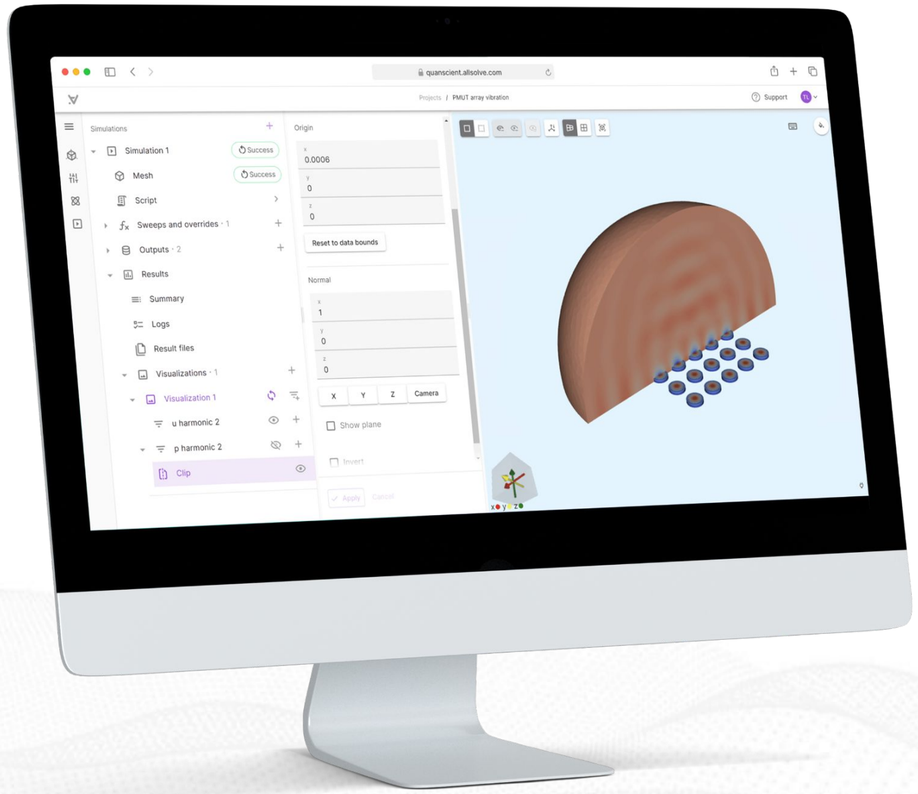
QUANSCIENT

30th January 2025

Accelerating nonlinear MEMS simulations with the harmonic balance method



Dr. -Ing. Abhishek Deshmukh
Team Lead - Application Engineering
Quanscient

Jukka Knuutinen
Head of Marketing
Quanscient

Housekeeping items

Before we start

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Submit your questions at any time

We'll address them throughout the event.

In addition, we'll have a dedicated Q&A session at the end.

We will give out some resources

During the event, we will be handing out some PDF documents.

Download them from the sidebar.

The cast

QUANSCIENT

Jukka Knuutinen

Head of Marketing

Quanscient

Dr. -Ing. Abhishek Deshmukh

Team Lead - Application Engineering

Quanscient

Webinar agenda

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1

Introduction (5 min)

Jukka Knuutinen
Head of Marketing, Quanscient

- → Welcoming words
- → Housekeeping items

2

Introduction to the harmonic balance method (5 min)

Dr.-Ing. Abhishek Deshmukh
Team Lead - Application Engineering, Quanscient

- → Background and introduction to the harmonic balance method
- → Comparison of the harmonic balance method to transient analysis

3

Live demo and results
Practical applications of the harmonic balance method (15 min)

Dr.-Ing. Abhishek Deshmukh

- → Live demo of spring softening in electrostatically actuated CMUTs using Quanscient Allsolve
- → Step-by-step demonstration of how harmonic balance is applied and how it enables faster and more accurate results in nonlinear periodic problems in the frequency domain

Webinar agenda

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4

Other applications and real-world results (15 min)

Dr.-Ing. Abhishek Deshmukh

- → The versatility of the harmonic balance method showcased through case examples of various MEMS applications
- → Discussion of the impact of harmonic balance on MEMS design and analysis

5

Q&A (15 min)

All speakers

- → Live discussion and answers to your questions about the harmonic balance method and its application with Quanscient Allsolve

6

Conclusion and key takeaways (5 min)

Jukka Knuutinen

- → Summary and key takeaways of the webinar
- → Additional resources to learn more

Handouts

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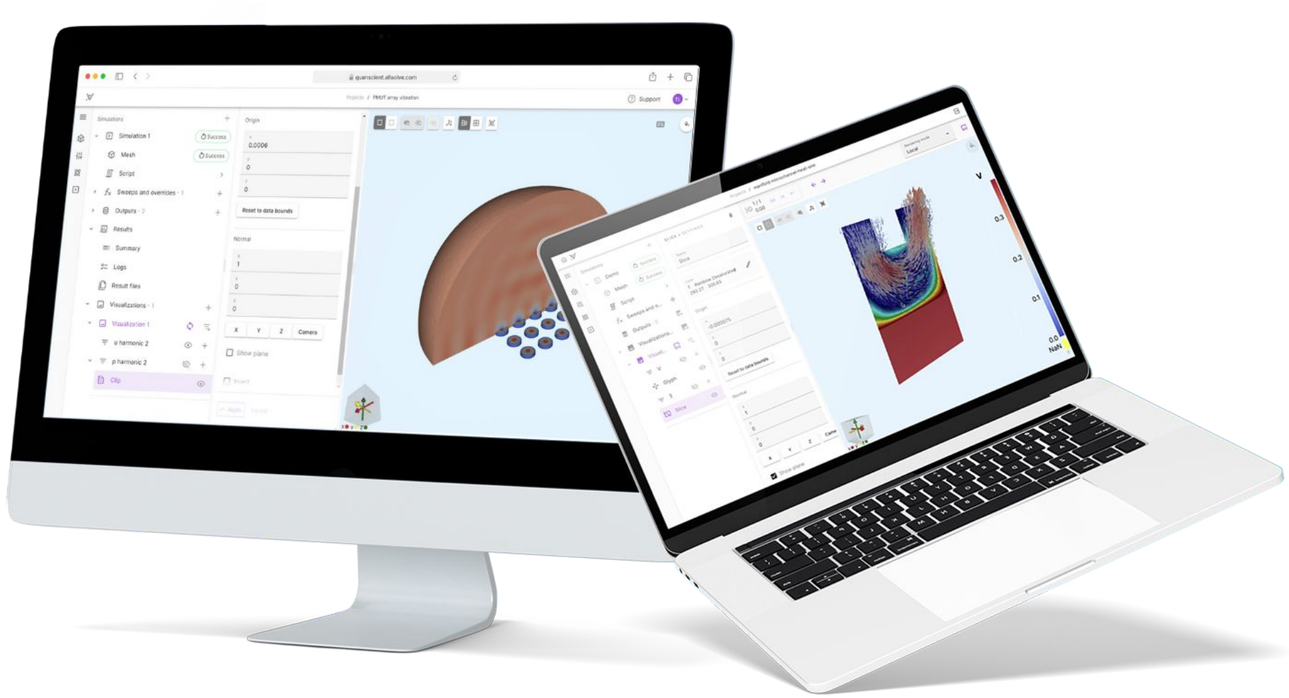
Introduction to Quanscient Allsolve
Overview

QUANSCIENT

- A cloud-based FEM multiphysics simulation platform
- Developed by Quanscient, a company established in 2021 in Tampere, Finland
- Built upon the open-source solver Sparselizard developed by our CTO, **Dr. Alexandre Halbach**



Introduction to Quanscient Allsolve

Trusted in industry and academia

QUANSCIENT

UK Atomic Energy Authority

infineon

TERA LOOP

Massachusetts Institute of Technology

Proxima Fusion

kiutra

VEXLUM

PAUL SCHERRER INSTITUT PSI

ENEA

imec

albis

Tampere University

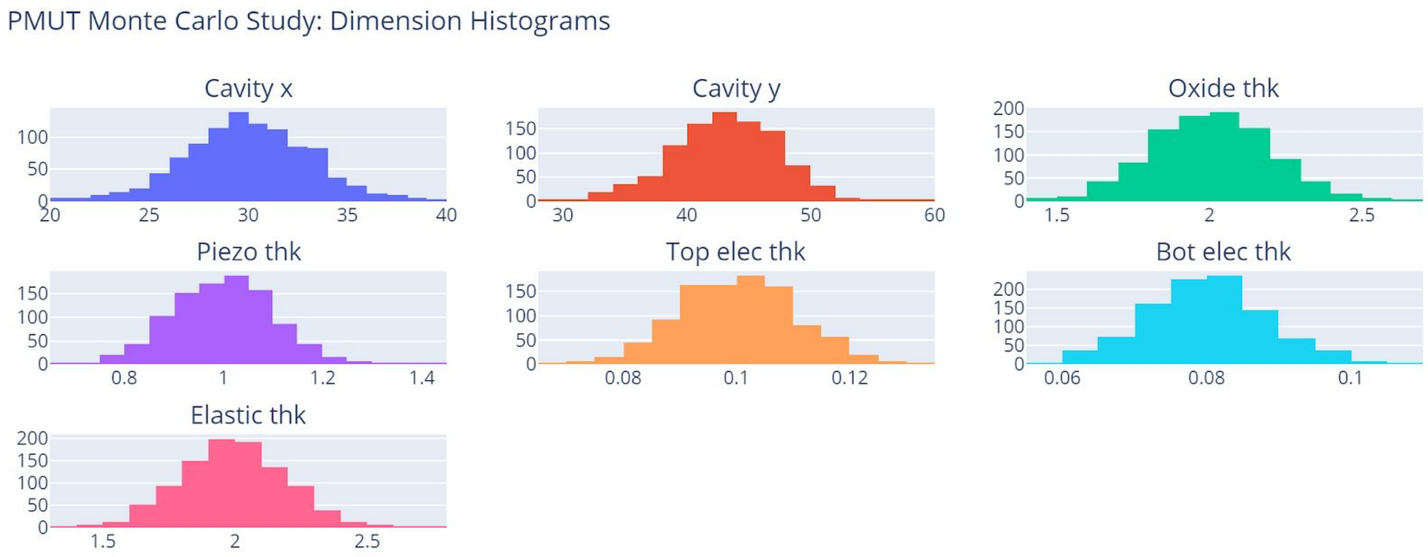
Introduction to Quanscient Allsolve

Why Quanscient Allsolve?

