MEMS Multiphysics Simulation in ANSYS Workbench

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Introduction

• Personally, have used ANSYS Classic/Mechanical MAPDL for about a decade of MEMS design at various Silicon Valley companies.

• Upon joining Ozen Engineering, I was “forced” (😊) to adopt Workbench.

• My first consulting project was for a MEMS structure and involved structural, electromechanical, modal, transient, and FSI simulations.

• Despite initial reticence, I’m now a “believer”.

• So, today I’ll share some examples of multiphysics simulation for MEMS using Workbench.

• Of course, I can’t share a client’s project so here I will use a basic MEMS micromirror structure for illustrative purposes.

• Note: Ozen Engineering, Inc. is developing a training class on Multiphysics Simulation for MEMS Using Workbench, and the initial offering is scheduled for next Month.
MEMS Micromirror Baseline Geometry

½-model by symmetry

Full model – 500 x 1000 x 20 µm (mirror diameter 300 µm)

Suspension beams with fillets for stress reduction

reflective metal layer

“anchor”

fixed displacement BCs on anchor’s perimeter faces
Displacement vs. Voltage Characterization

Electrostatic gap between the micromirror bottom (grounded) and the actuation electrode is 3 µm.

Voltage is varied from 0 to 50 volts, then back down from 50 volts to 0. (Only ~12 volts would be required for likely actuation requirements, but an increased range is considered to investigate overall physical performance.)

Nonlinear, coupled, electro-mechanical transducer elements (TRANS126) are used for coupling of the electrostatic and structural domains. A contact stop offset of 0.1 µm from the actuation electrode is assumed.

Displacement of the bottom edge of one side of the micromirror and the top edge of the other side are plotted vs. applied voltage.

Various effects are observed, including hysteresis and electrostatic pull-in, collapse, and release. The various physical phenomena are described in more detail on subsequent slides.

Nonlinear, path-dependent solutions are obtained.
TRANS126 Electromechanical Transducer Elements

In my experience, this is one of the *single most useful* elements for MEMS applications in the entire ANSYS element arsenal.

Allows for direct (rather than sequential) coupling of the electrostatic and structural domains.

Has built-in contact functionality to stop contact between an electrode and the opposing ground plane.

1-D elements with extent equal to the specified electrostatic gap (3 µm).

Voltage is applied to nodes corresponding to bottom plane/electrode.

These nodes are also assigned zero displacement BC in the vertical direction (z).
TRANS126 EMT Elements – EMTGEN Macro

TRANS126 elements are generated using the EMTGEN macro.

Requires MAPDL commands; entered by inserting a Command Snippet in the Static Structural Analysis.

Create a Named Selection for the component of nodes corresponding to the mirror electrode.

APDL commands:
- EMTGEN macro
- Voltage BCs
- Zero disp. BC (ground nodes)
- [Substepping]
Displacement vs. Voltage - Hysteresis

Displacement (um) vs. Voltage (V) - Path-Dependent Solutions

- Mirror top - increasing V
- Mirror top - decreasing V
- Mirror bottom - increasing V
- Mirror bottom - decreasing V

- Electrostatic pull-in
- Electrostatic collapse
- Release from pull-in
- Release from collapse
Different Solution Paths – Voltage Regimes

**Increasing voltage**
- $0 < V \leq 14.44$: Stable equilibrium states of rotational displacement.
- $\sim 14.46$ V: Electrostatic pull-in.
- $14.48 \leq V \leq 40.25$: Pulled-in state with micromirror bottom edge contacting stop (torsional flexure of suspension beams).
- $\sim 40.31$ V: Electrostatic collapse.
- $40.38 \leq V \leq 50$: Collapsed state with entire micromirror bottom contacting stop (vertical flexure of suspension beams).

**Decreasing voltage**
- $50 \geq V \geq 10.60$: Structure remains in collapsed state.
- $\sim 10.58$ V: Release from electrostatic collapse state to pull-in state.
- $10.55 \geq V \geq 2.45$: Structure remains in pulled-in state.
- $\sim 2.42$ V: Release from electrostatic pull-in state.
- $2.40 \geq V > 0$: Stable equilibrium states of rotational displacement.

- Pull-in/collapse and corresponding release states occur at (very) different voltages.
- Example of *path-dependent solutions* – at a given voltage there can be multiple stable solutions. Very difficult nonlinear mathematical problem, but ANSYS handles it very well.
- Note that if the problem is solved using only one loadstep with an applied voltage of 20 V the solution obtained corresponds to an electrostatic collapse state, not a pull-in state → substepping and/or multiple load steps are useful, if not necessary.
Increasing V – Electrostatic Pull-in

At 14.4375 V, structure is in equilibrium state of rotational (torsional) displacement.

