IFASD 2024: Experimental Investigation of a Highly Flexible Wing – for AePW/LDWG

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Outline

- Motivation
- Infrastructures
- Results: Flutter Boundary
- Results: LCO
- Conclusions

Motivation

- Similar models were already installed in two Wind Tunnels (ZHAW, ETHZ), we now add another one (Roma Sapienza); are results from different wind tunnels, comparable? Can we obtain «wind tunnel independent» results?

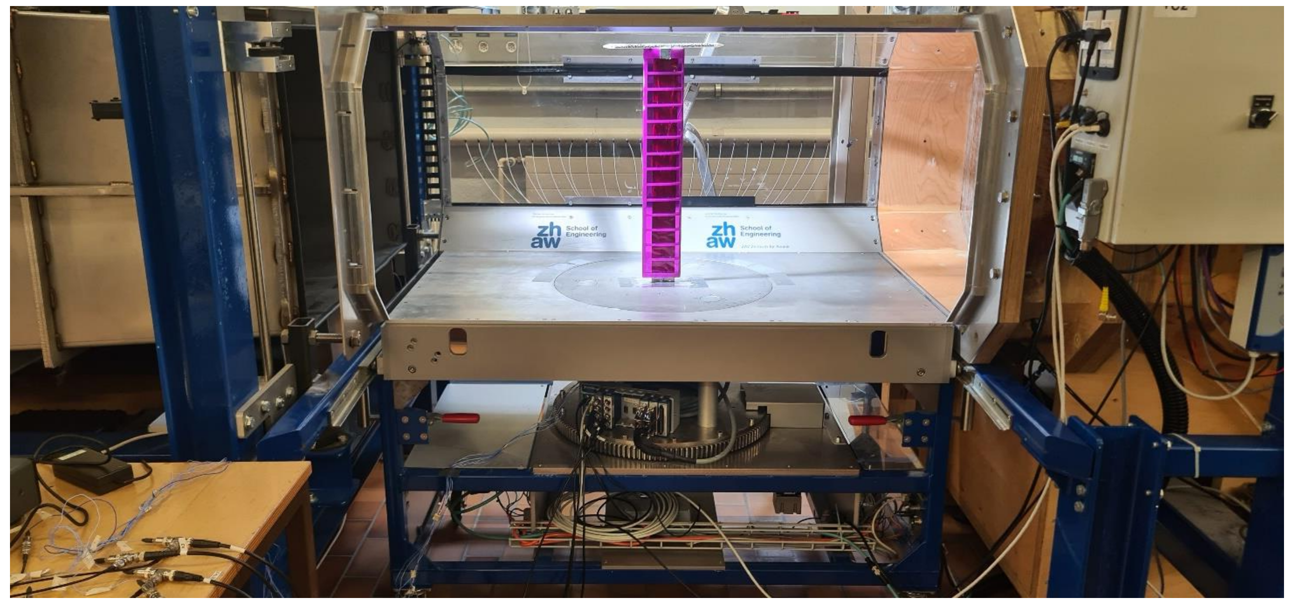
- Experimental characterisation of flutter on- and offset, as well as the LCO, subcritical nature of LCO?

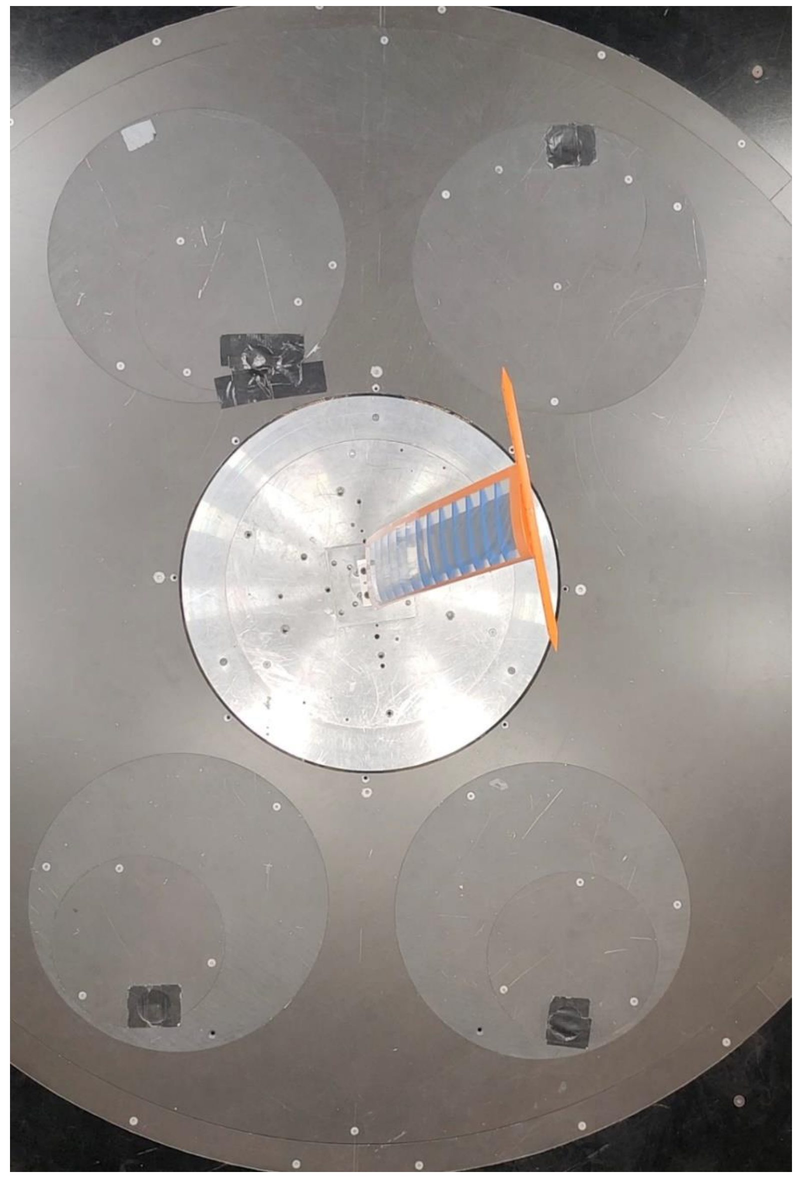
- Exploiting Operational Modal Analysis (OMA) to identify the modes involved,

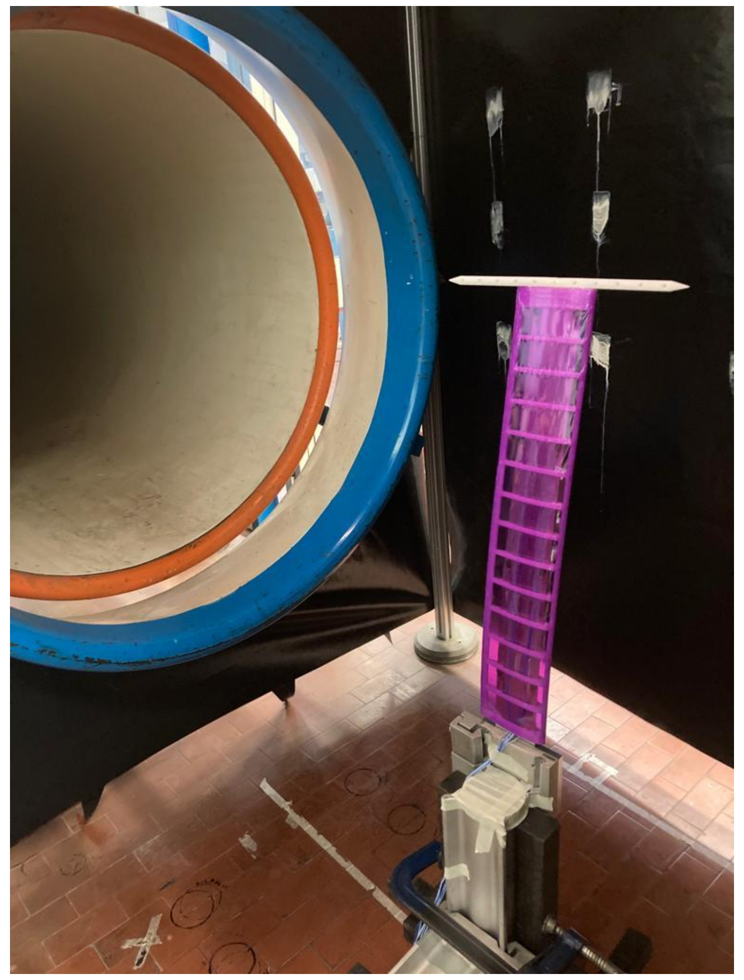
- Make data available.

Infrastructures, methodologies

- Wind Tunnel 1, ZHAW, Winterthur, closed test section,
- Wind Tunnel 2, La Sapienza, Rome, open test section,
- (Wind Tunnel 3, large subsonic WT, ETH, closed test section (used in 2021)),
- Operational Modal Analysis, OMA, (identification of modal properties under operational conditions),
- Wind Tunnel models build consistently with the «true» PAZY wing; however, the spar is only 2.0 mm thick,

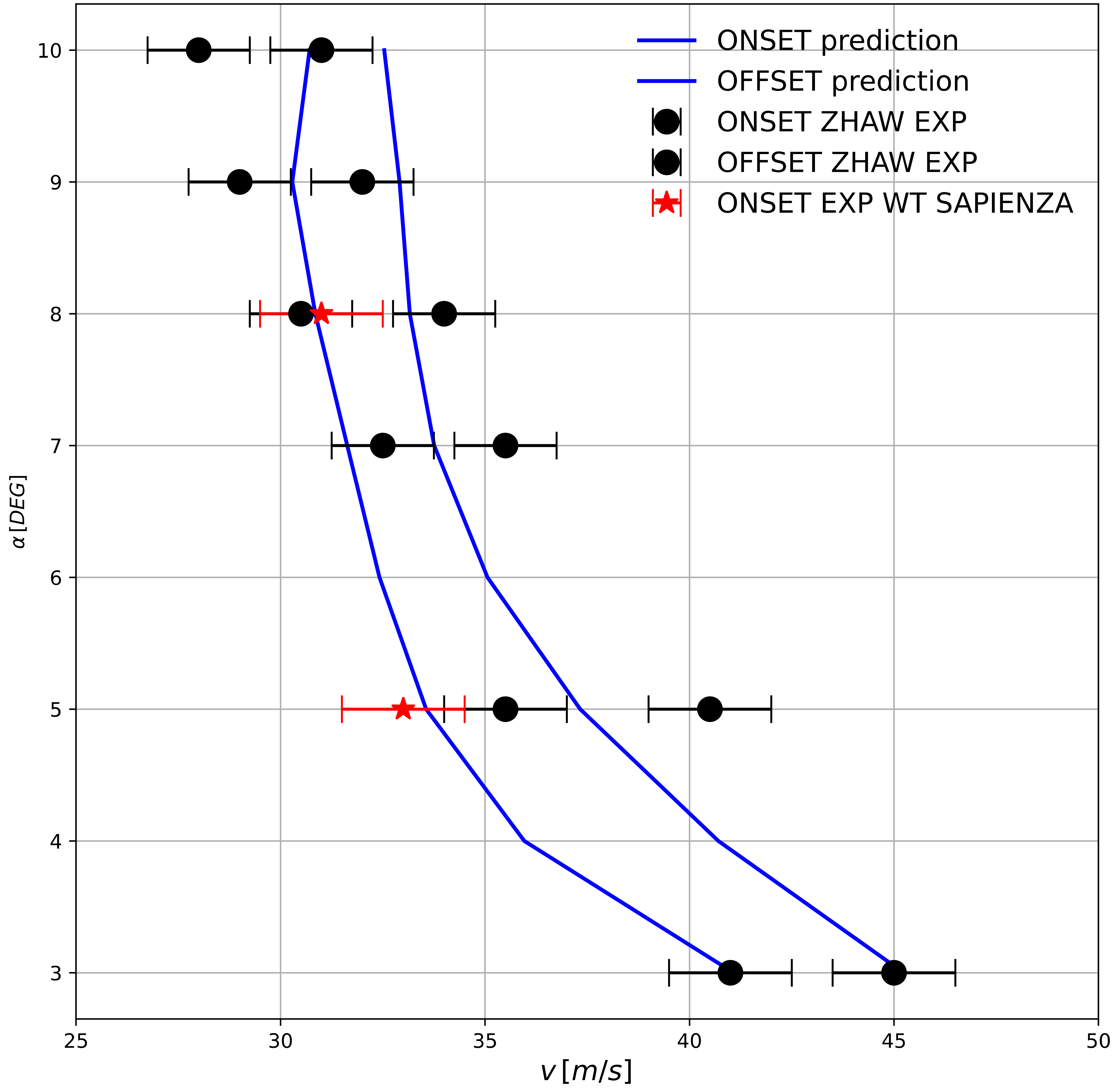






Flutter Boundary

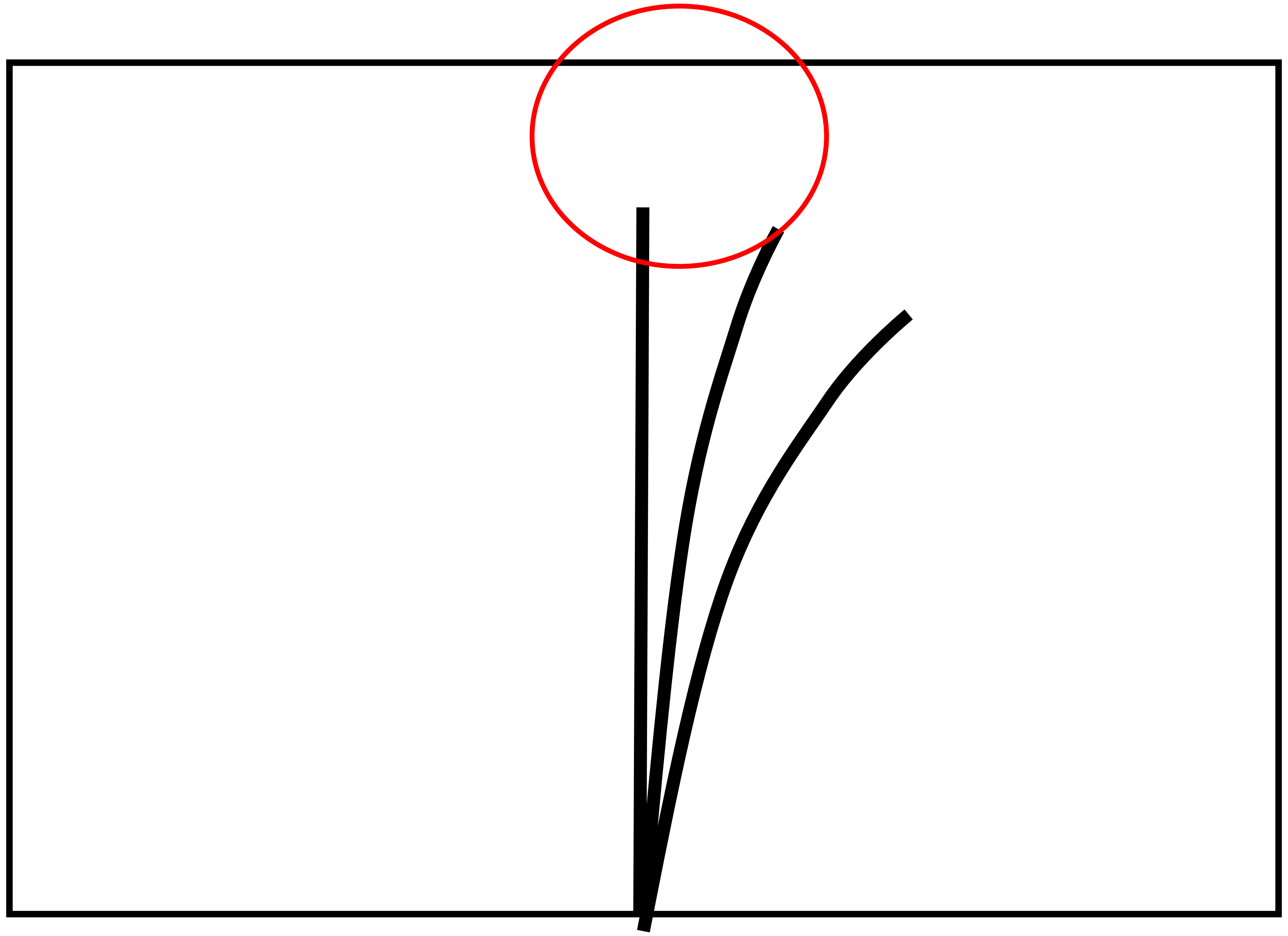
- Behaviour comparable to «true» PAZY (thicker spar),
- Flutter speed from the experiment at ZHAW, for comparison also flutter speed from Sapienza WT reported,
- Acceptable agreement with experimental flutter speed higher at AoA 5 to 7 degrees (probably due to opening in WT),
- Agreement with experiments of 2021 less good but still within a few m/s,



