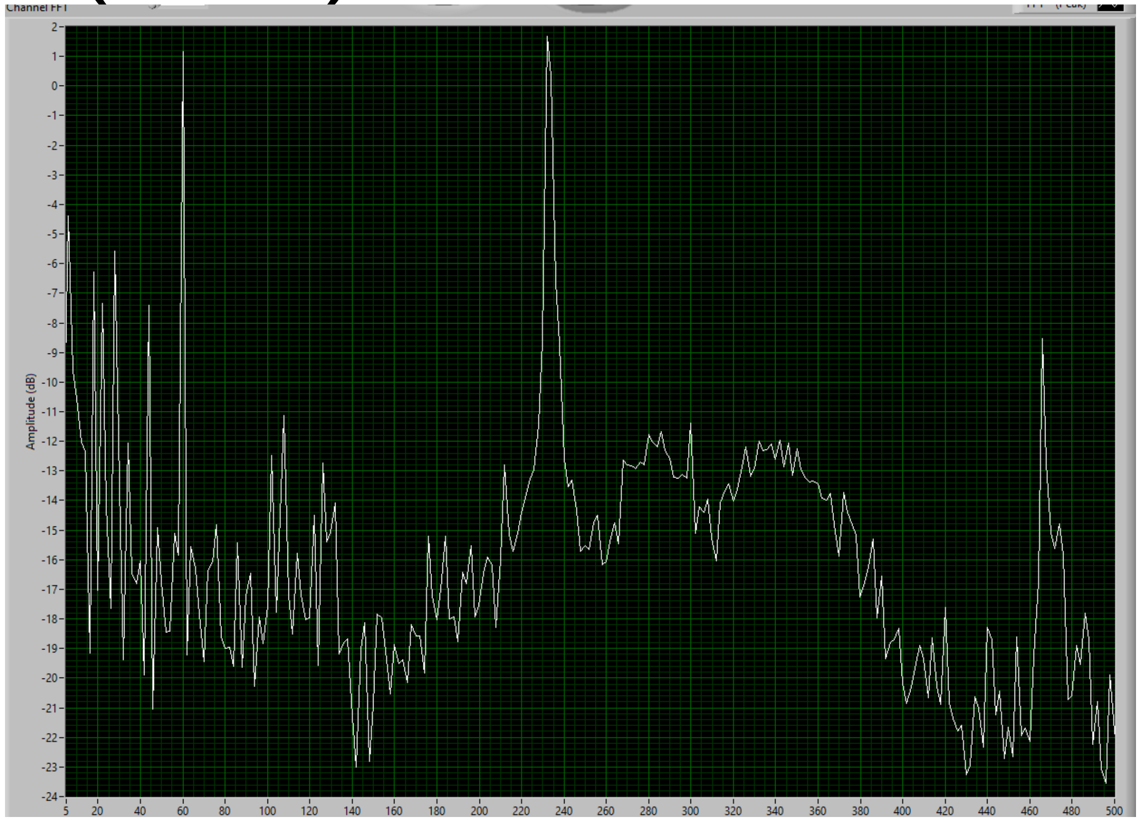
FEM 0, CHIP 3, Channel 13 (U20)



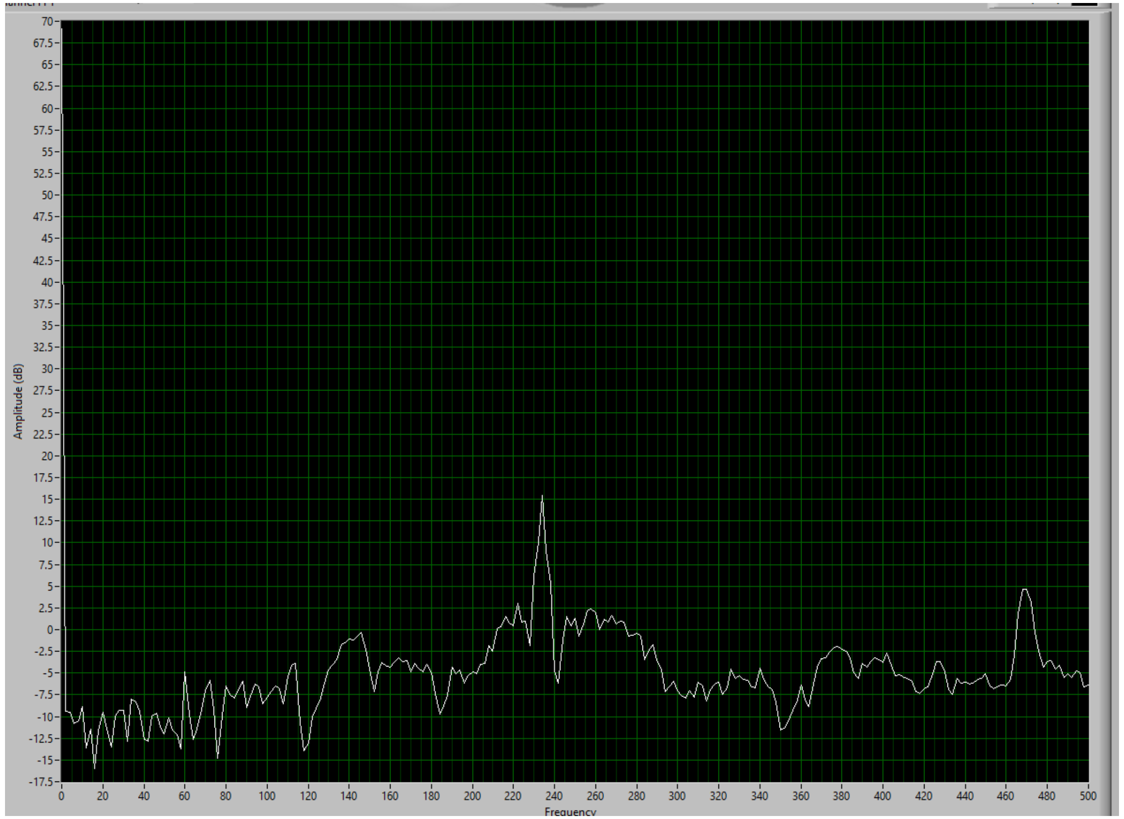


We can excite the intrinsic frequency at 210 Hz with both methods

Consistency Check FEM0, CHIP3, Ch15 (U19)



G on with 10 V, touch this particular wire



Everything off,
touching this particular wire

Signal is much higher, can see the 2^{nd} harmonic