QUANSCIENT

Drive confident design decisions

- → Ensure product reliability and minimize risk with more accurate and robust multiphysics simulations
- → Gain deeper insights into product behavior **taking into account real-world conditions and manufacturing constraints.**
- → Make design decisions confidently with more simulation data to improve product quality and reduce costly errors.



Histograms showing the distribution of dimensional variations for 1,000 PMUT simulations with randomized geometry parameters.

Introduction to Quanscient Allsolve

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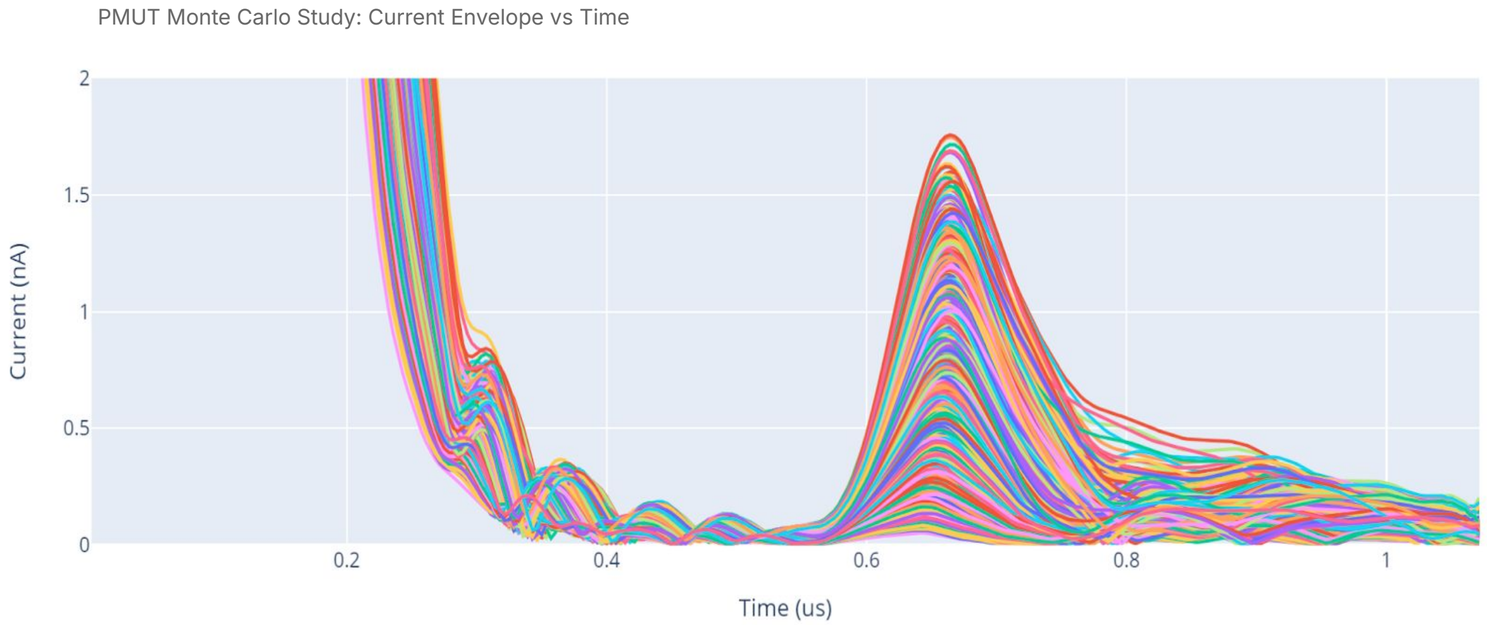

Current envelope vs. time for 1,000 PMUT simulations with randomized geometry parameters, illustrating the impact of dimensional variations on device performance.

Introduction to Quanscient Allsolve

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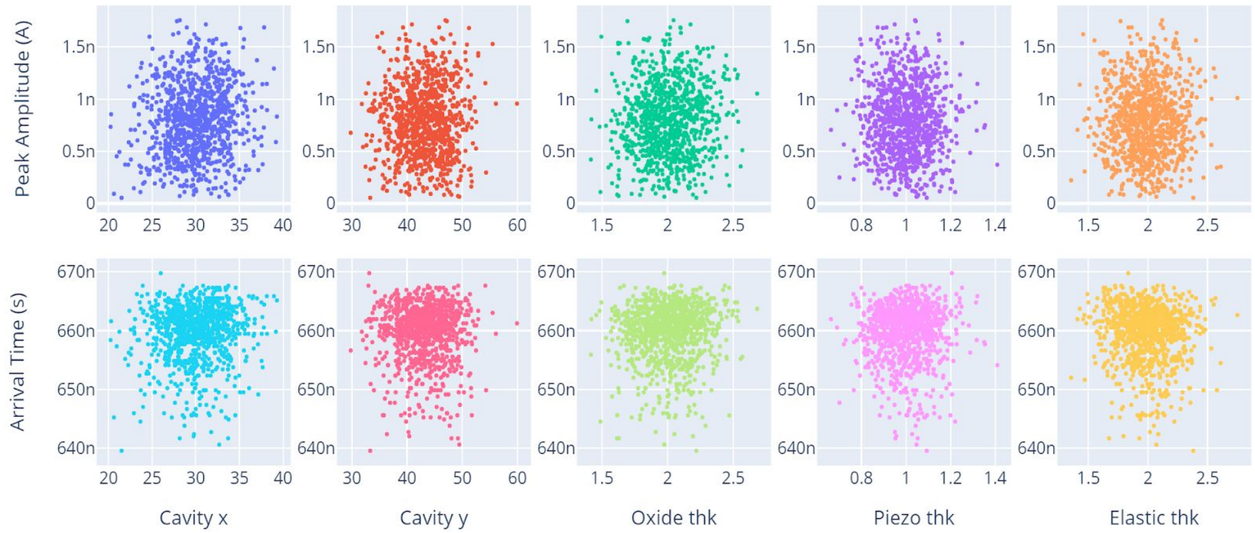
PMUT Monte Carlo Study: Dimensions vs KPI Cross Plot (all dimensions in µm)



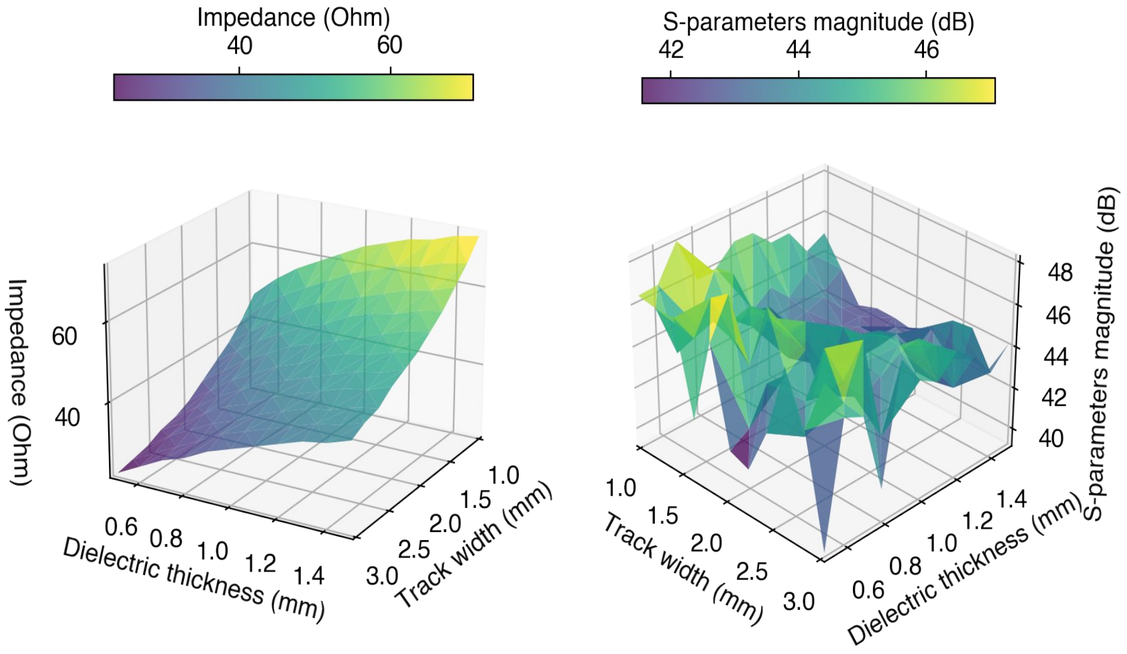
Cross-plot of key performance indicators (KPIs) against dimensional variations for 1,000 PMUT simulations, revealing the relationship between geometry and performance.

Why Quanscient Allsolve?

QUANSCIENT

Accelerate engineering productivity

- → Accelerate design cycles and bring products to market faster with cloud-powered multiphysics simulations.
- → Enable engineers to **explore more design options and optimize product performance** without being constrained by local resources.