ALFA Wind Tunnel, ZHAW

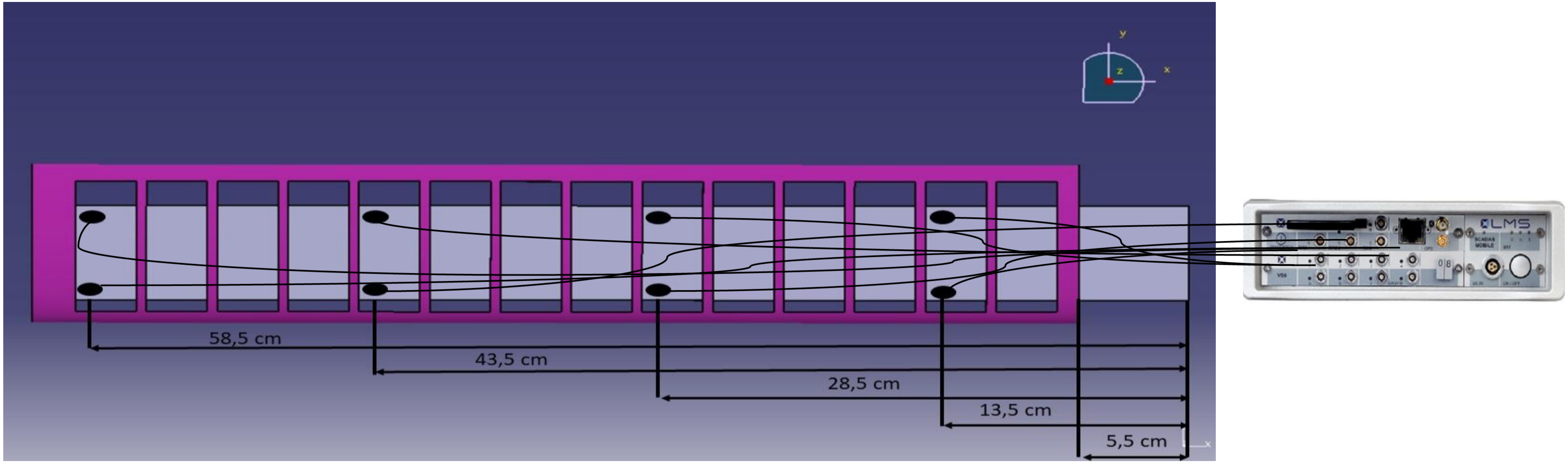
Test section, 900 mm, 640 mm, wind speed up to 45-50 m/s, «very low» turbulence level

Limited clearance, especially at smaller static deflection



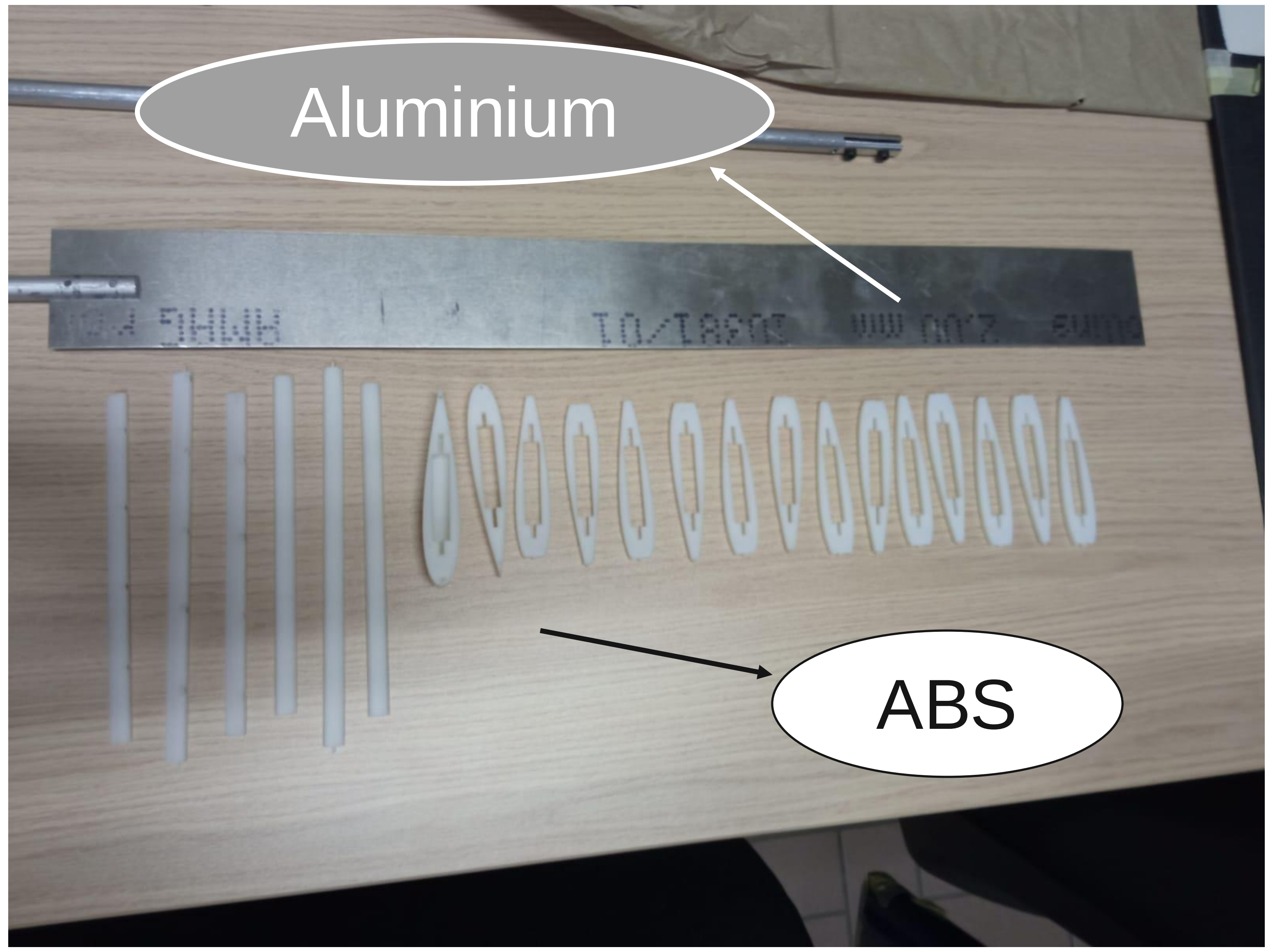
Sapienza takes over here

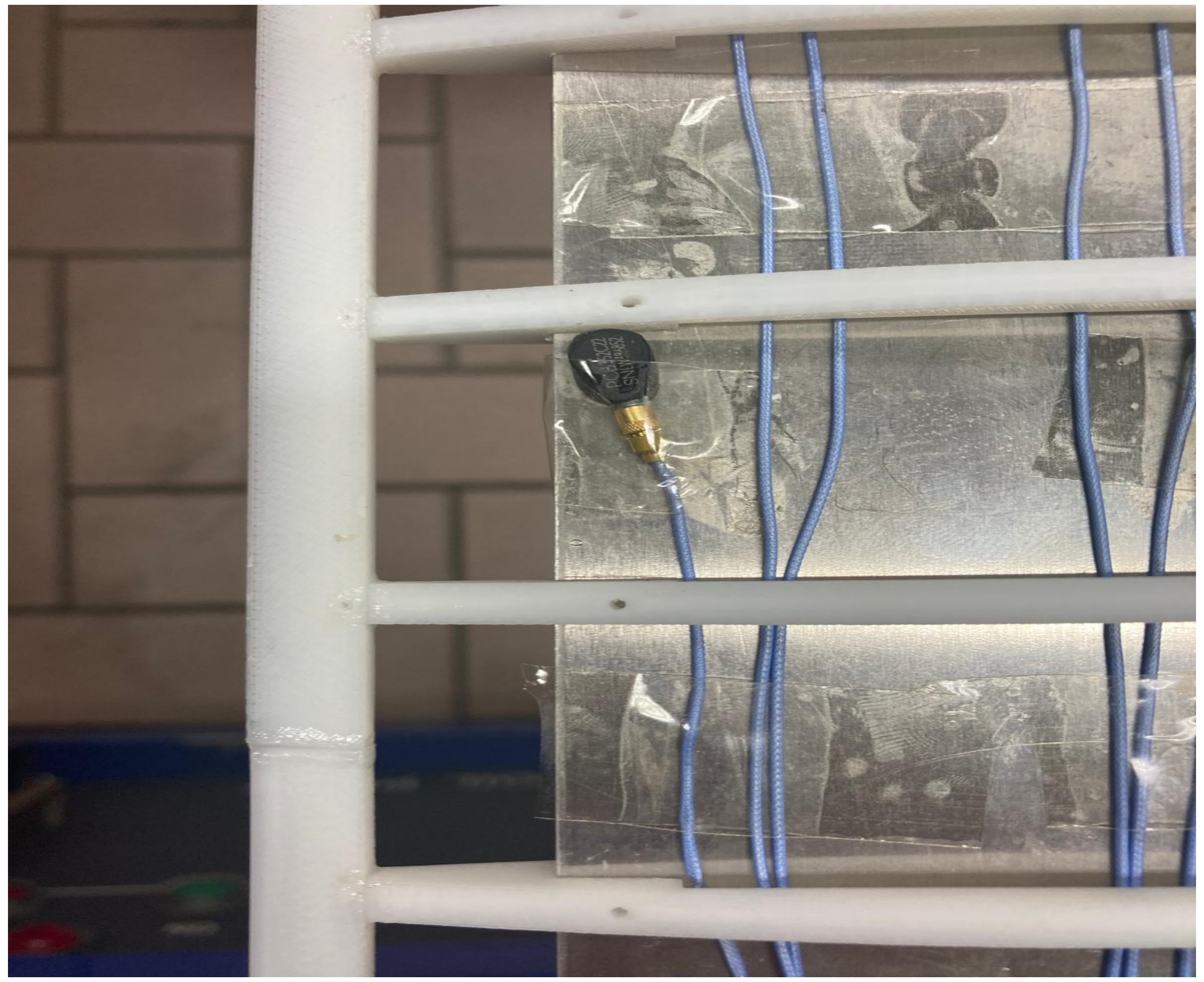
Instrumentation

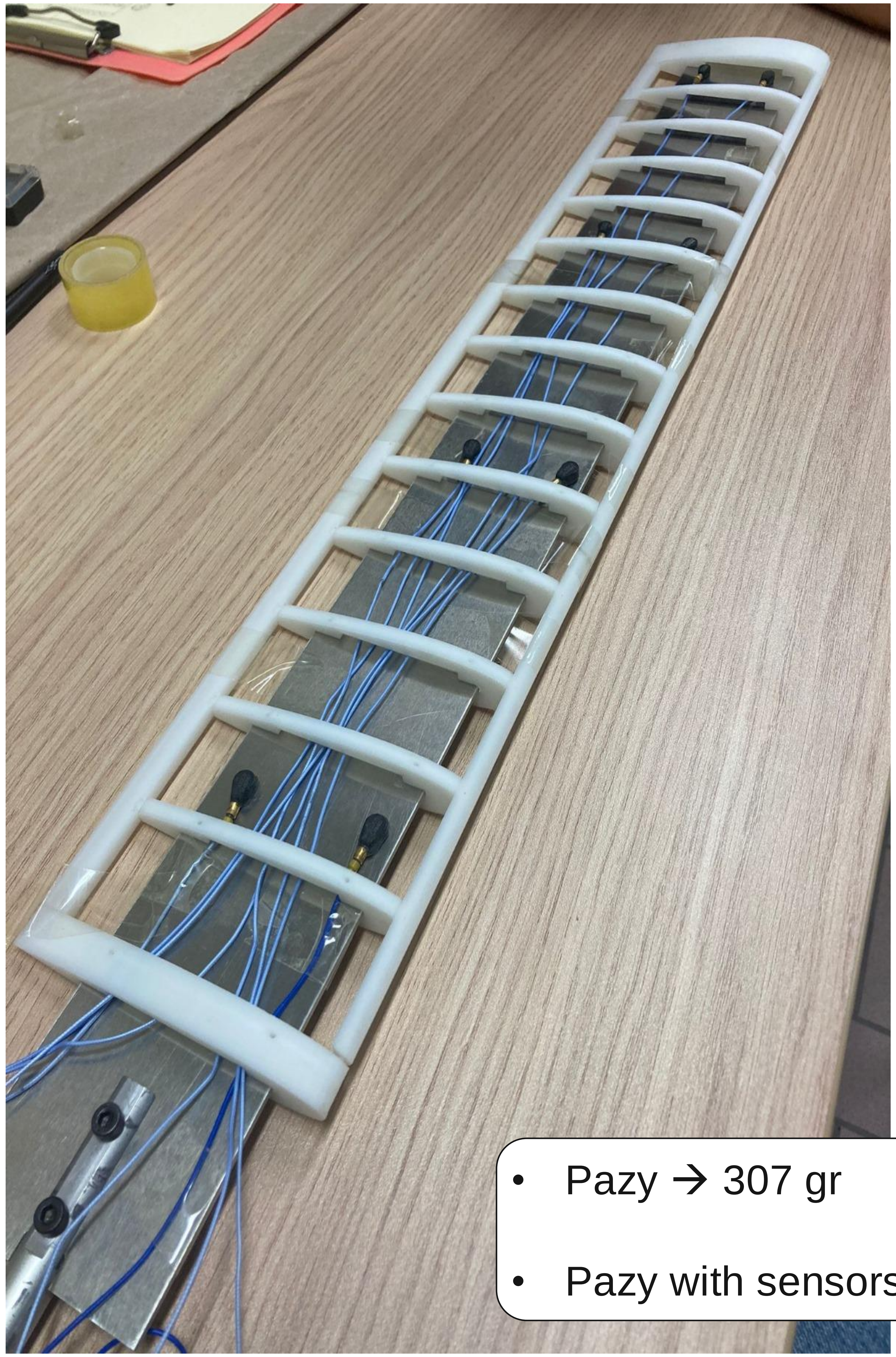


- 8 one-directional accelerometers
- Acquisition system LMS SCADAS Recorder with 8 channels for ICP/Voltage sensor acquisitions. Compliant with standard MIL-STD-810F

Instrumentation



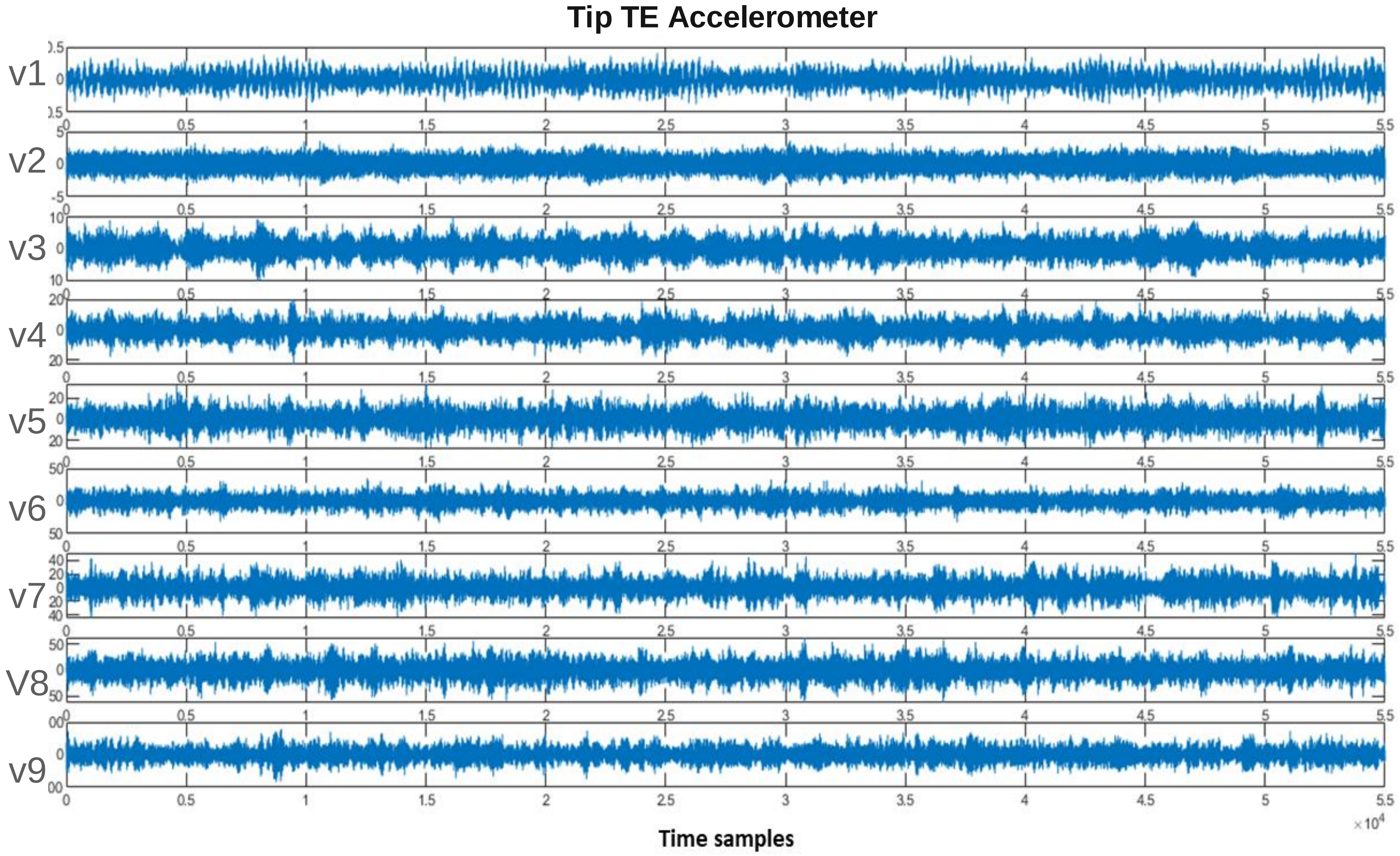




- Pazy → 307 gr
- Pazy with sensors → 320 gr

Measurements / Methodology

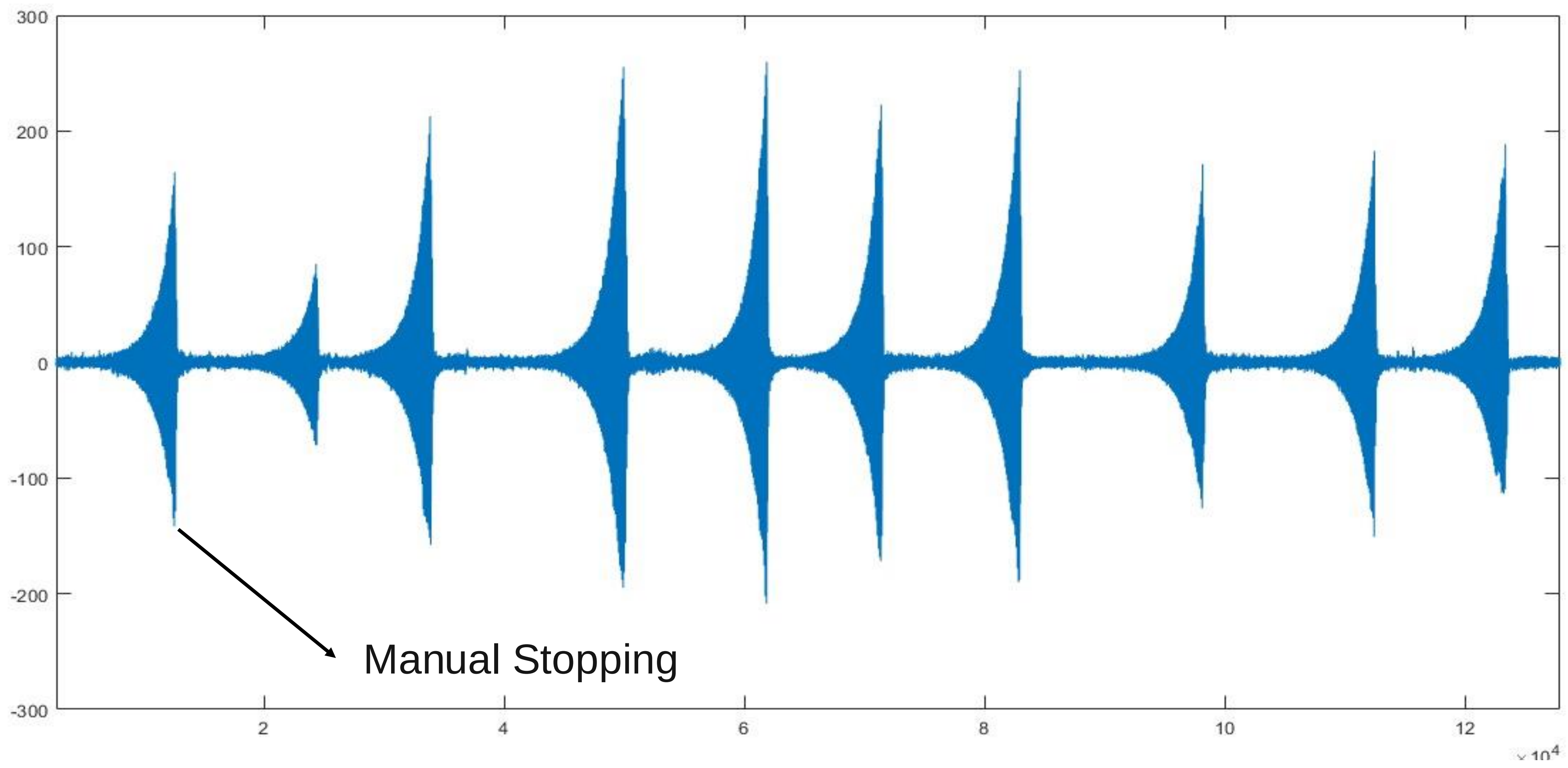
- Excitation through Wind Tunnel turbulence (OMA), for 3 AoA (3°,5°,7°)
- Sequence of steady state velocity measurements (each 1 m/s), assessment of poles (OMA)

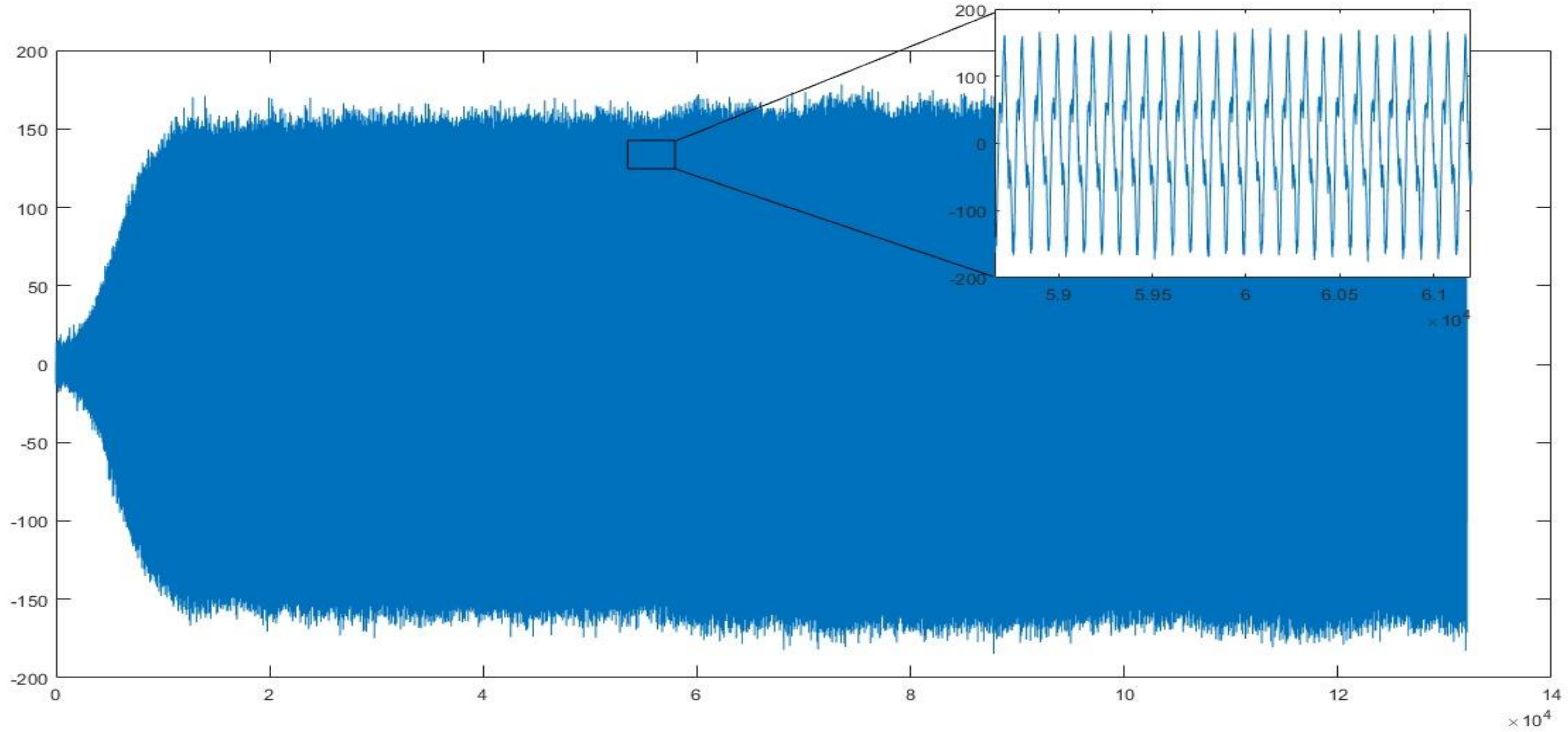


- Close to flutter onset, we took smaller steps (1 RPM or 0.1 m/s) and introduced excitations by physically applying forces

Measurements / Methodology

- For a few wind speed values, LCO were not limited,
- «Too» large oscillations are limited by manually grasping the model through an opening
- For other wind speed values, LCO were limited and observable