A total of 12221 simulations with 0.5 million DoFs performed, each impedance sweep finishing parallely in less than a minute on 101 cores [NAFEMS Electronics, December 2024]

Introduction to Quanscient Allsolve

Why Quanscient Allsolve?

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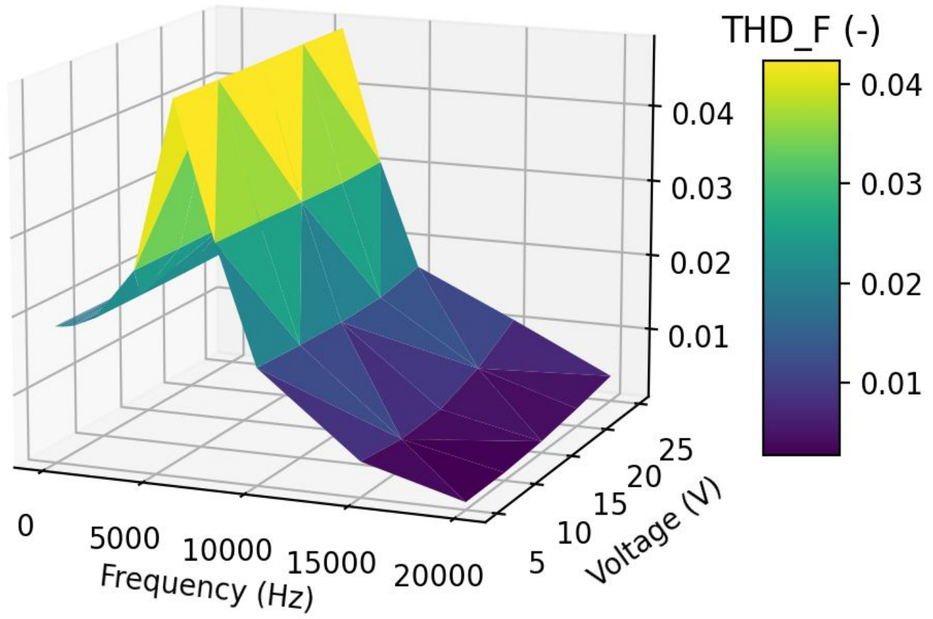

Response surface generated from 75 simulations, illustrating the total harmonic distortion of a microspeaker across frequency and voltage ranges [MEMS Webinar, June 2024]

Introduction to Quanscient Allsolve

Why Quanscient Allsolve?

QUANSCIENT

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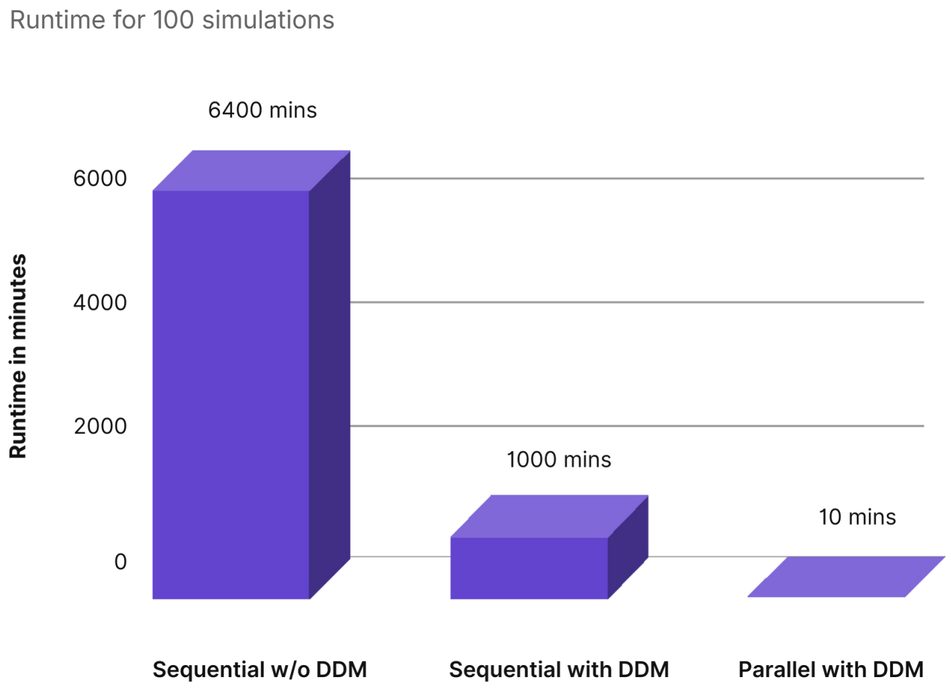


Domain Decomposition Method (DDM) and parallel simulations in Quanscient Allsolve enabled a 640x speedup for a 100-simulation DOE study [Semiconductor Webinar, November 2024]

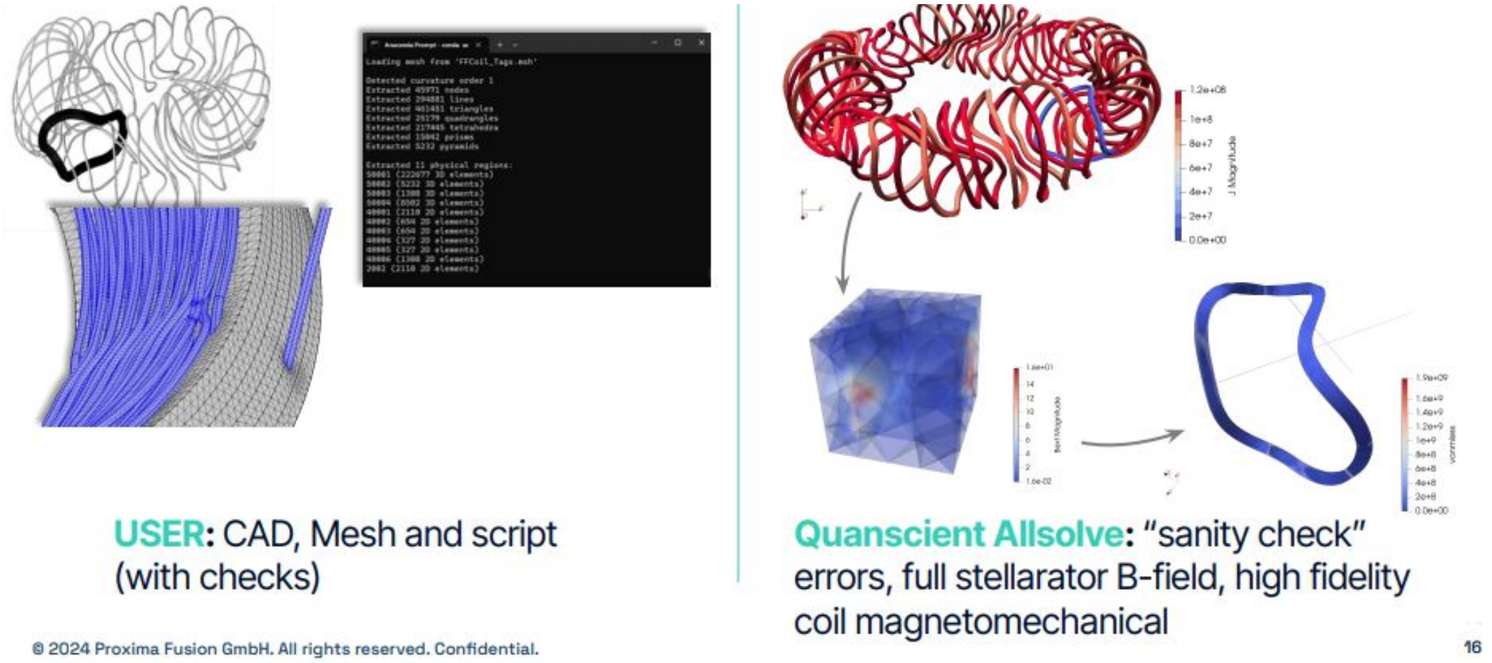
Introduction to Quanscient Allsolve
Why Quanscient Allsolve?

QUANSCIENT

Scale your simulation capabilities and automate your workflows

→ Scale your simulation resources up or down with **no license or hardware restrictions.**

→ Use the Quanscient API to **build and automate efficient proprietary design workflows.**



A fusion energy company, Proxima Fusion, uses the Quanscient API to automate tasks ranging from basic checks to high-fidelity analysis of stellarator coils. [HTS Webinar, September 2024]

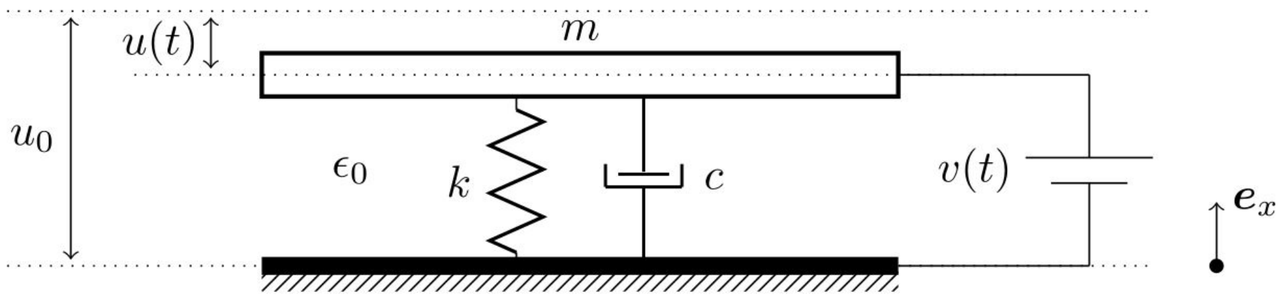
The harmonic balance method
Introduction and background

QUANSCIENT

Solves nonlinear periodic problems in frequency domain

→ Method has been around since 1970s, but limited to lumped models due to high computational demands of FEM

→ Leveraging on-demand cloud resources and efficient implementation, Quanscient Allsolve eliminates the hardware bottlenecks of memory and processing power



Electrostatically actuated spring-mass-damper system

Nonlinear terms:

- Mechanical motion
- Electrostatic force $\propto V^2$

[1] Nakhla M. S. and Vlach J.: "A piecewise harmonic balance technique for determination of the periodic response of nonlinear systems", IEEE Transactions on Circuits and Systems, vol. 23, pp. 85-91, 1976.
[2] Halbach A.: "Domain decomposition techniques for the nonlinear, steady-state, finite element simulation of MEMS ultrasonic", PhD Thesis, University of Liège, 2017.