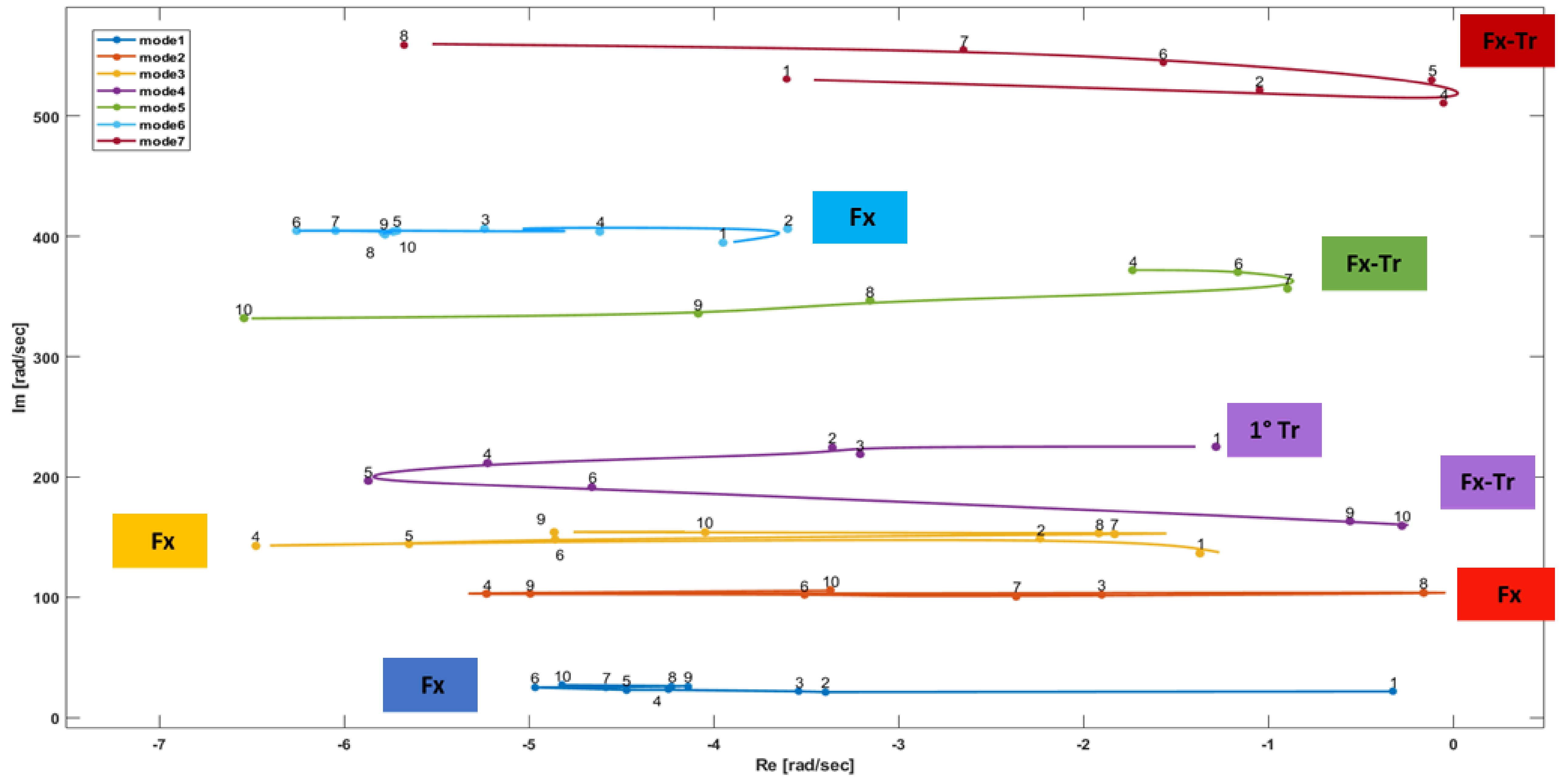




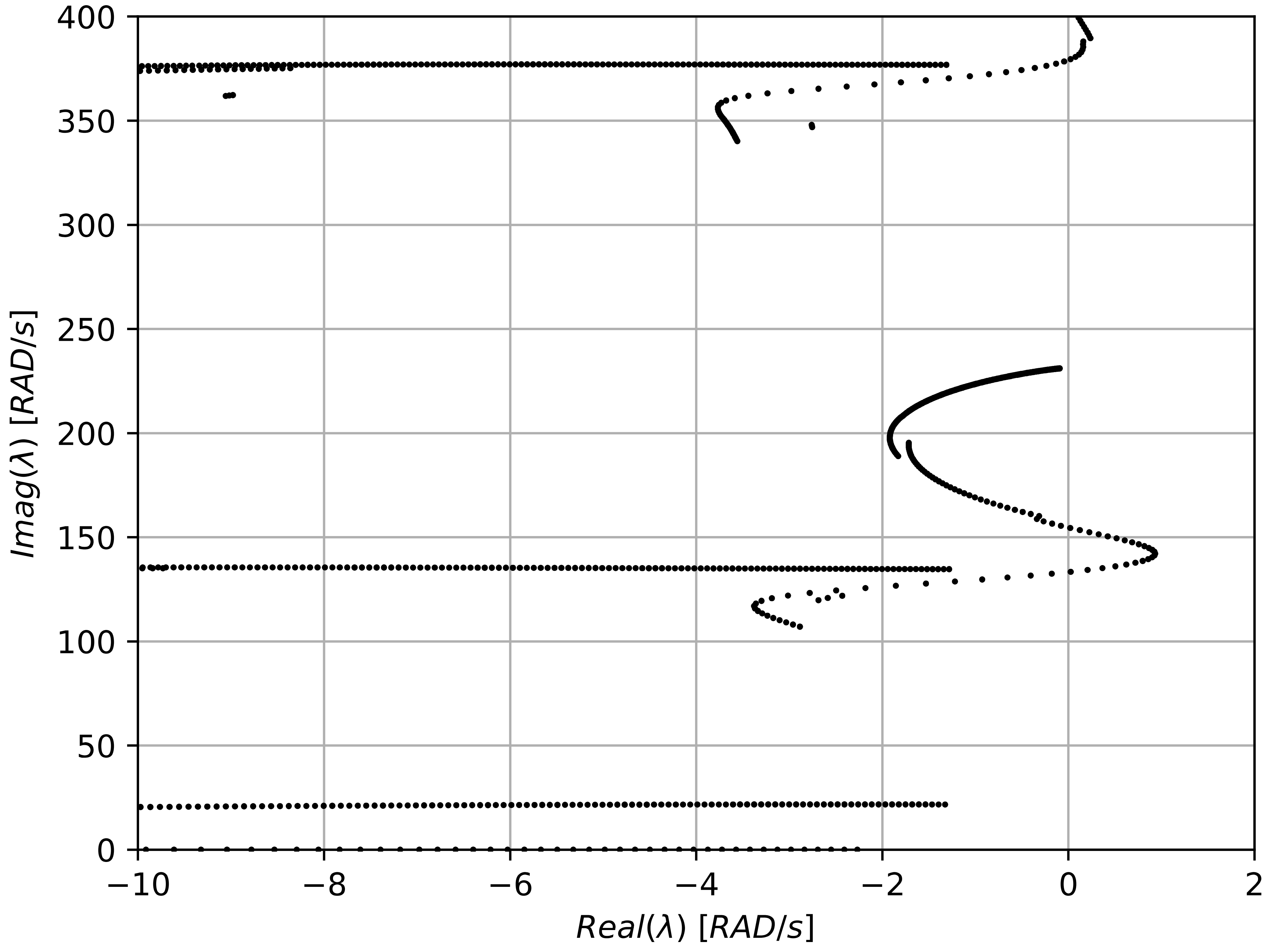
Analytical model

- Strip theory (corrected),
- 2D lift, drag, moment from CFD, including surface irregularities,
- Unsteady formulation, Theodorsen, state-space (Leishman),
- FE (beam elements),
- Non-linear static solution,
- Eigenvalues analysis,
- Acceptable agreement in AePW3 LDWG,

Root Locus AoA = 3 deg

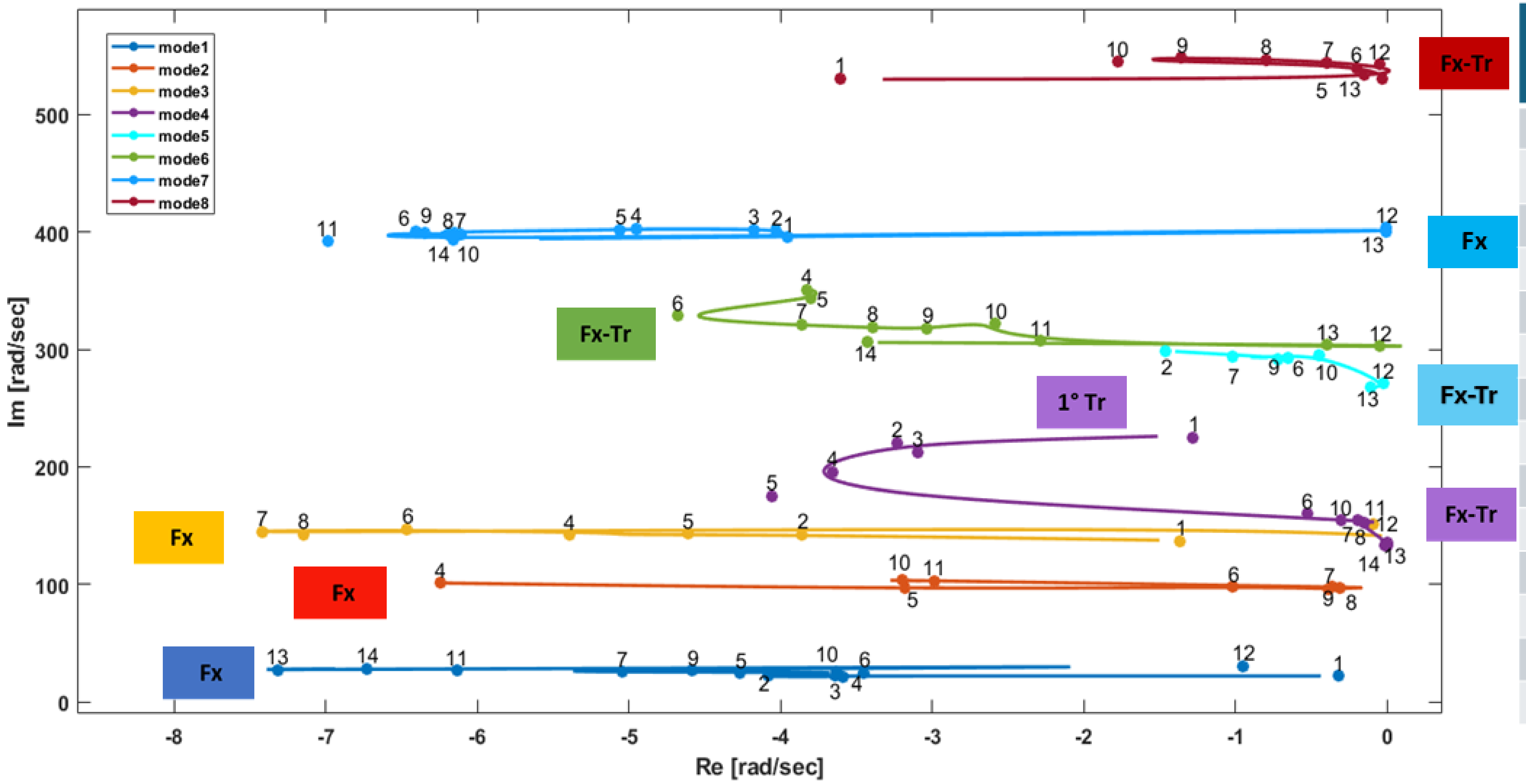


	q (Pa)	V (m/s)
1	0	0
2	222,3	20
3	319,2	24
4	434,1	28
5	566,1	32
6	637,3	34
7	696,8	35,5
8	756,4	37,1
9	815,7	38,5
10	858,6	39,6



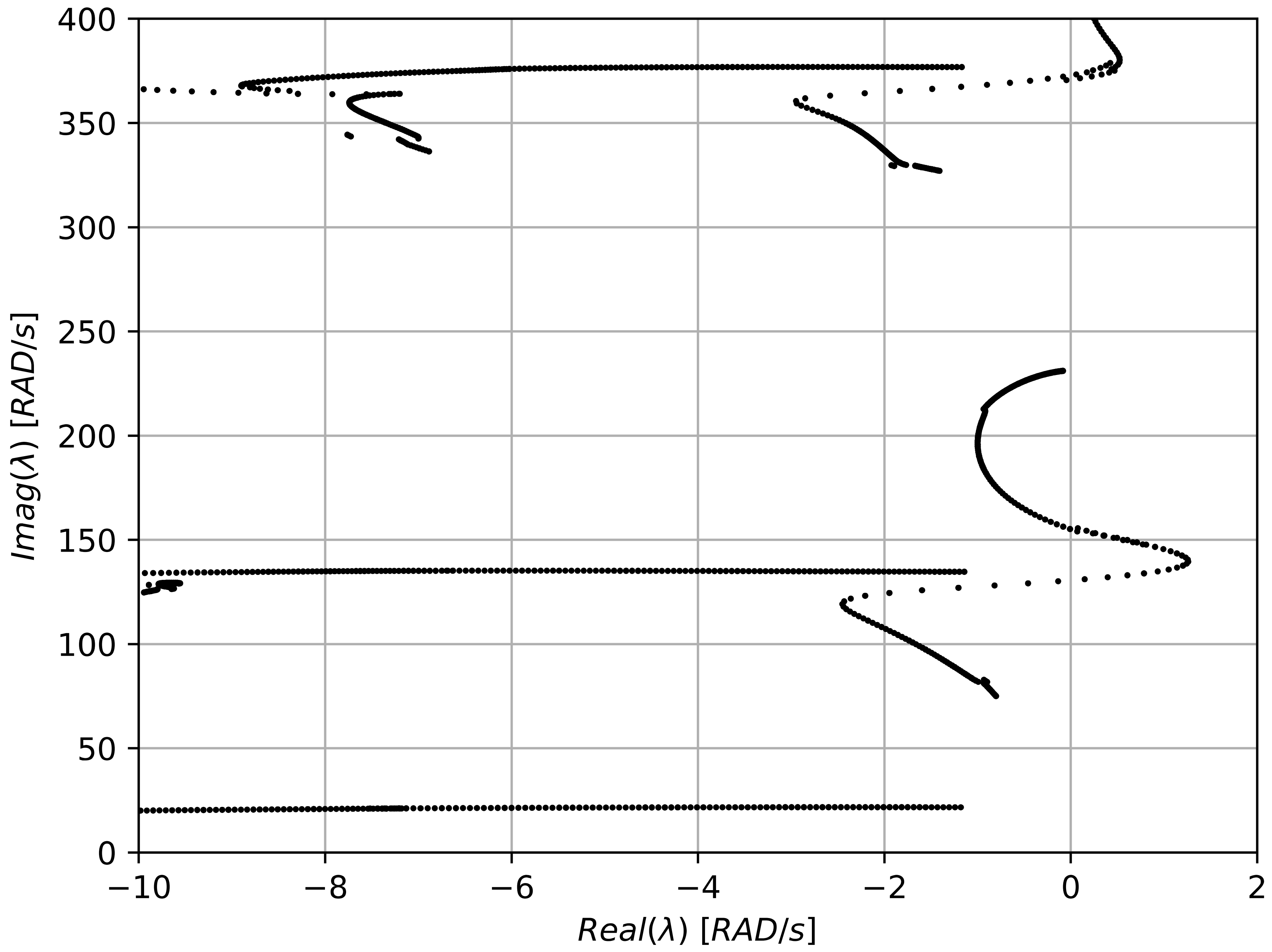
First torsional mode couples with second bending mode and becomes unstable.
A second instability is visible between the second torsional and third bending modes.
OMA identifies a «ghost» mode just below the second bending mode (probably balance?).

Root Locus AoA = 5 deg



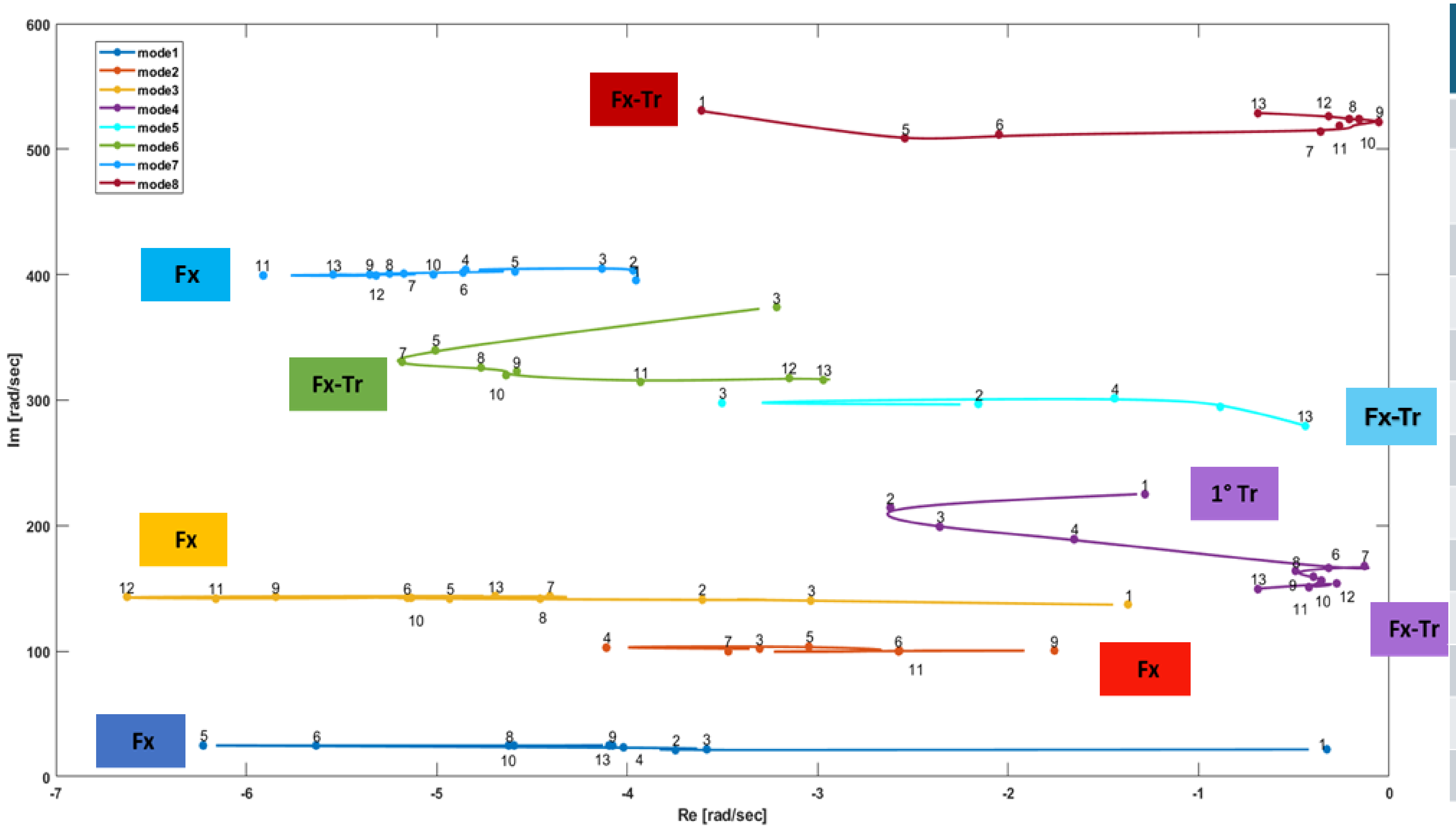
	q (Pa)	V (m/s)
1	0	0
2	222,3	20
3	319,2	24
4	434,1	28
5	566,1	32
6	637,3	34
7	696,8	35,5
8	756,4	37,1
9	815,7	38,5
10	858,6	39,6
11	952,2	41,5
12	823,6	38,3
13	856,4	39,1
14	860,0	39,3

LCO

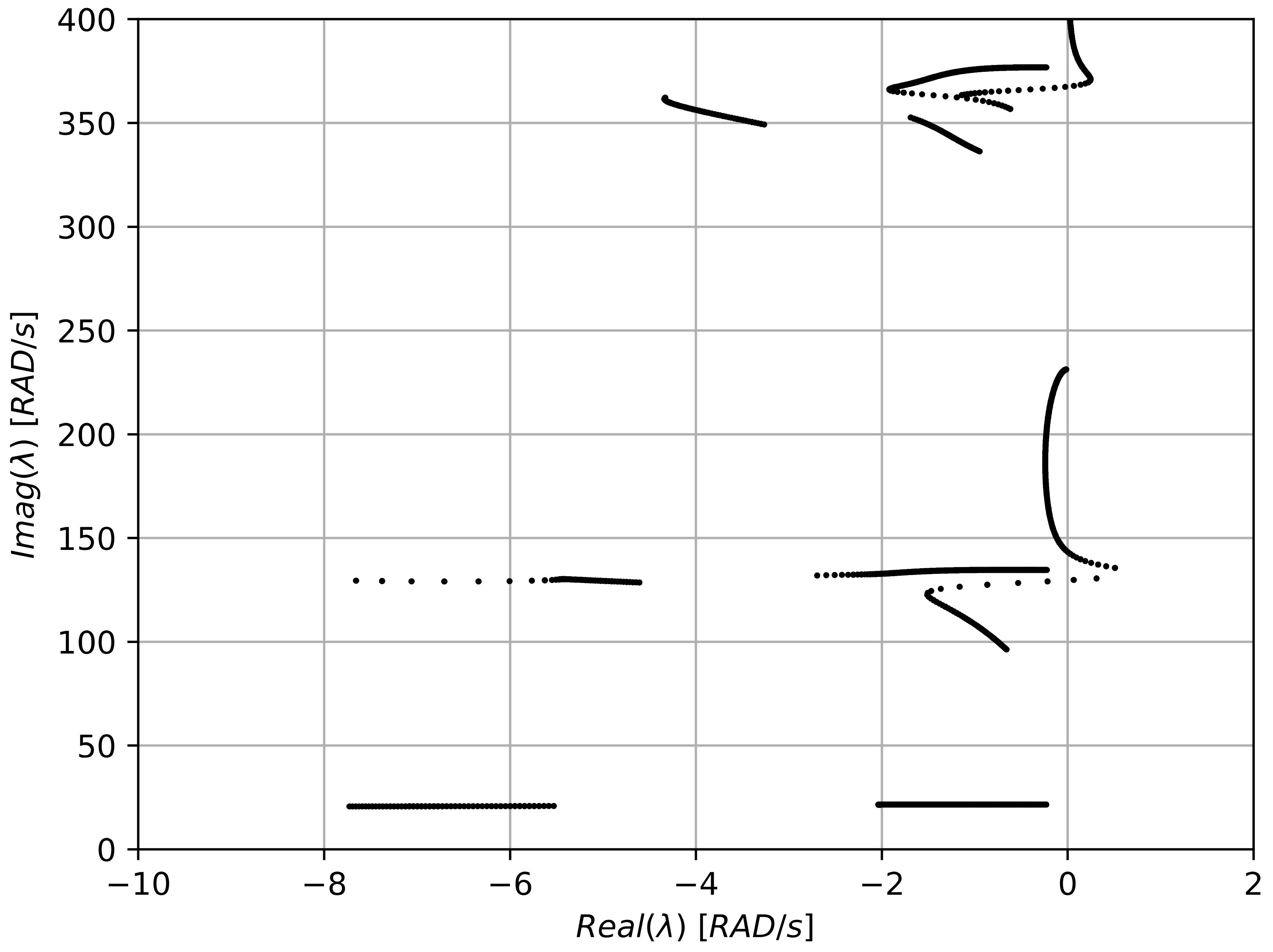


Good agreement between numerical and experimental results. The second instability is observable in both root loci. A fifth mode is excited and move towards the imaginary axis. LCO points with a value of damping close to zero are plotted.

Root Locus AoA = 7 deg

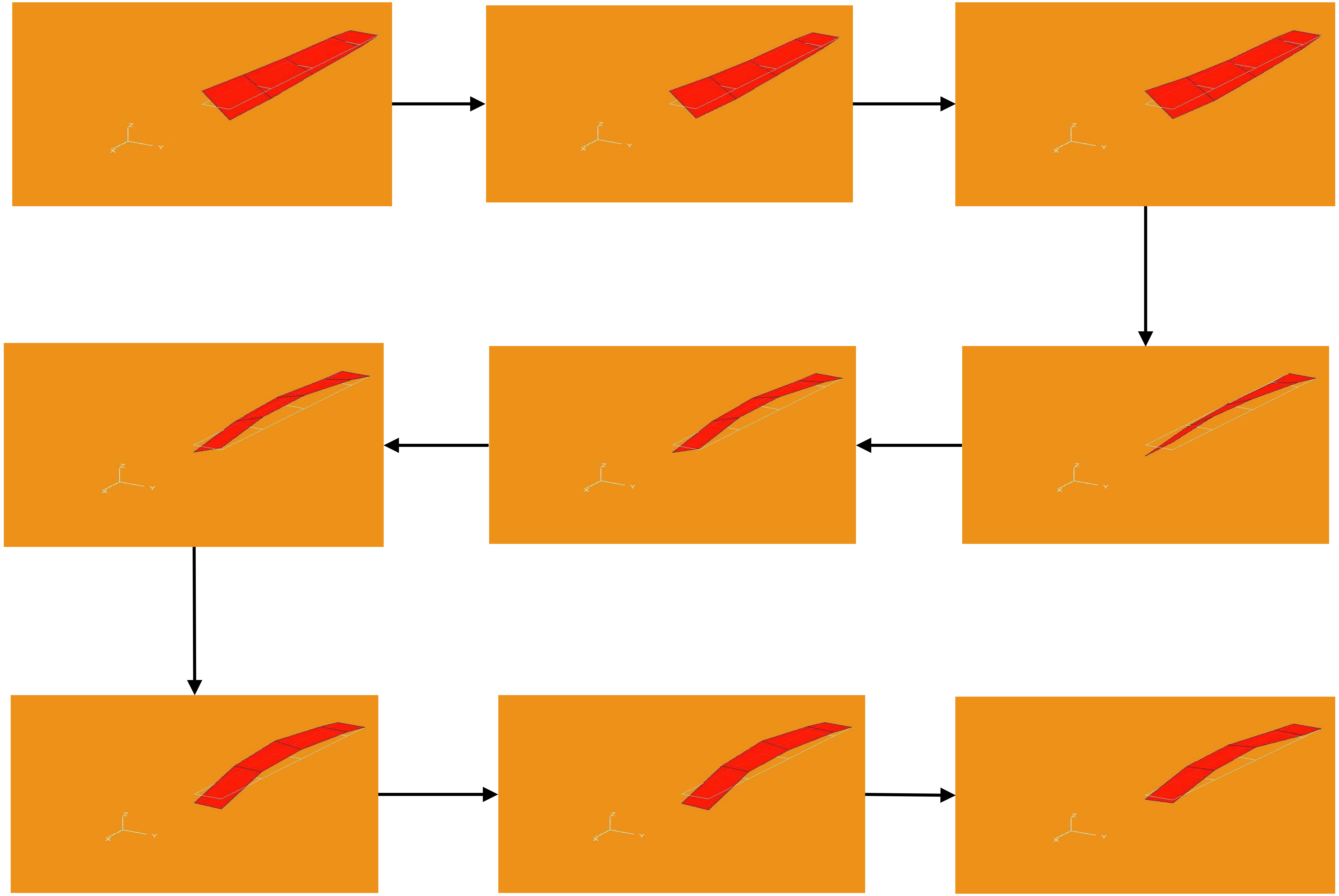


	q (Pa)	V (m/s)
1	0	0
2	222,3	20
3	320,1	24
4	374,5	26
5	433,0	28
6	463,8	29
7	478,2	29,5
8	494,8	30
9	509,6	30,5
10	526,3	31
11	535,3	31,3
12	545,6	31,5
13	561,7	32



The fifth flexural-torsional mode is evident. This mode is probably not properly excited for low angles of attack.

Mode Shape Evolution

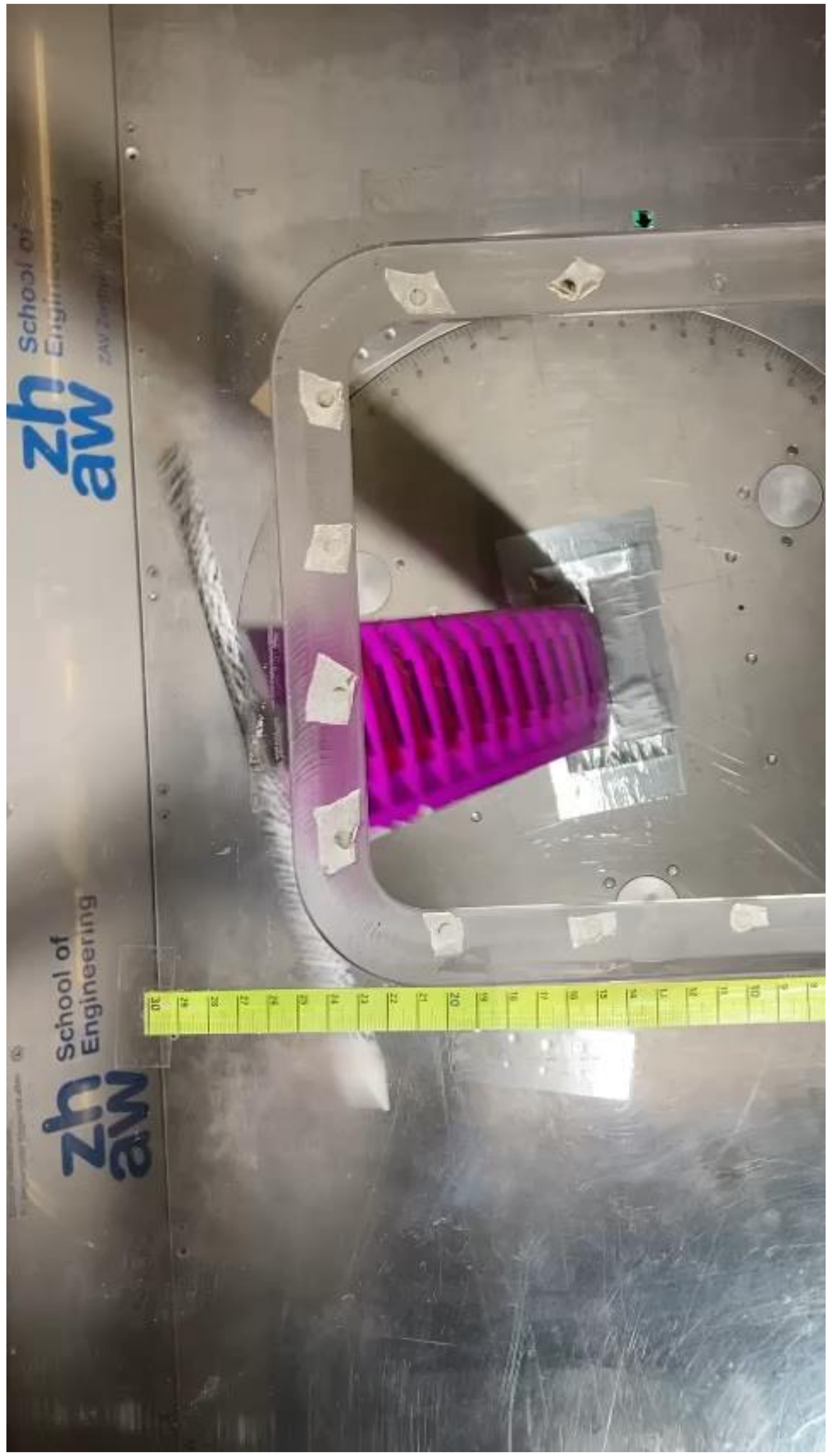


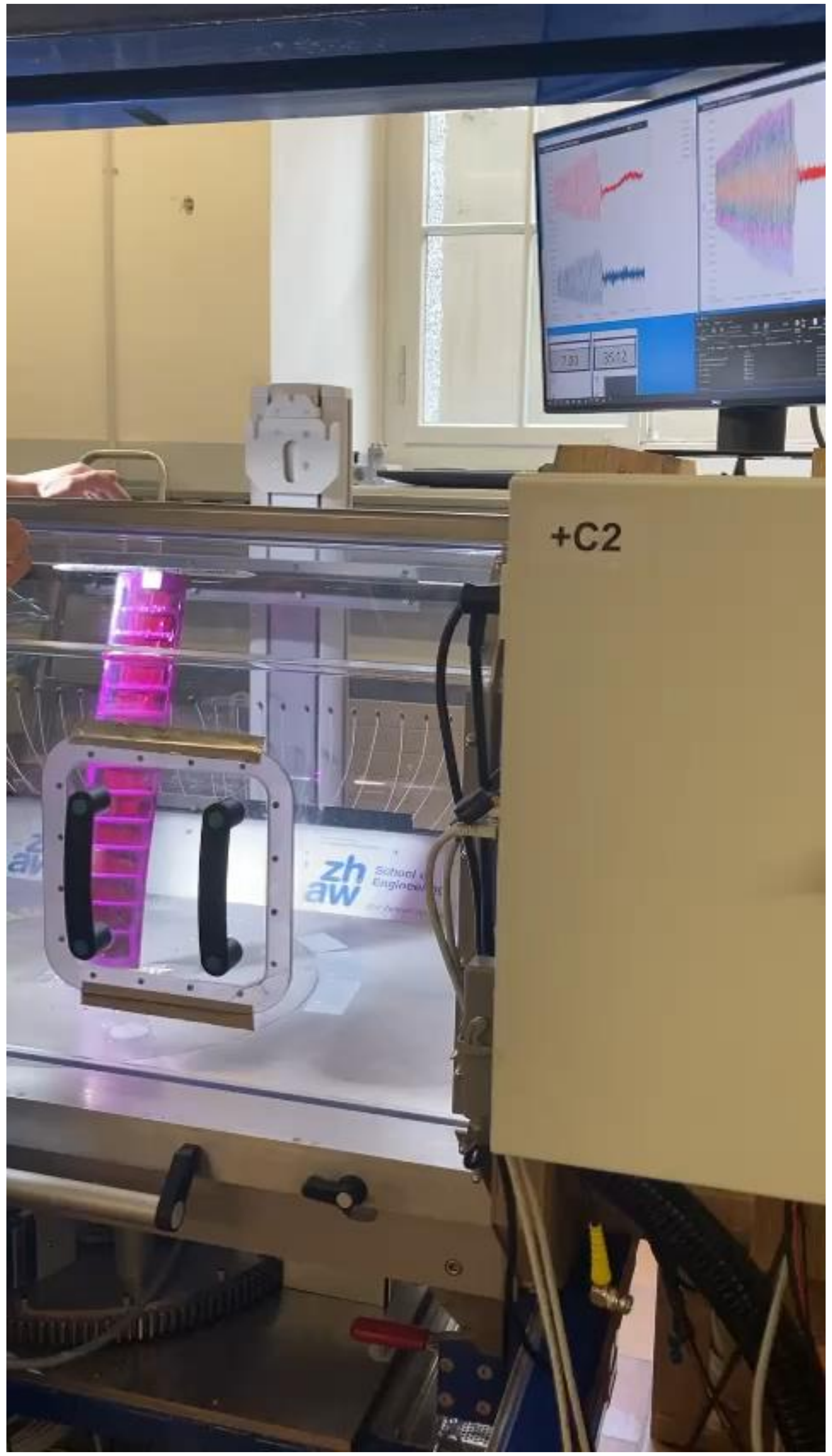
The 1st torsional mode becomes a flexo-torsional, decreasing the frequency at increasing values of velocity

→ Tracking performed using NIMA code.