The harmonic balance method
Comparison to transient analysis

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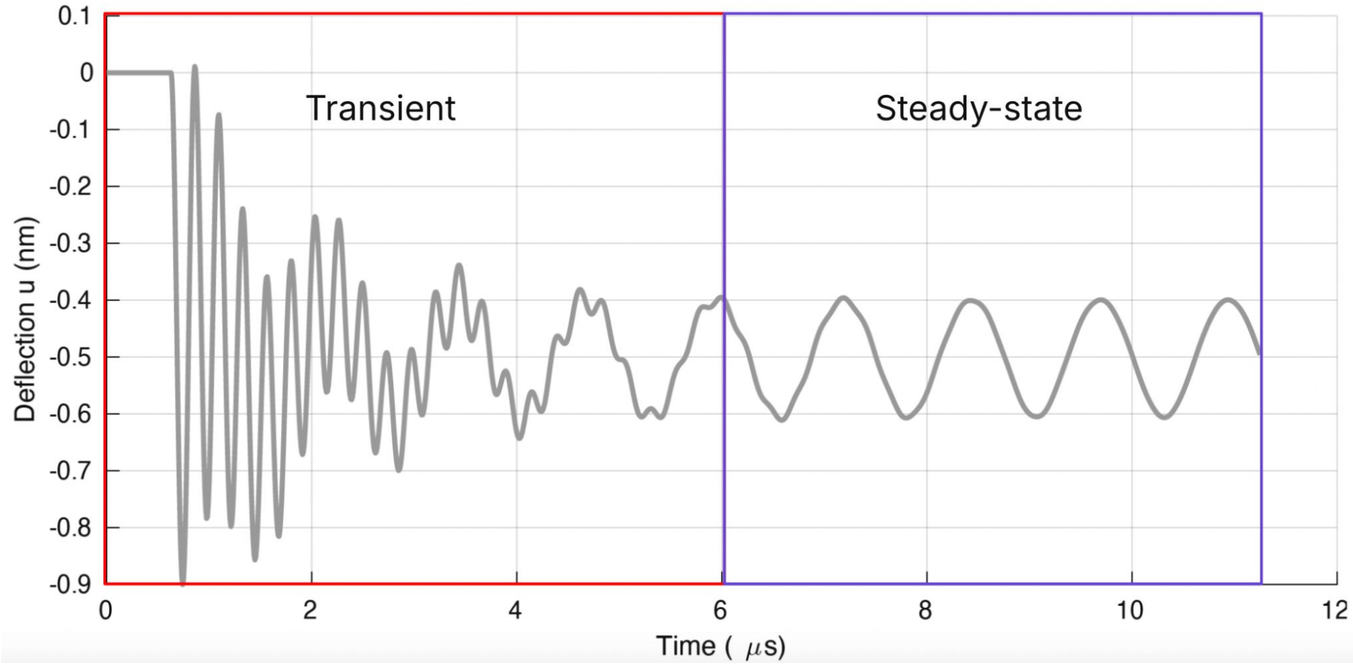


Transient analysis to get the steady-state:

- Transient can be very long (more than 1000 cycles in practical cases)
- More likely manual steps
- Noise on extracted frequencies

[1] Nakhla M. S. and Vlach J.: "A piecewise harmonic balance technique for determination of the periodic response of nonlinear systems", IEEE Transactions on Circuits and Systems, vol. 23, pp. 85-91, 1976.
[2] Halbach A.: "Domain decomposition techniques for the nonlinear, steady-state, finite element simulation of MEMS ultrasonic", PhD Thesis, University of Liège, 2017.

The harmonic balance method
Key working principle

QUANSCIENT

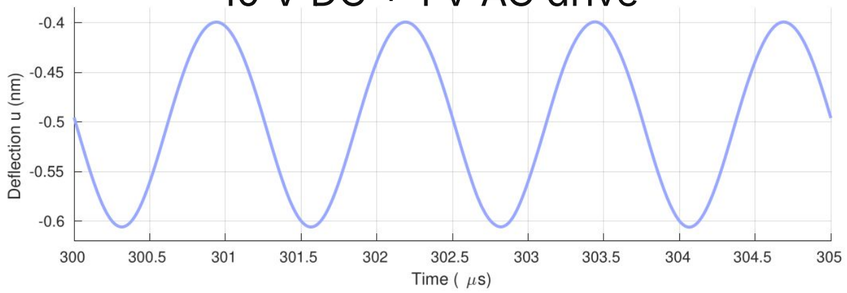
Decomposing each field into Fourier coefficients

→ Use truncated series with required harmonics

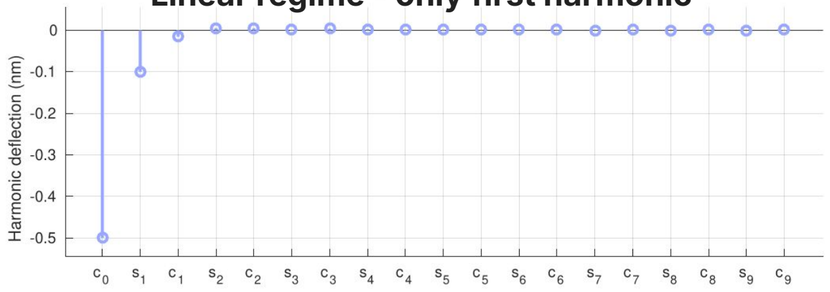
→ Nonlinear regime - higher harmonics required

$$\phi(\boldsymbol{x}, t) = \sum_{k=0}^{N} \phi_{sk}(\boldsymbol{x}) \sin(\omega_k t) + \phi_{ck}(\boldsymbol{x}) \cos(\omega_k t)$$

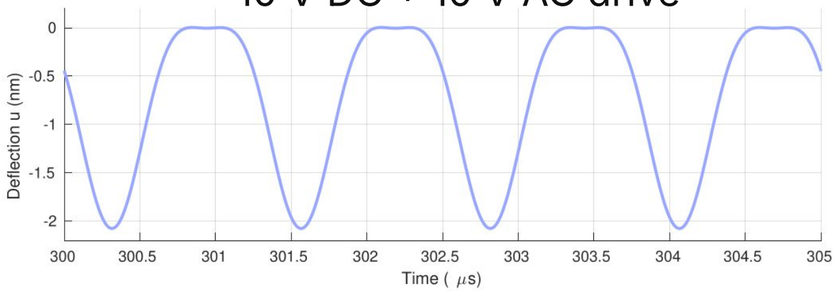
10 V DC + 1 V AC drive



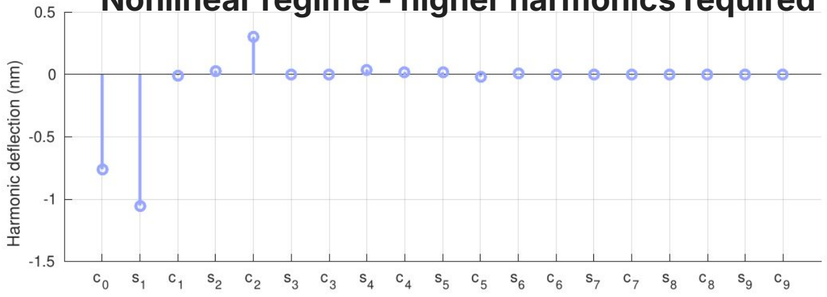
Linear regime - only first harmonic



10 V DC + 10 V AC drive



Nonlinear regime - higher harmonics required



[2] Halbach A.: "Domain decomposition techniques for the nonlinear, steady-state, finite element simulation of MEMS ultrasonic", PhD Thesis, University of Liège, 2017.