I take over here

LCO



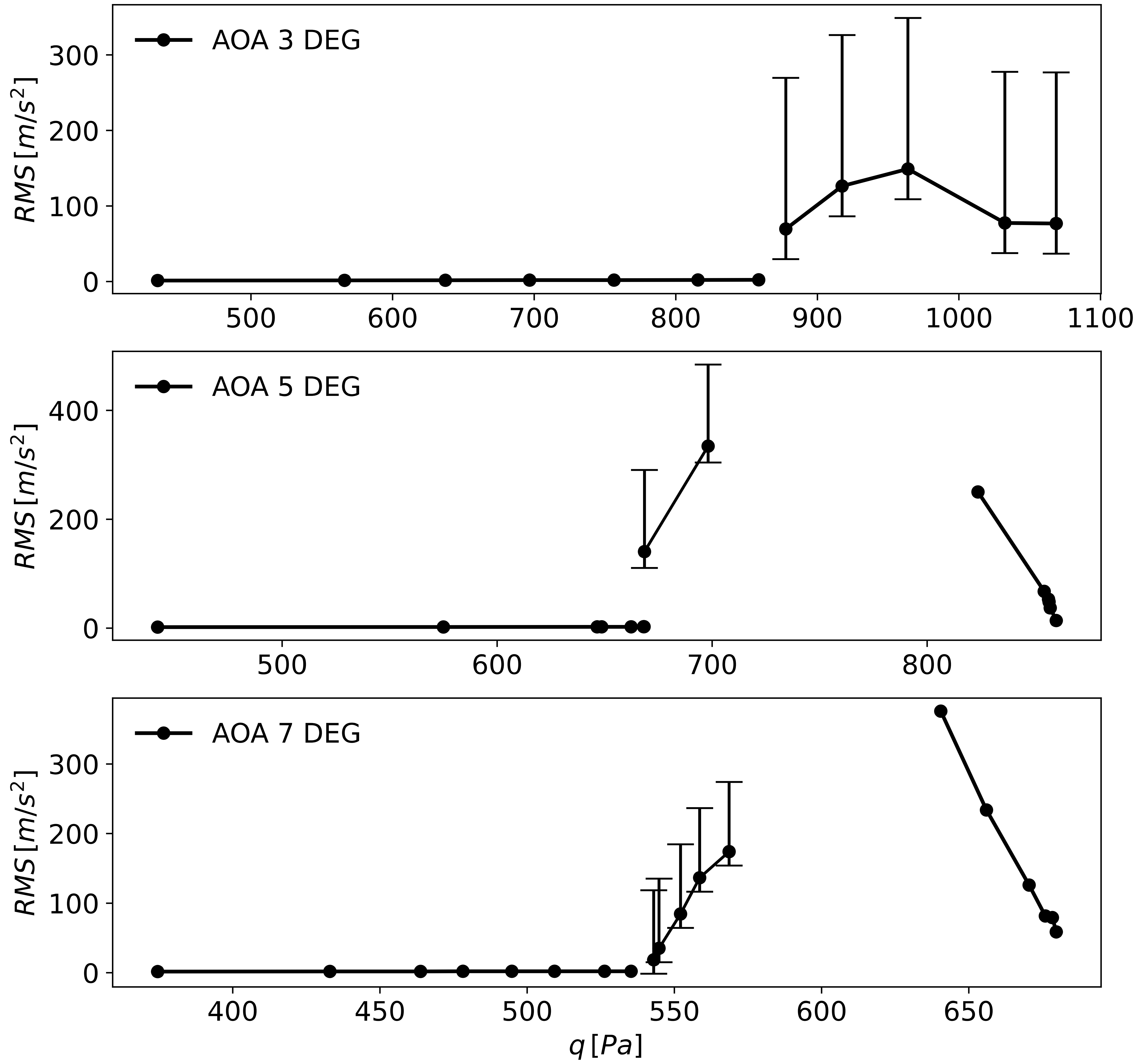


LCO, amplitude

- LCO amplitude varies substantially across wind tunnels, a proper LCO could be observed only in the ZHAW wind tunnel,

- ZHAW: LCO amplitude measurable only for a few speed values (oscillations were too large for most of the speed values),

- Is LCO amplitude meaningful? If we consider past measurements at ZHAW and ETHZ, models geometrically identical (differing in materials and workmanship, damping ratio about 150% to 200% larger) exhibited oscillations around 50 m/s2 (videos)

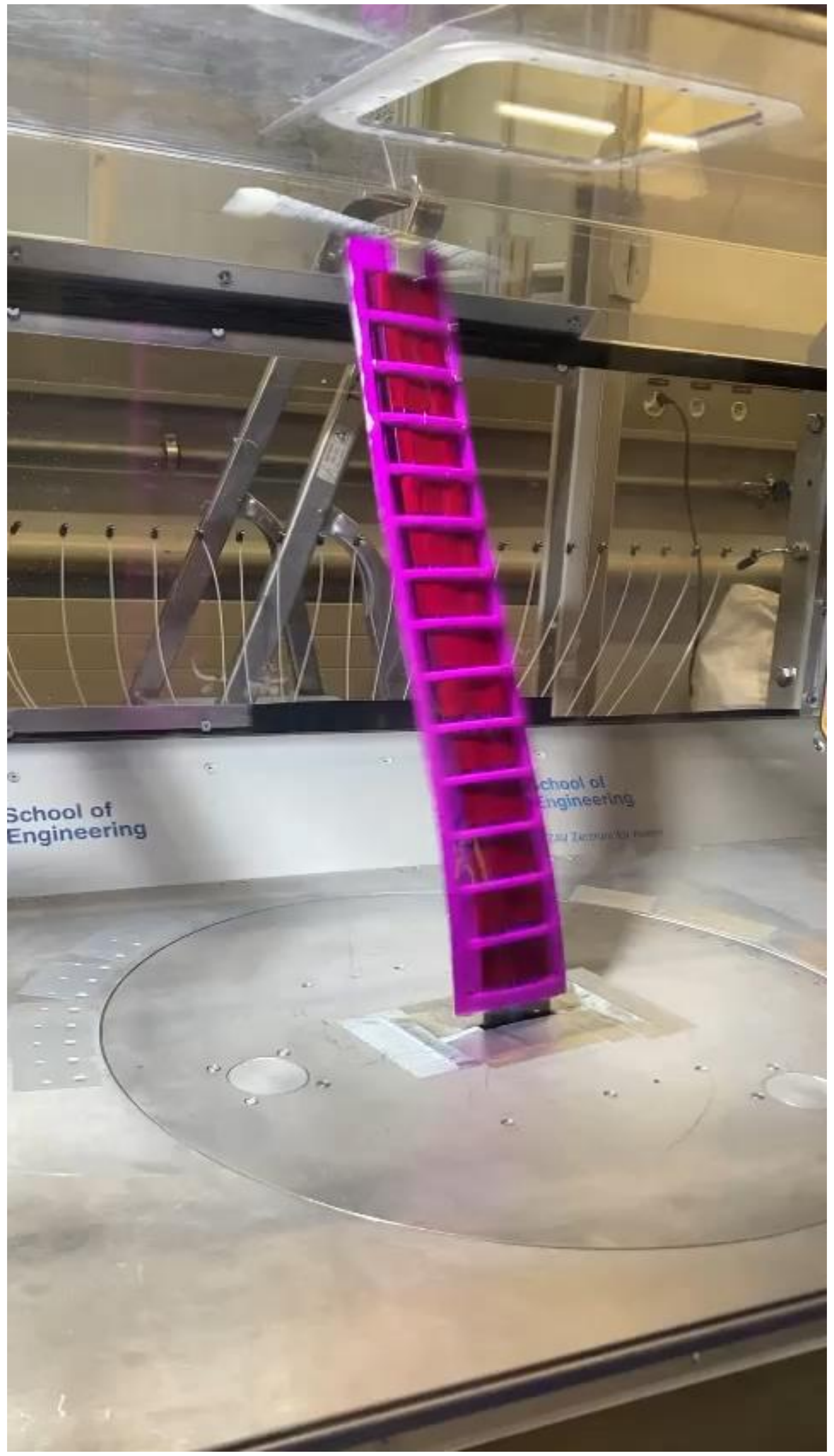


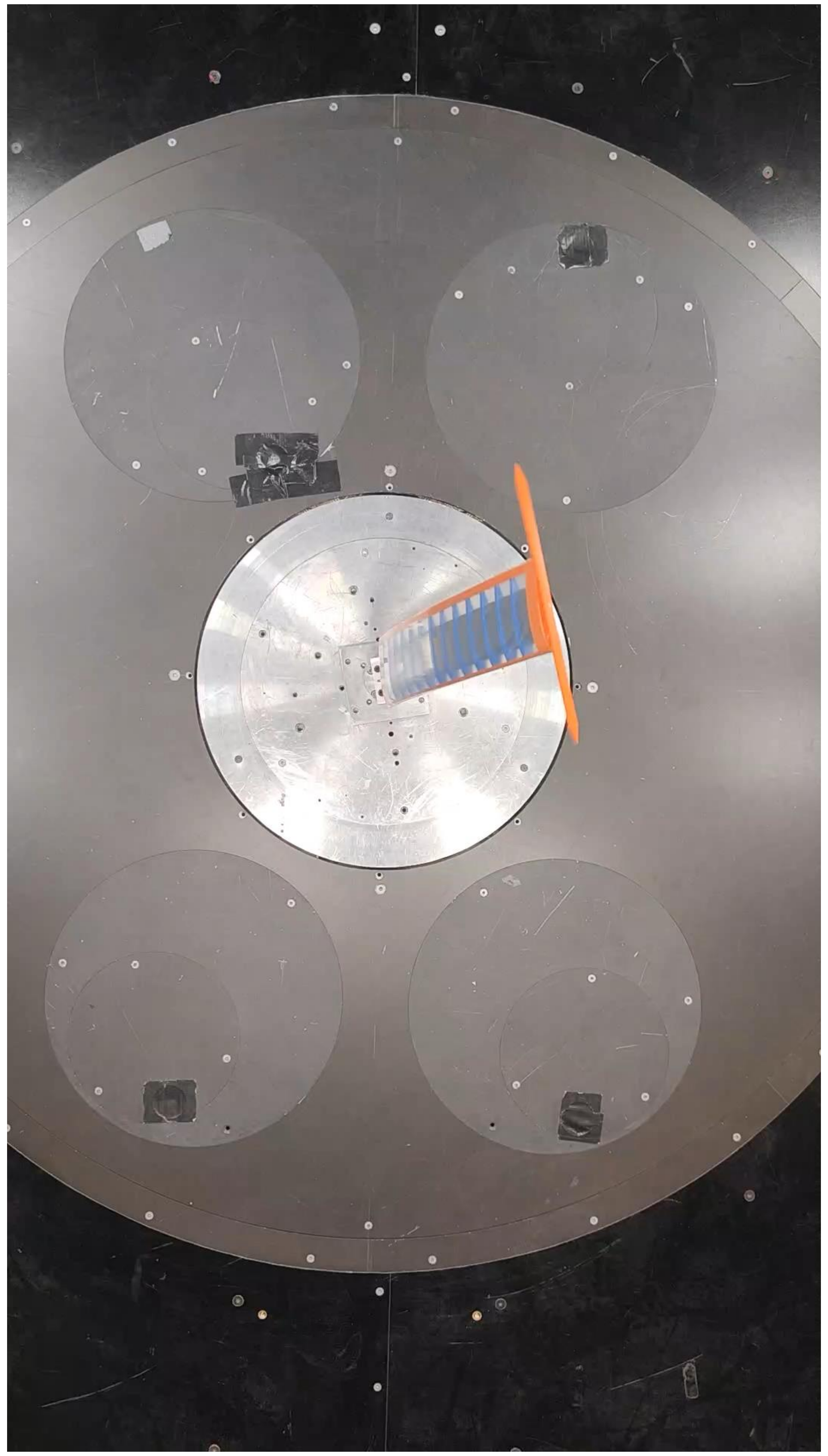
LCO, amplitude

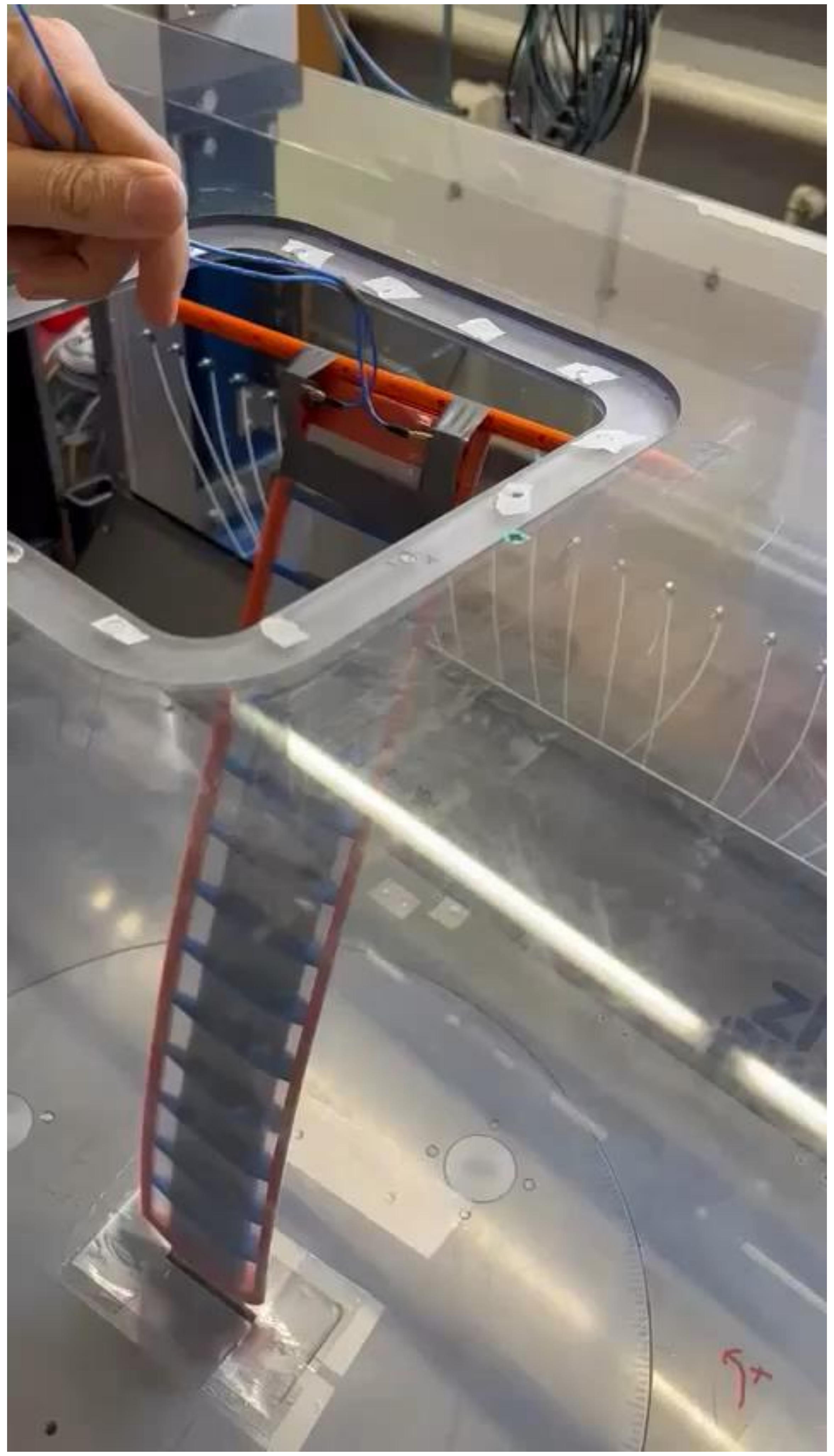
- Model 2021, large subsonic wind tunnel ETH: **smaller** amplitude LCO
- Model 2021, smaller wind tunnel ZHAW: **smaller** amplitude LCO
- Model 2024, smaller wind tunnel ZHAW: **larger** amplitude LCO
- Model 2024, open section wind tunnel (Sapienza): **much smaller** amplitude LCO, not even comparable

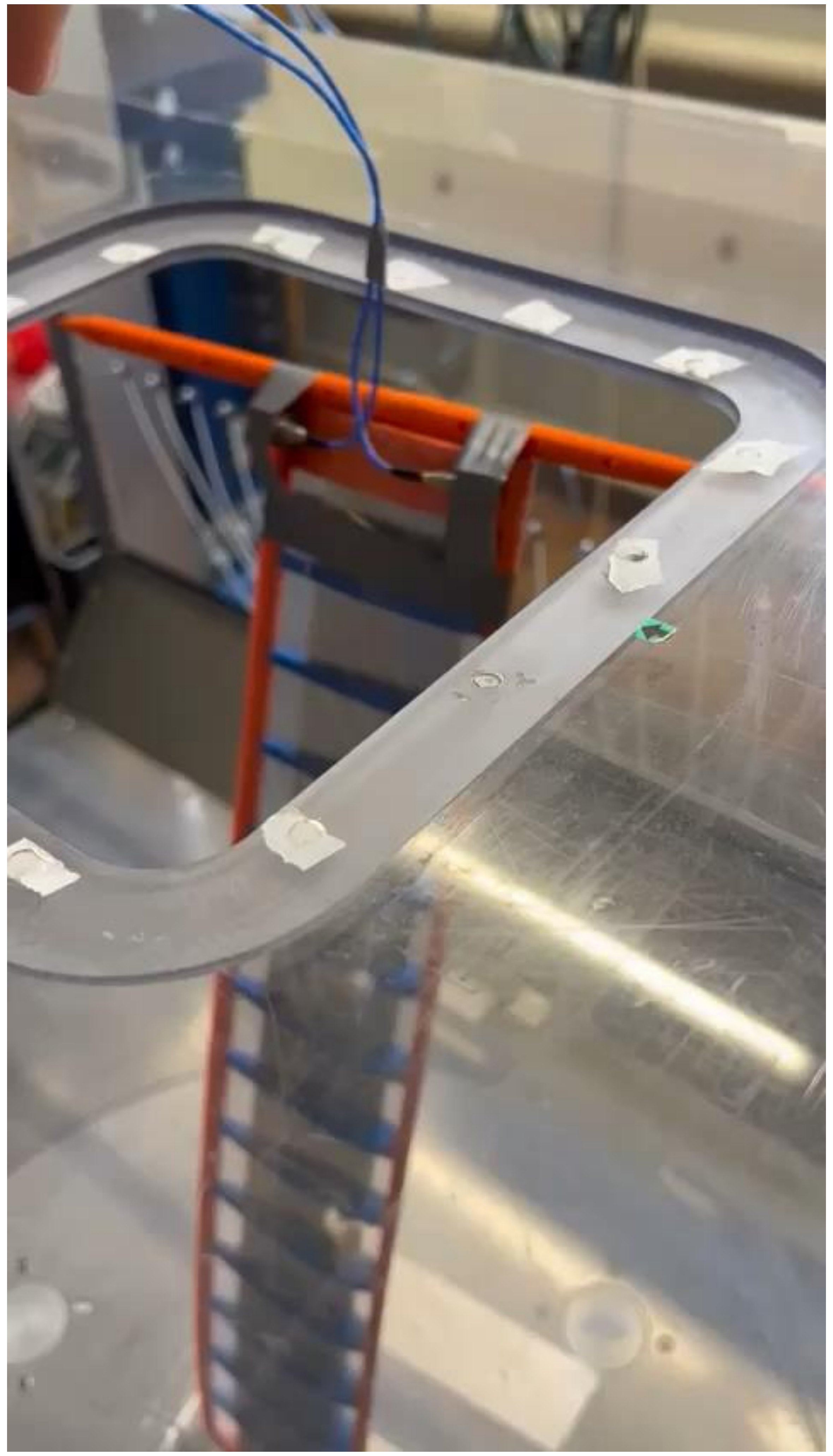
- Differences in mass and modal damping (1st bending) not sufficient to explain:
  - Model 2021, approximately 1.25% (first mode), 320 g,
  - Model 2024, approximately 0.75%-1% (bending modes, OMA), 310 g, < 0.5 Hz higher natural frequencies.

LCO amplitude, meaningful?









Flutter onset

- At 3, 5 and 7 degrees root AoA, in correspondence of flutter onset, we moved with steps of 1 RPM (wind tunnel propeller), i.e. less than 0.1 m/s,
- We tried to excite the model with (i) wind tunnel turbulence, (2) a soft «kick» and (3) a softer «kick»
- The following slides show the response.

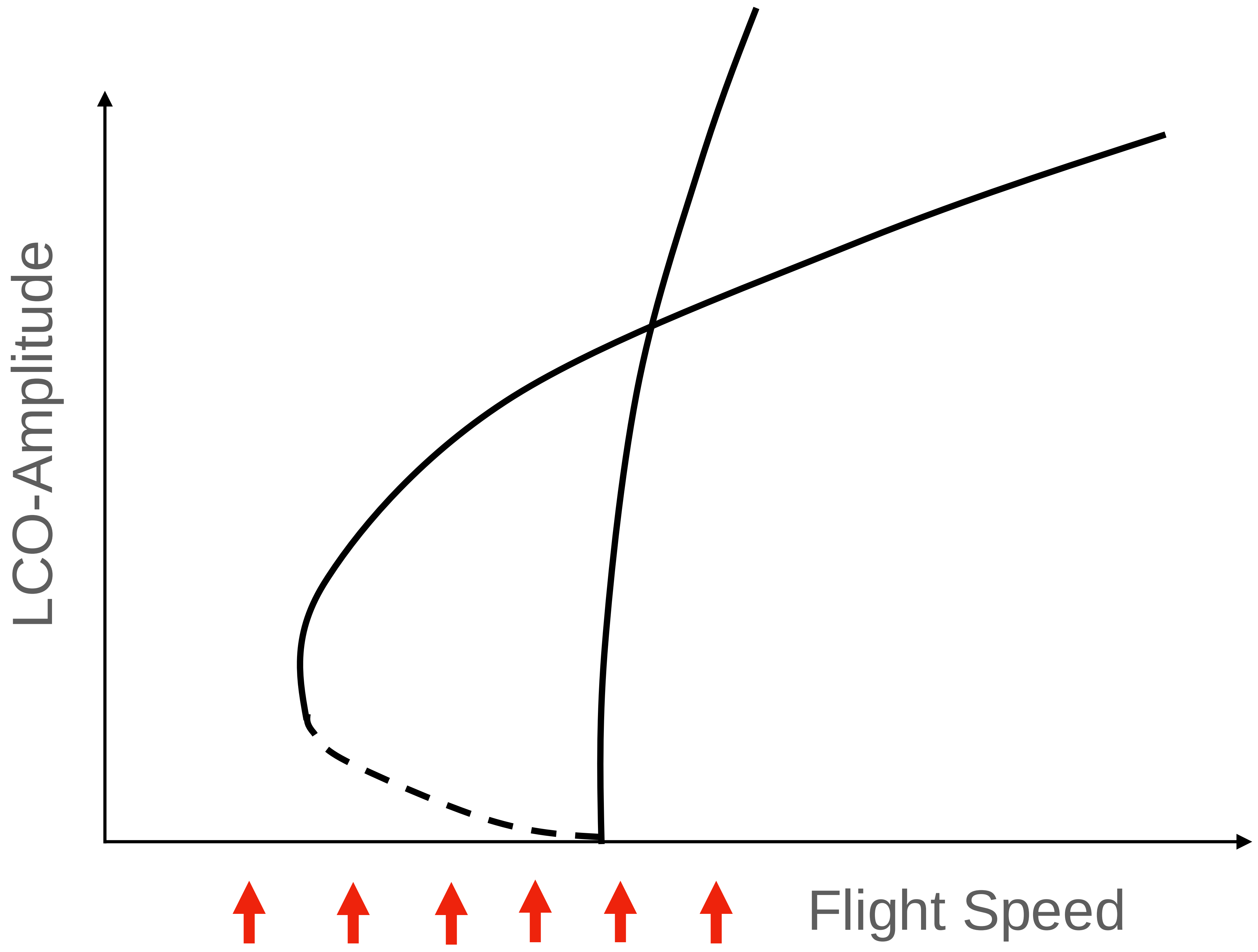
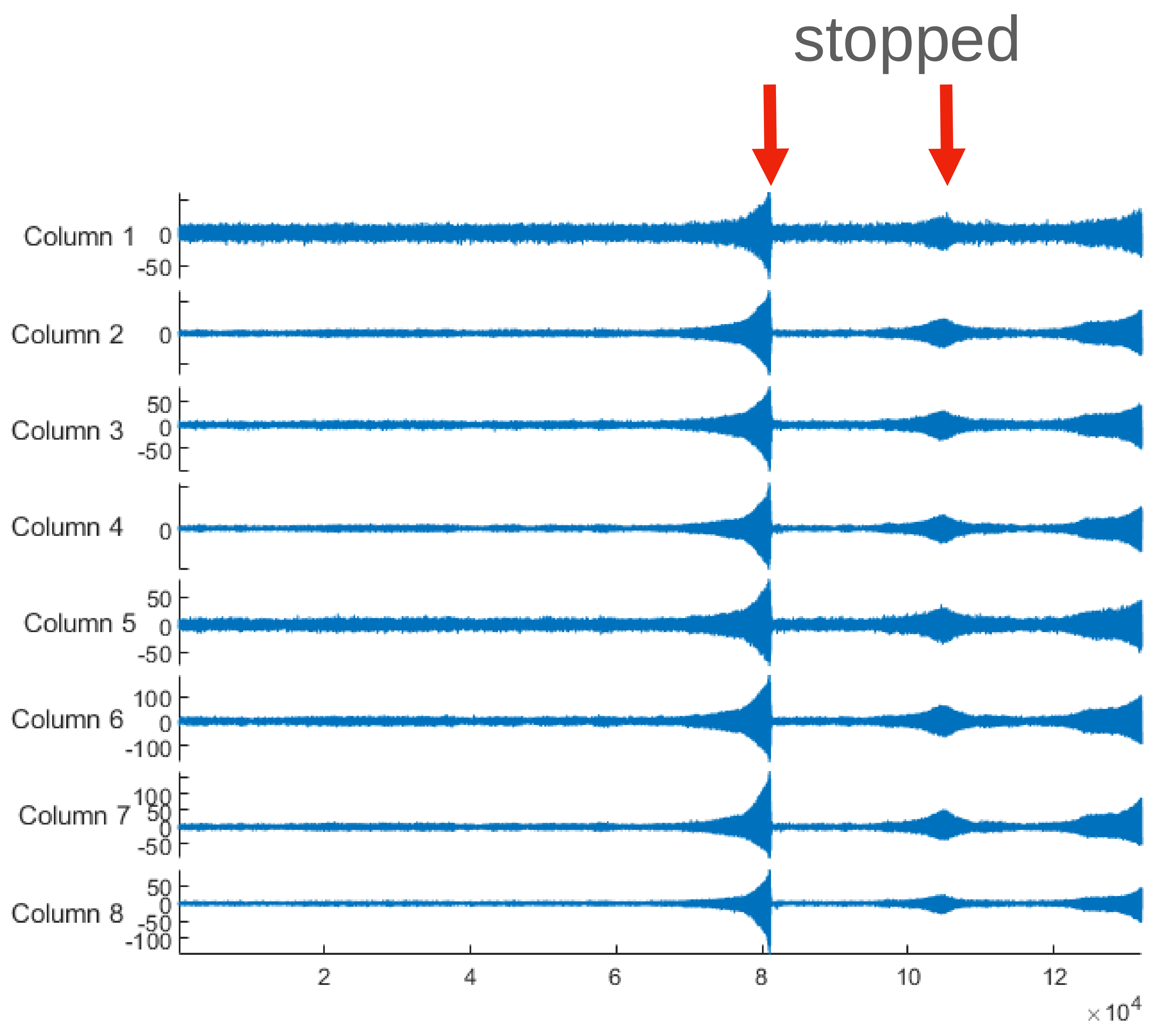


Image inspired by E. Dowell, A Modern Course in Aeroelasticity, Springer, 6th edition, 2022