The harmonic balance method
Live Demo: CMUT Spring softening

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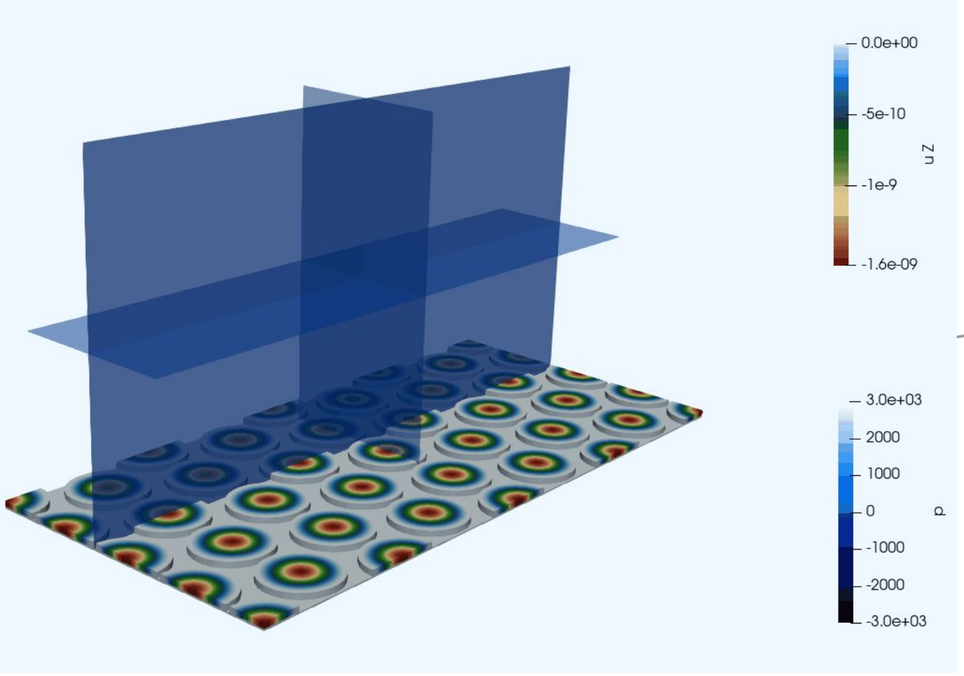
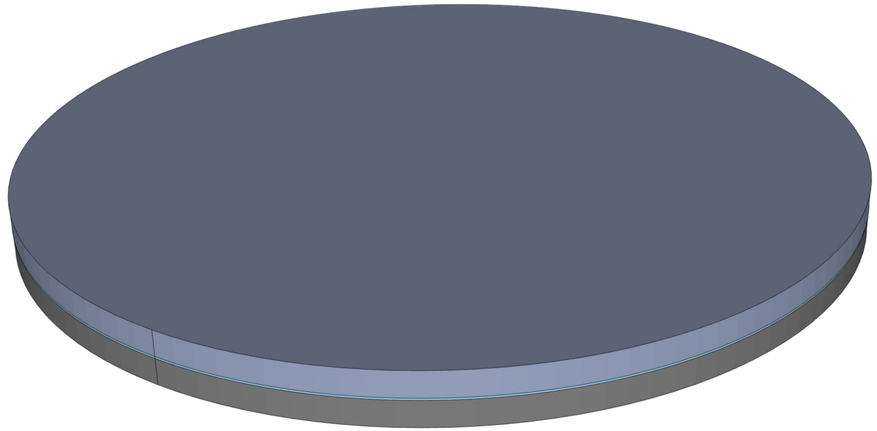
Spring softening

→ Effective spring constant of the system is reduced



Single CMUT cell



[3] Analyze your MUT design with cloud-based multiphysics simulation. [MUT Webinar, December 2024]

The harmonic balance method
Live Demo: CMUT Spring softening

QUANSCIENT

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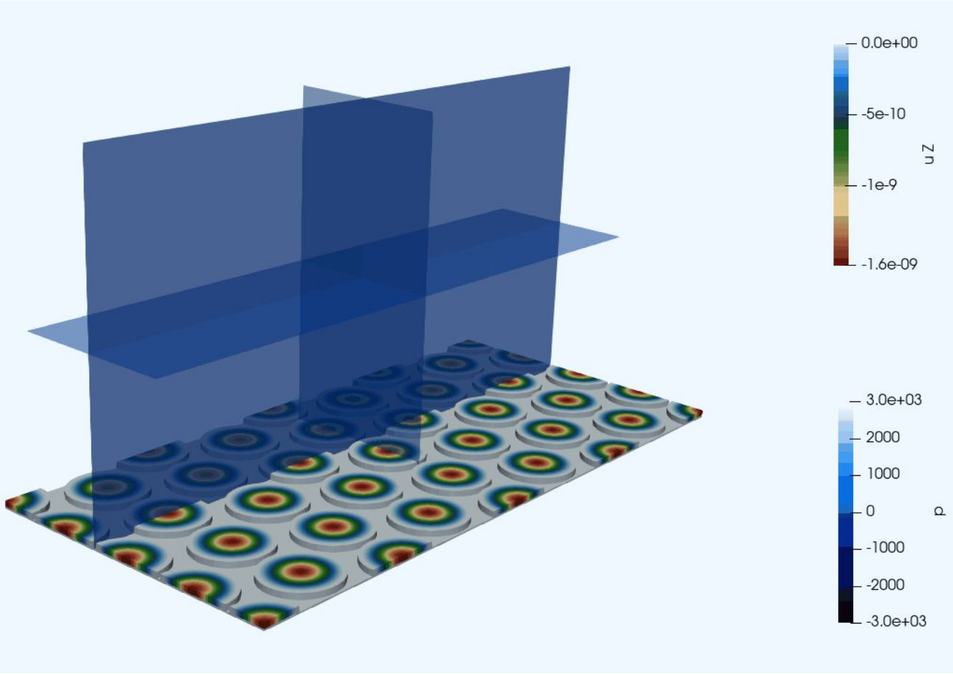
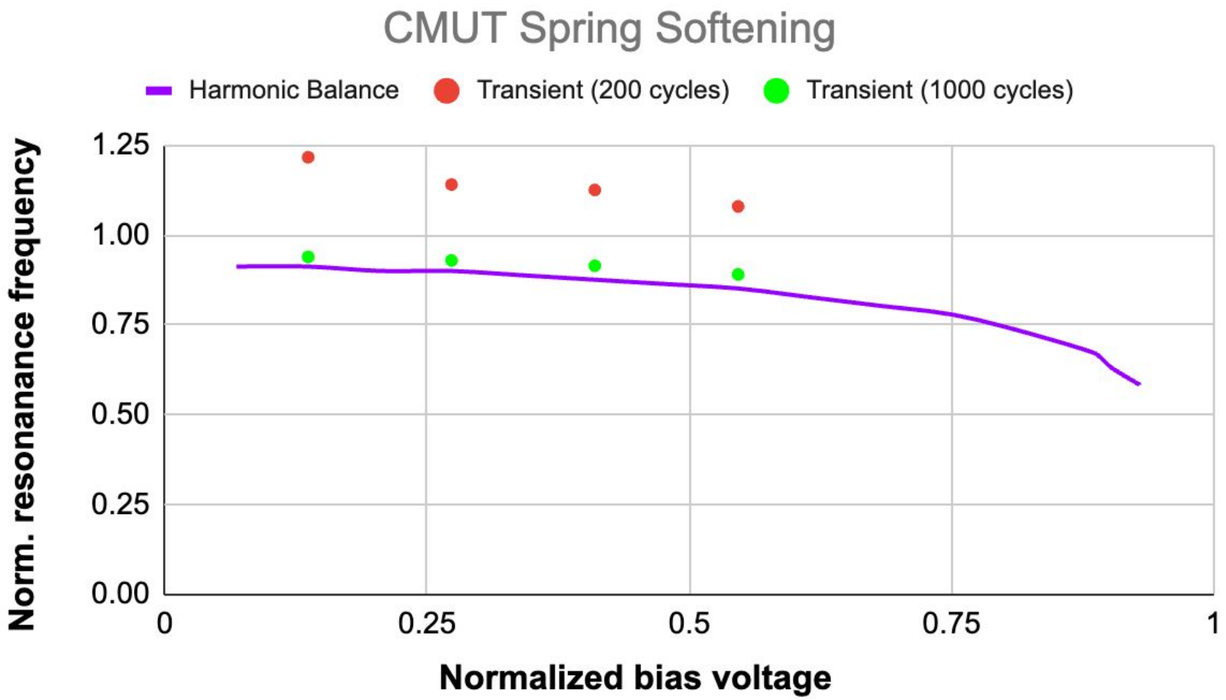


Transient vs. Harmonic balance



*One transient simulation for 1000 cycles takes about 3 hours

[3] Analyze your MUT design with cloud-based multiphysics simulation. [MUT Webinar, December 2024]

The harmonic balance method
Other applications and real-world results

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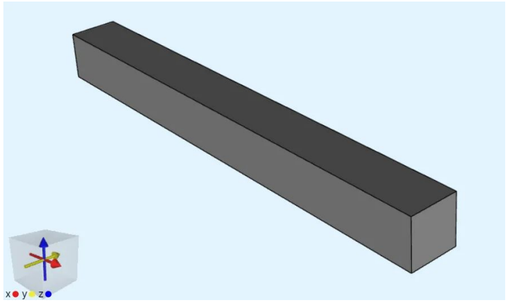
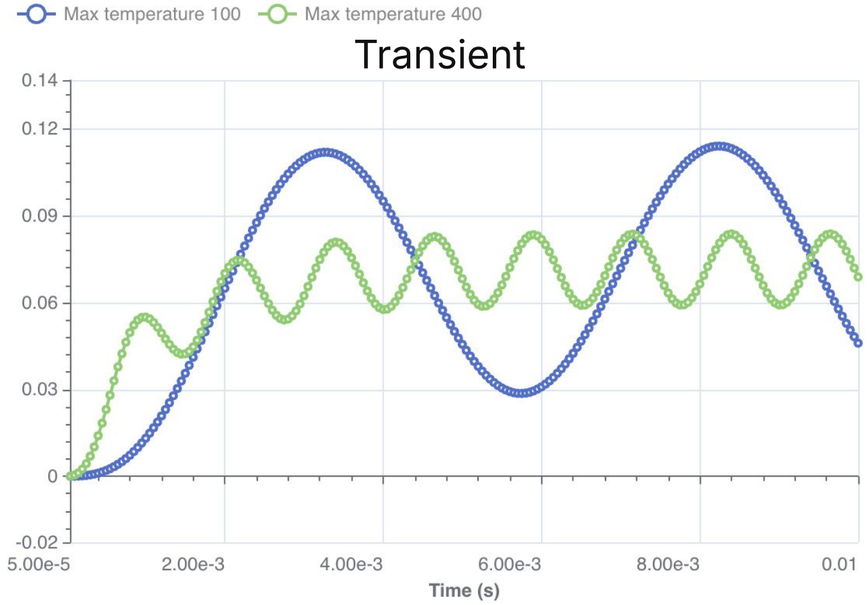
AC Joule heating

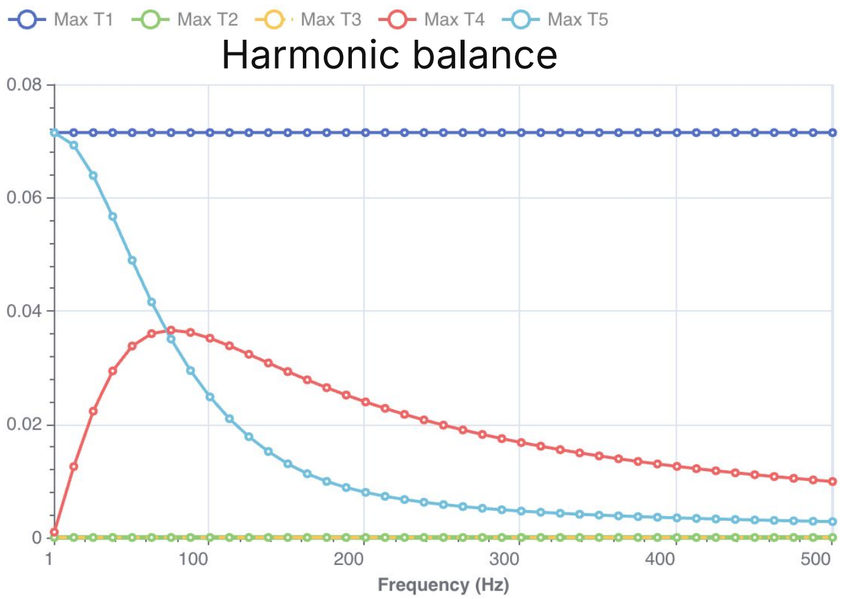
→ Electrical systems, from the wiring in our homes to the circuits in our smartphones, generate heat as electricity flows through their conductors. This phenomenon, known as Joule heating, can significantly impact the performance and lifespan of these systems.



Fundamental driving frequency f0: 100 Hz, 400 Hz



Frequency sweep: 1 Hz to 500 Hz in 40 steps



The harmonic balance method
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$$\dot{Q} \propto I(t)^2$$

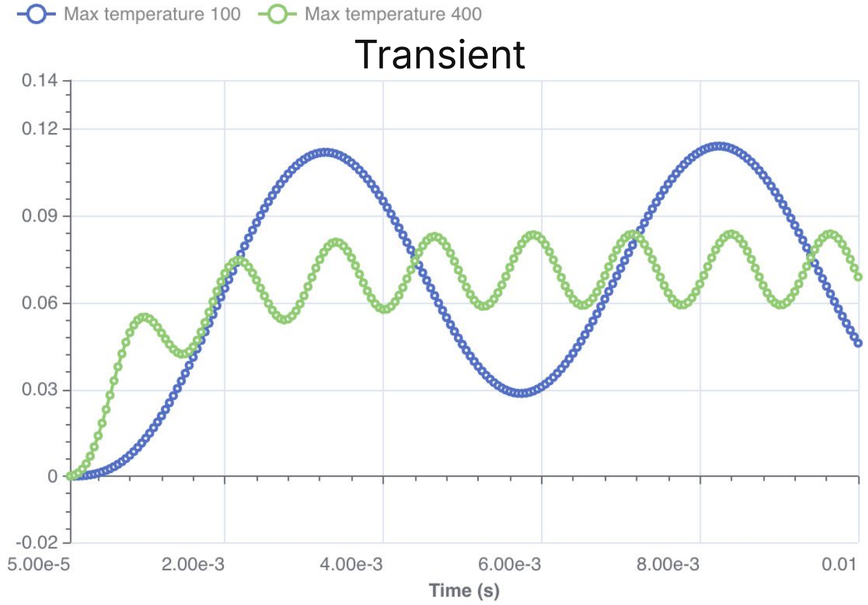
$$\dot{Q} \propto I_0^{\,2}\ sin^2(2\pi f0\ t)$$

$$\dot{Q} \propto I_0^{\,2}\ \frac{1}{2}(1\ -\ cos(2\pi\ 2f0\ t))$$

$$T \propto \frac{1}{2} I_0^{\,2}(\vec{x})\ + \phi_{s1}(\vec{x})\ sin(2\pi\ 2f0\ t)\ + \phi_{c1}(\vec{x})\ cos(2\pi\ 2f0\ t))$$

$$\rho C_p \dot{T} = k\nabla^2 T + \dot{Q}$$

Fundamental driving frequency f0: 100 Hz, 400 Hz



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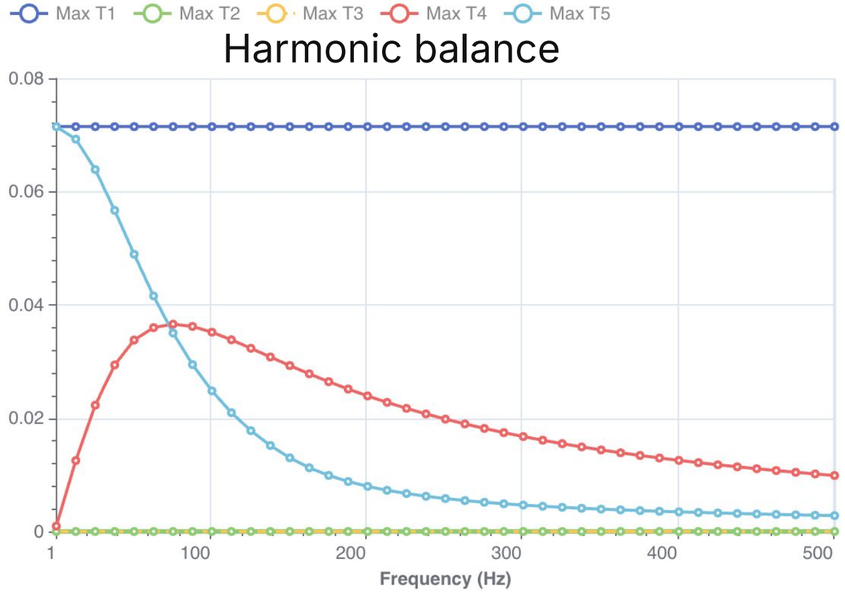

The harmonic balance method
Other applications and real-world results

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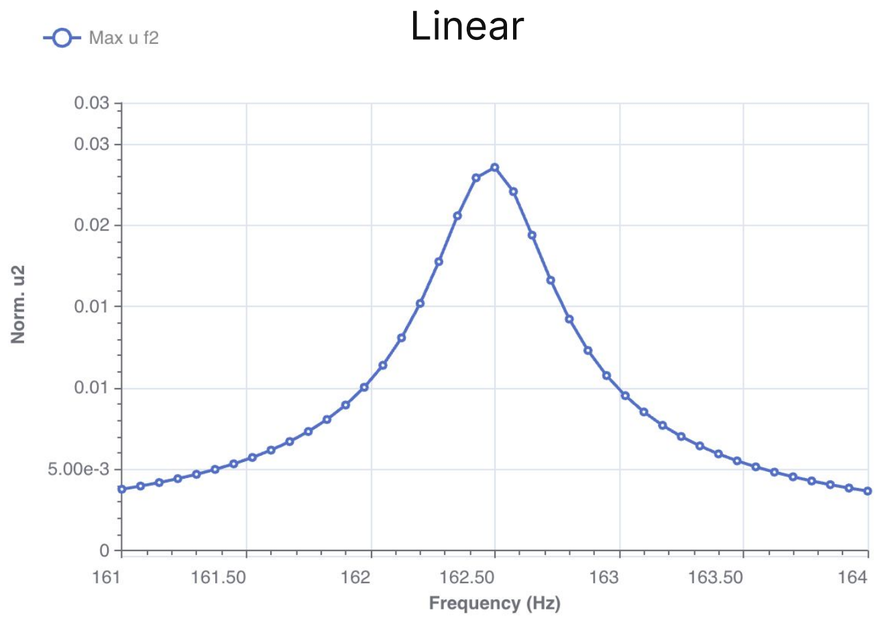
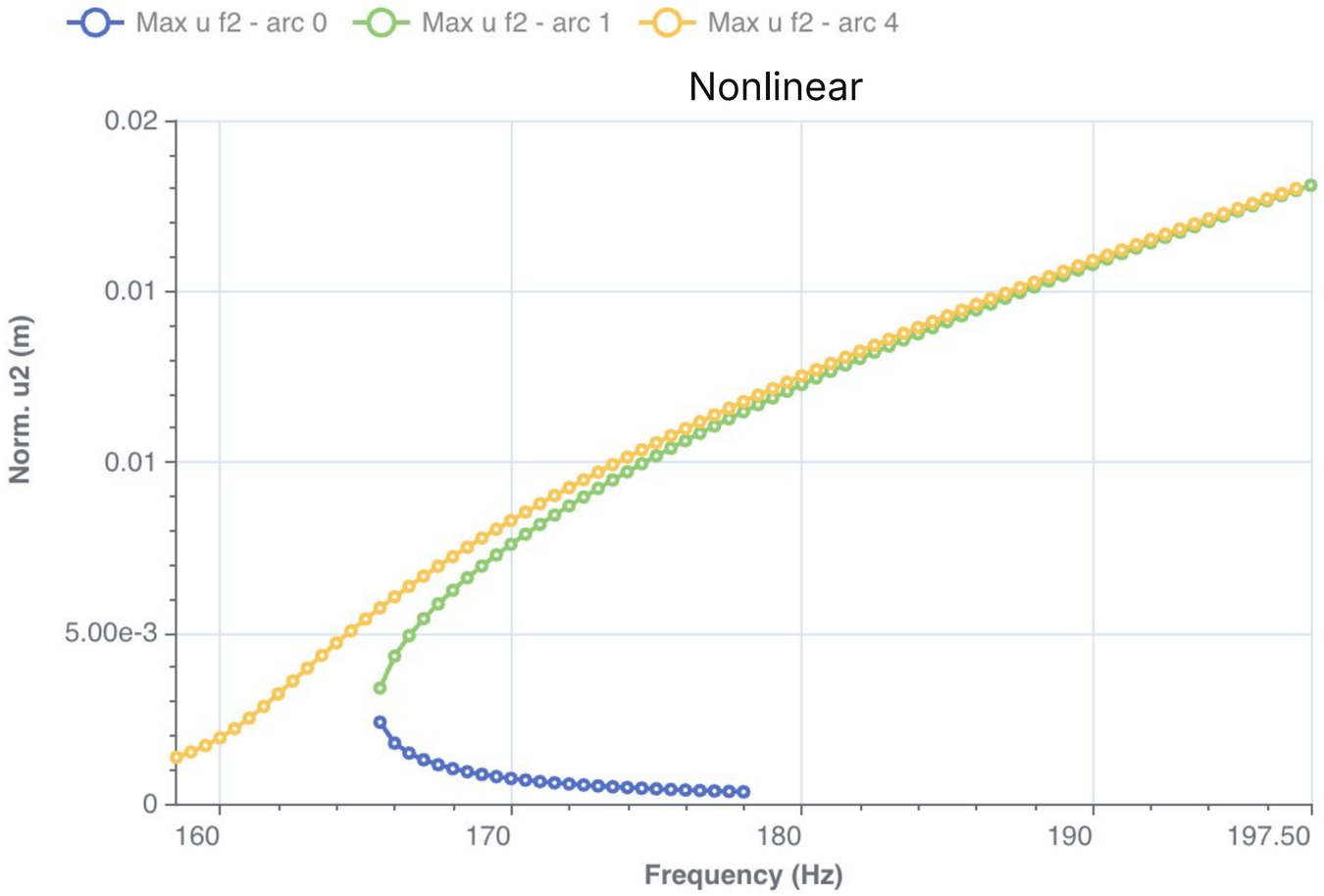
Backbone curve: clamped-clamped beam