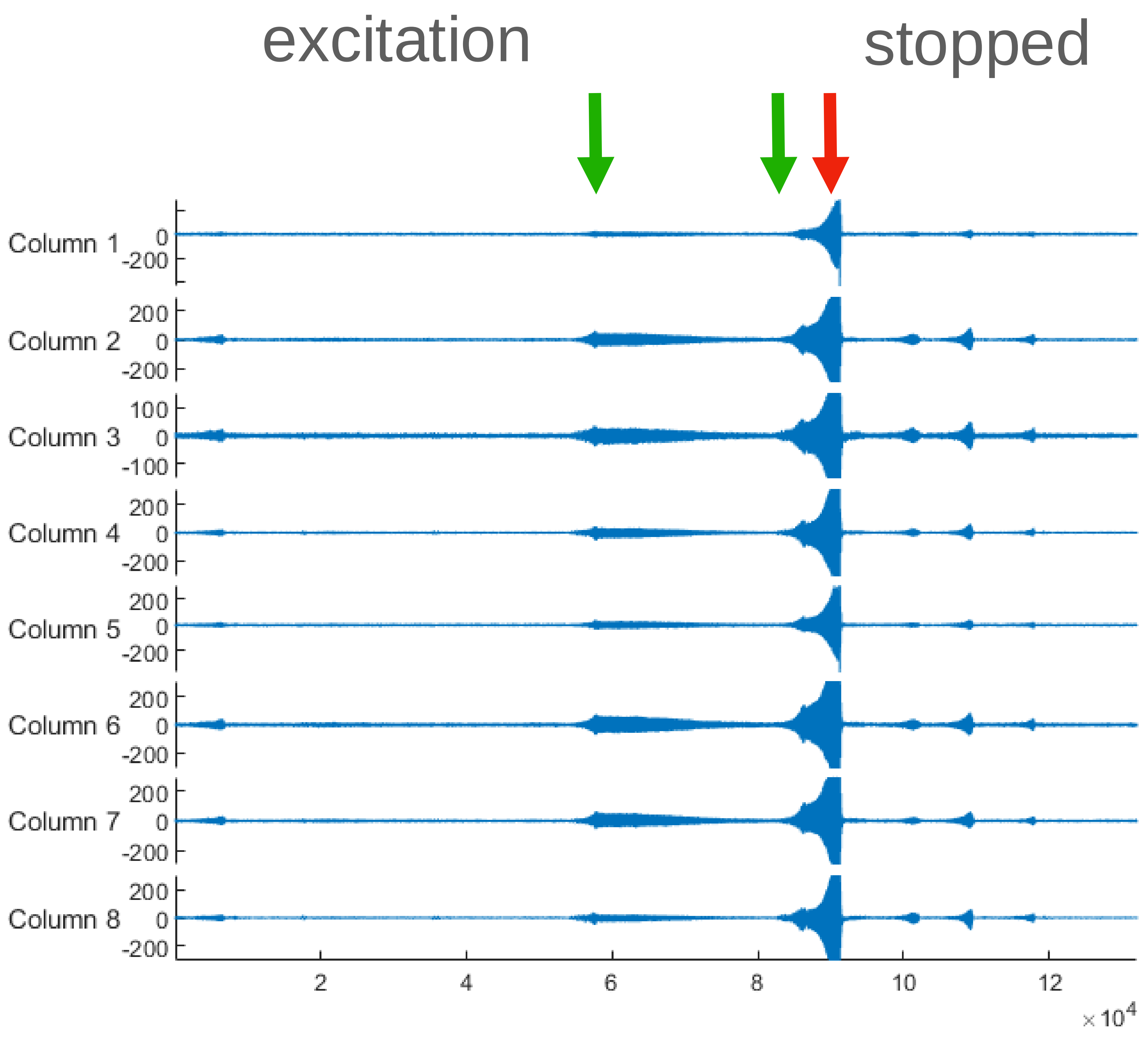
Flutter onset, AoA 3

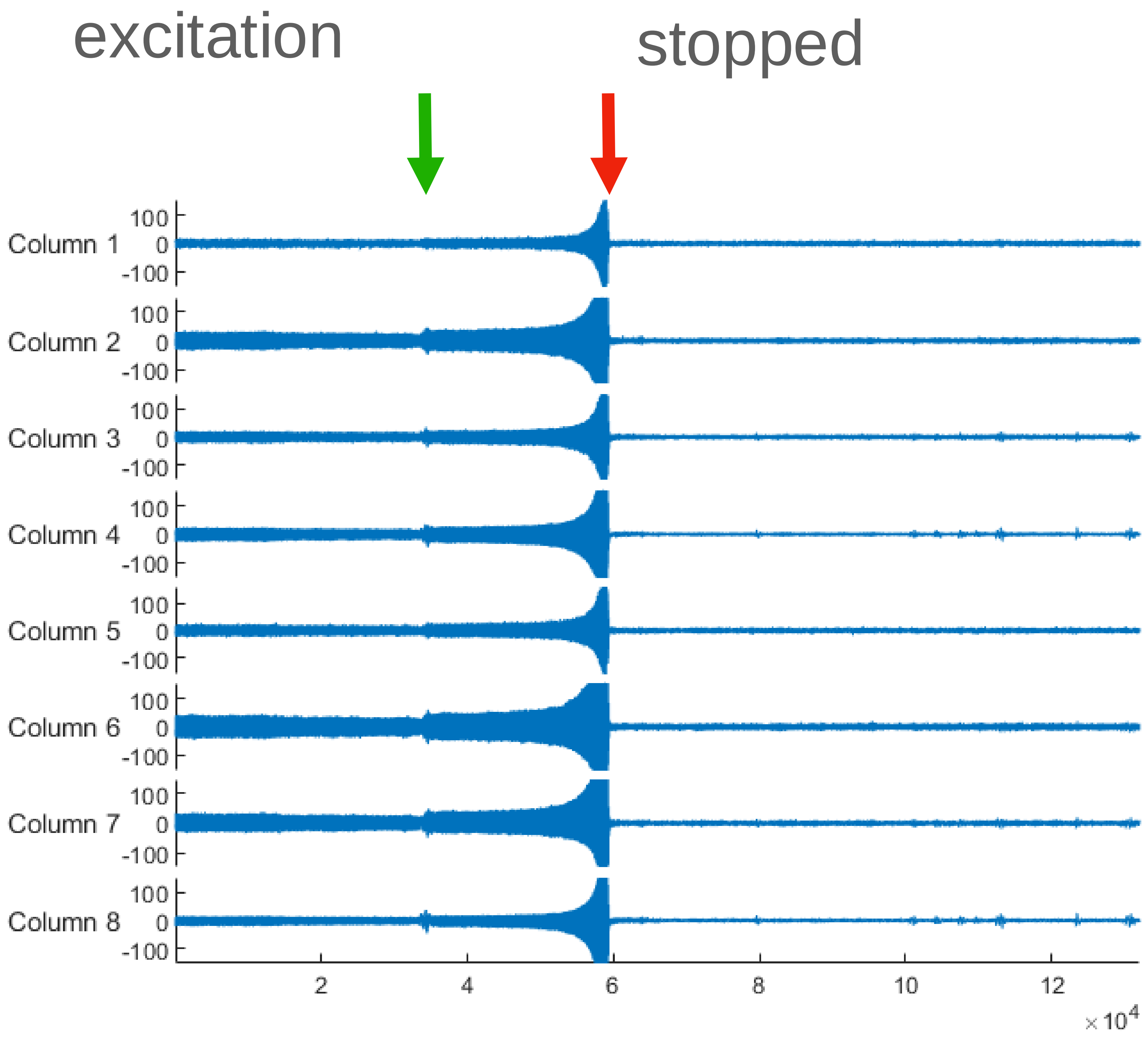
Signals from the 8 accelerometers



The wind tunnel turbulence is sufficient to trigger the flutter onset at this specific dynamic pressure. From the analysis of the signal, we notice that the system is unstable, develops rapidly increasing oscillations

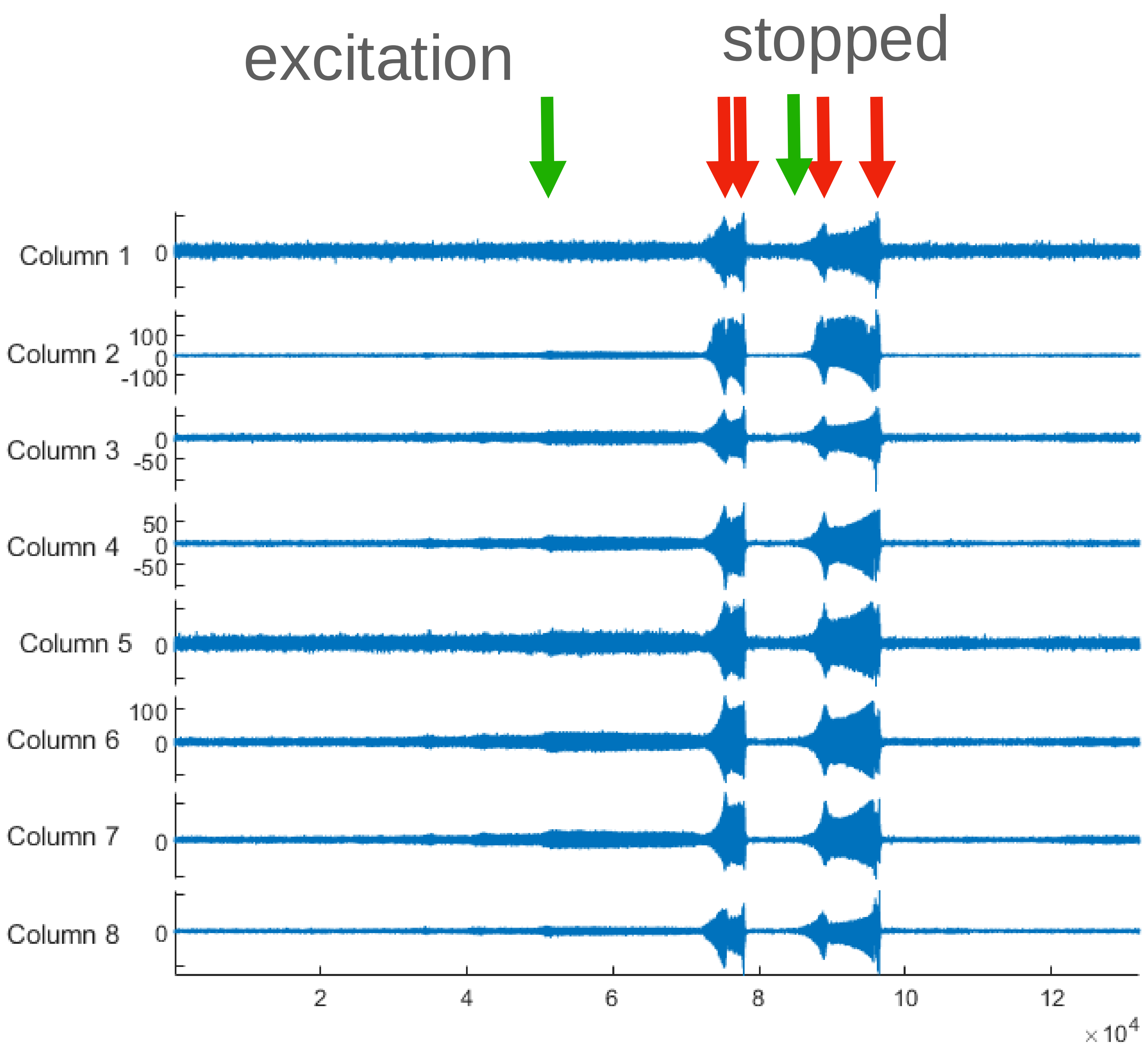
Flutter onset, AoA 5

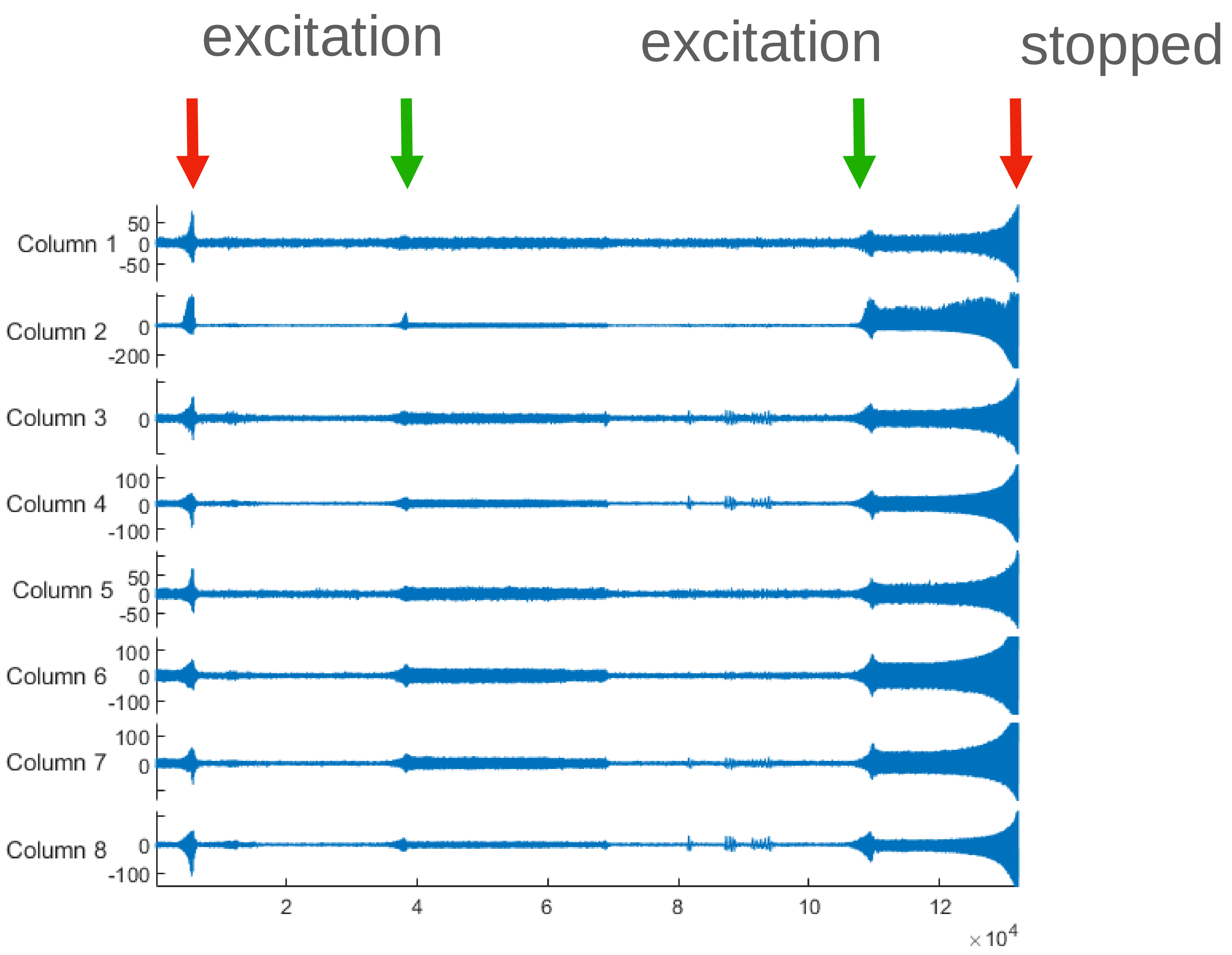




The wind tunnel turbulence is not sufficient to trigger the flutter onset at this specific dynamic pressure. A smaller perturbation are introduced in correspondence with the green arrow and slowly evolves either into rapidly increasing oscillations or towards the trivial solution.

Flutter onset, AoA 7





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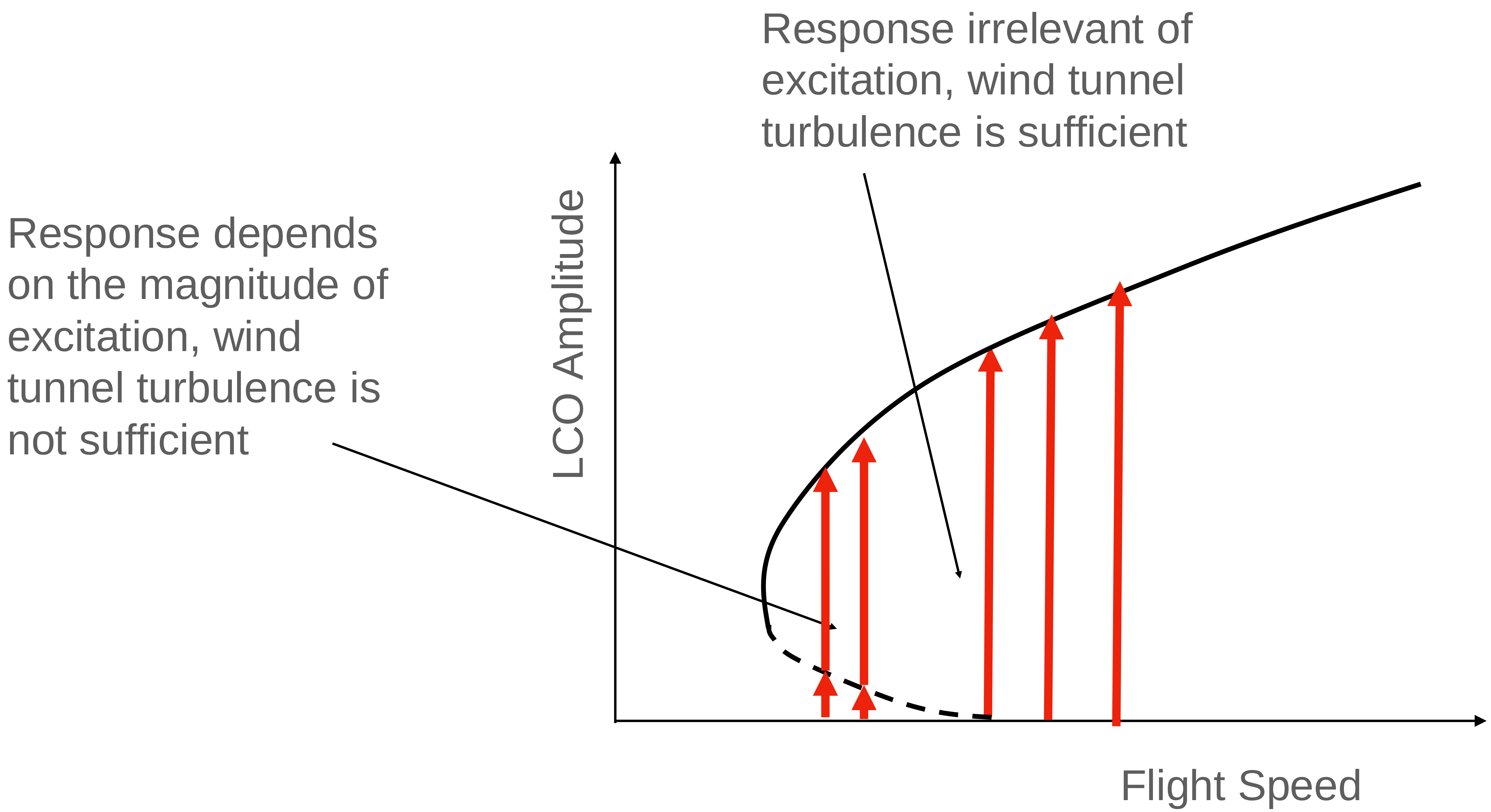
Flutter onset



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