→ Mechanical resonance in case of geometric nonlinearity

→ Max displacement versus driving frequency

→ Transient is difficult in this case





[4] Hayashi, S., Gutschmidt, S., Murray, R. et al. Experimental bifurcation analysis of a clamped beam with designed mechanical nonlinearity. Nonlinear Dyn 112, 15701–15717 (2024). https://doi.org/10.1007/s11071-024-09873-5

The harmonic balance method
Other applications and real-world results

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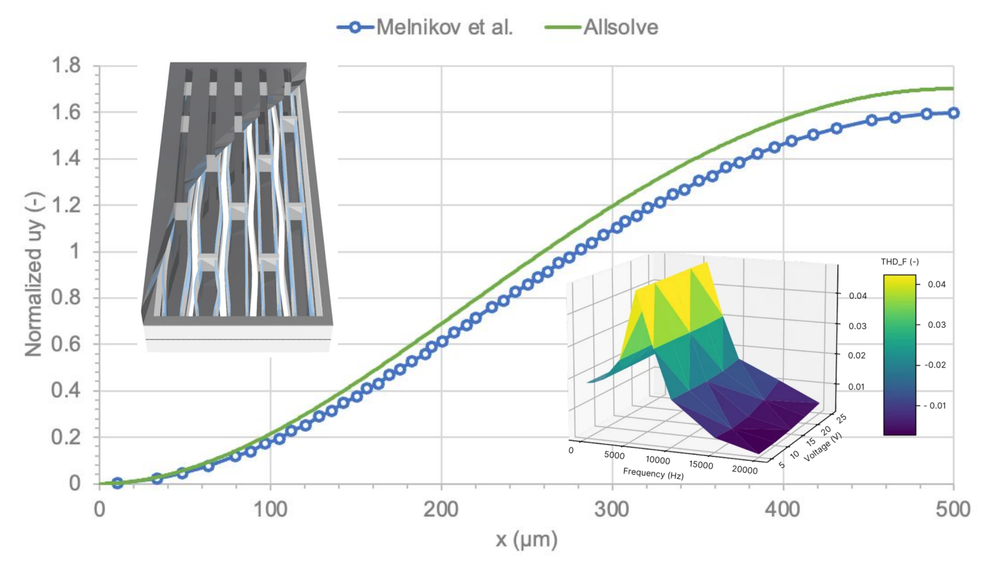
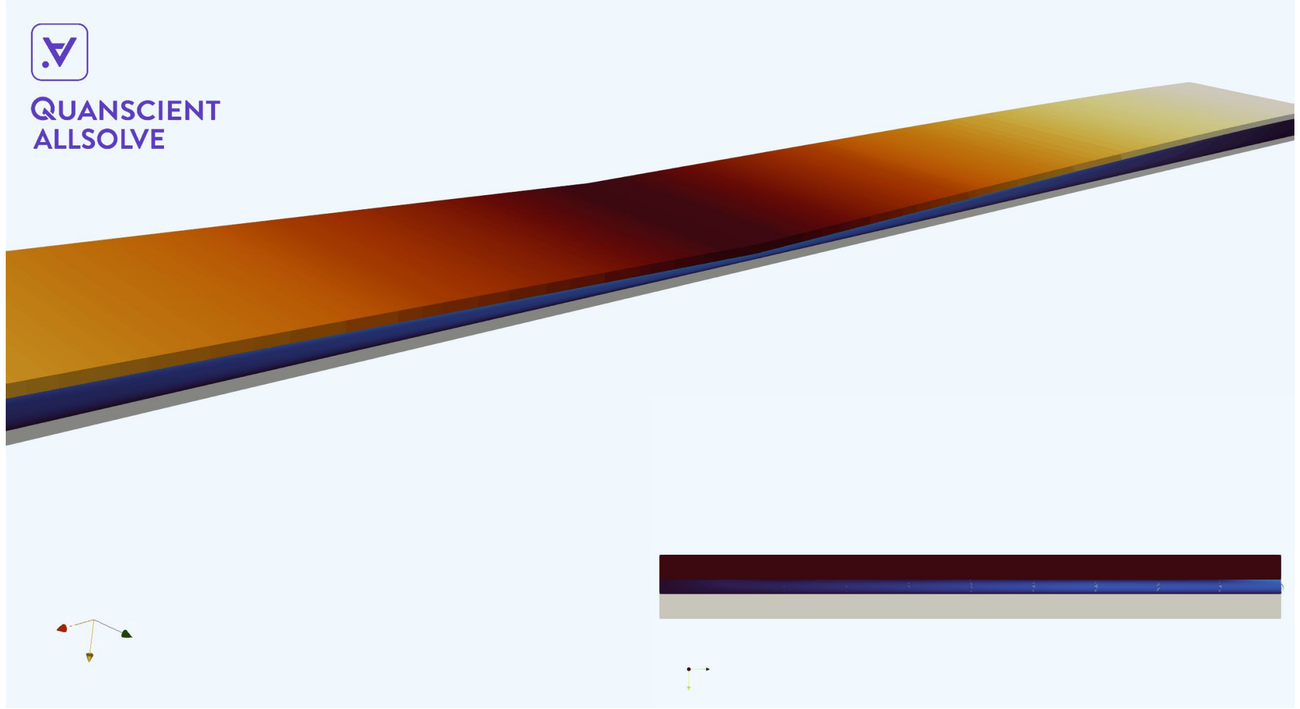
Microspeaker

→ Electrostatically actuated silicon-based microspeakers

→ Two parallel plates with air gap

→ First three harmonics used





Electrostatics + Solid mechanics + Fluid dynamics

100 Hz | DoFs: 800k | < 7 min | 12 cores

[5] Kaiser, B. et al. Concept and proof for an all-silicon MEMS micro speaker utilizing air chambers. Microsyst Nanoeng 5, 43 (2019). https://doi.org/10.1038/s41378-019-0095-9.

[6] Melnikov, A., Schenk, H.A.G., Monsalve, J.M. et al. Coulomb-actuated microbeams revisited: experimental and numerical modal decomposition of the saddle-node bifurcation. Microsyst Nanoeng 7, 41 (2021). https://doi.org/10.1038/s41378-021-00265-y

The harmonic balance method
Other applications and real-world results

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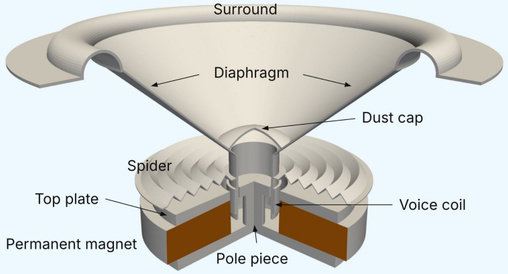
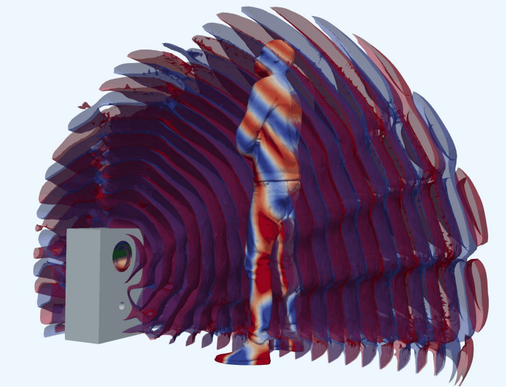
Loudspeaker

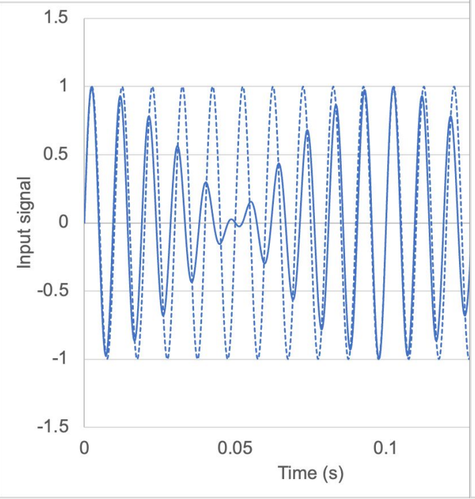
→ Electromagnetics + acoustic structure interaction

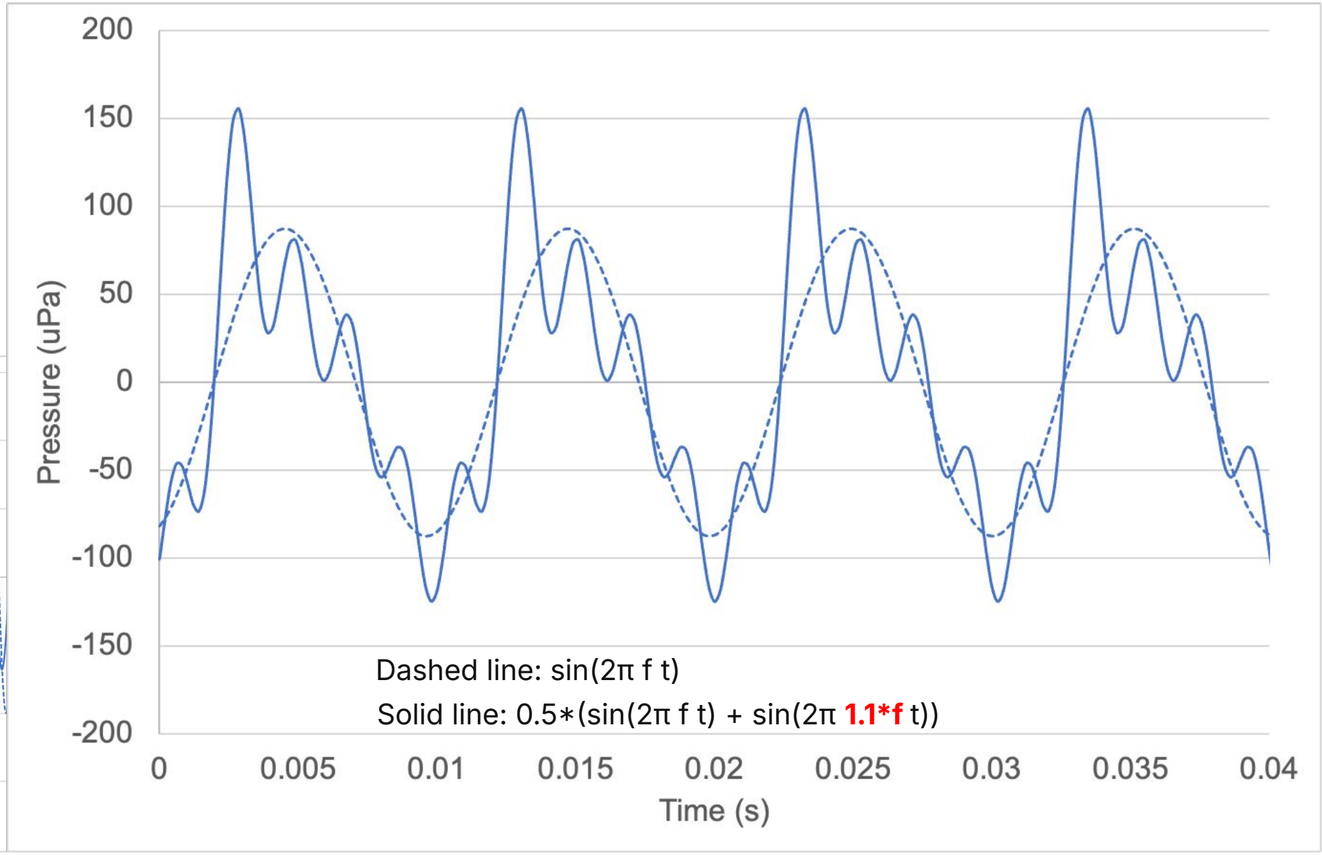
→ Fully coupled multiphysics

→ Frequency domain simulation of intermodulation







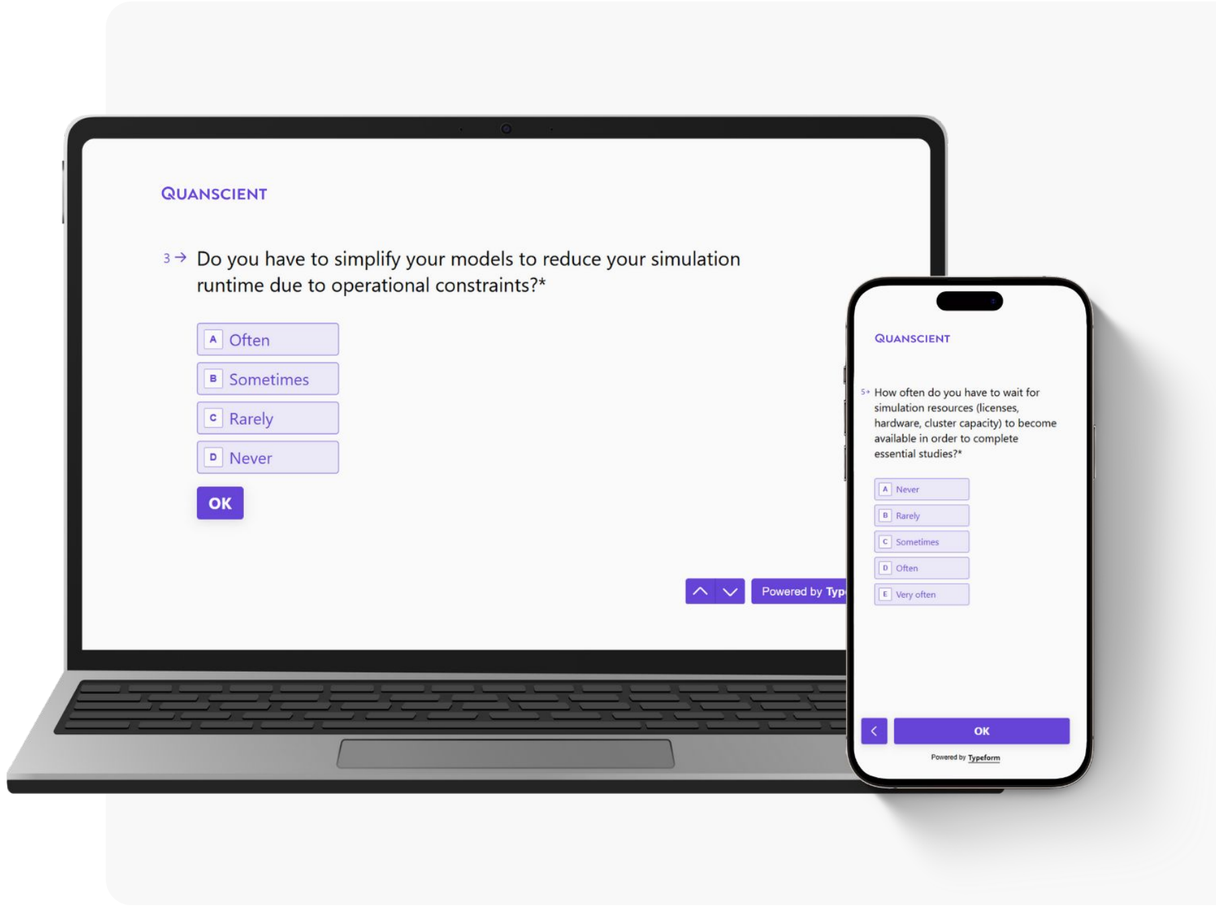


[7] Deshmukh, A, Halbach, A., Khouya, B., Nagaraja, R.K., Lahtinen, V., Strongly coupled multiphysics simulation of a loudspeaker driver using a multiharmonic approach, NAFEMS NORDIC Conference, May 2024.

Market research
Participate in our study

QUANSCIENT

Take the survey here. Answering the questions can take as little as 5 minutes.



We’re conducting market research on multiphysics simulation

- Through a 5-minute survey, we’ll establish **challenges, opportunities, and overall perceptions** on modern simulation tools and trends in the space
- We’ll compile all the findings in a report we’ll share with **all the respondents** by the end of March

Why should you participate?

- A complimentary copy of **the report before public release**
- An **invitation to the results debrief** with our CEO, Juha Riippi
- **A tree planted** in your name through the One Tree Planted foundation
- Participation in a raffle for the **500 USD main prize**

Q&A

Submit your questions now!

QUANSCIENT

When is harmonic balance preferred over transient analysis?

Why is harmonic balance important for MEMS?

How can does cloud computing help with harmonic balance simulations?

Is harmonic balance always better than transient analysis?

Thank you for your participation!

QUANSCIENT

You'll receive the executive summary PDF early next week.

In the meantime, we want to invite you to get in touch with us!

Scan the QR-code and schedule a 30-minute introductory call with us to discuss

- → Specific challenges you'd like to solve
- → Particular aspects you're interested in exploring
- → Specific goals related to your work

Finally, join our active community of more than 6000 simulation experts by following us **on LinkedIn**!

https://quanscient.com/harmonic-balance-webinar/contact