At 14.475 V, structure undergoes electrostatic pull-in.
Increasing V – Electrostatic Collapse

At 40.25 V, structure is still in pulled-in state.

At 40.38 V, electrostatic collapse occurs.
Decreasing \( V \) – Release from Collapse

At 10.60 V, structure is still in collapsed state.

At 10.55 V, structure is released to pull-in state.
Decreasing V – Release from Pull-in

At 2.45 V, structure is still in pull-in state.

At 2.40 V, structure is released to equilibrium state of rotational displacement.
Late-Breaking News...

- The above simulation results (as well as the FSI ones to follow) were recently presented at ANSYS HQ in Canonsburg, PA last month as part of the periodic Technical Certification required for ANSYS Channel Partners.

- Following the certification, we received an e-mail from Al Hancq (Senior Development Manager, WB Physics Group) from ANSYS HQ, indicating his interest in, in particular, our hysteresis simulations using TRANS126. So, I sent him the Workbench project file for these simulations.

- Just last week I was discussing with other OEI engineers the possibility of incorporating custom analysis types into Workbench, thinking it would be nice not to have to use MAPDL command snippets for TRANS126, EMTGEN, etc.

- The next day, coincidentally, I received an e-mail from Al Hancq, indicating that ANSYS Workbench developers had done exactly that!

- This capability will be incorporated into the Beta version of the release of V.14 later this year.
EM Transducer (TRANS126) in V.14 (Beta)

• In V.14 the new structural load “EM Transducer” will be created under the “Direct FE” folder (also new in V.14) in Workbench structural environments.

• This load uses the EMTGEN MAPDL macro to internally create a set of coupled-field (electrostatic-structural) TRANS126 elements.

• The EM Transducer load should be scoped only to nodes using node-based Named Selections as with other Direct FE loads.

• The GAP Direction specifies the structural (UX, UY, or UZ) DOF to be used in the analysis together with the VOLT DOF.

• Initial and Minimal Gap value parameters specify the range of motion in the GAP Direction.
Transient/Modal Analyses

Response time for MEMS structures is often of high importance.

Particularly true for micromirrors.

Here use a different baseline geometry: Suspension beams have length x width x thickness of 200 x 14 x 20 µm, rather than 250 x 8 x 20 µm, i.e. considerably increased stiffness → higher resonant frequencies and faster response times.

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- First three modes are the most important.
- Large separation between 3rd and higher modes.

1st mode: rotation about y-axis – beam torsion
2nd mode: horizontal/in-plane – beam y-flexure
3rd mode: vertical/out-of-plane – beam z-flexure
Transient Analysis – No Damping

In the absence of damping, settling time is very large - ~4-5 ms or more.

- Of course, damping is present in the form of air damping.
- Particularly true with small air gap = electrostatic gap of 3 µm.

⇒ Use FSI to determine air damping.
- Note: Resulting simulation involves coupling of electrical, structural, and fluidic domains – truly multiphysical.
In solid model (left), tapering (fillets) on suspension beam is removed for easier meshing.

Air gap beneath structure = electrostatic gap = 3 µm.

Air gap to each side is 100 µm.

Air gap above structure is 12 µm.
FSI Model – Boundary Conditions

Boundary conditions: Wall boundary condition regions have meshes highlighted.

FSI interface with mesh highlighted. Wall boundary condition regions in wireframe.
Transient Analysis with Air Damping (FSI)

Observed settling time is reduced from \(~4-5\) ms (or more) to \(~1\) ms.
Inverse Problem – Determine Critical Damping Ratio

FSI calculations are generally time- and resource-consuming.

→ If multiple analyses are desired – for example, varying suspension beam geometry, which should not affect air damping – it is more economical to solve non-FSI transient analyses.

But, damping is always present and should definitely be included to obtain physically meaningful results.

→ Look at inverse problem of determining the critical damping ratio corresponding to the observed transient behavior (amplitude, decay, etc.) obtained from FSI air damping calculations.

Using Rayleigh damping theory and values for a pair of resonant frequencies, determine beta (stiffness) and alpha (mass) damping coefficients for use in transient analyses for various assumed values of the critical damping ratio; run multiple transient analyses to see what values produce transient profiles best corresponding to those obtained using FSI.

Use these in conjunction with much less expensive damped/non-FSI transient analyses for further investigations of design space.
Rayleigh Damping Basics

From a modal analysis determine a range of frequencies to be damped: \([ f_1, f_2 ]\).

Assume a value for the critical damping ratio \(\xi\).

The damping matrix is \([C] = \alpha [M] + \beta [K]\), where \([M]\) and \([K]\) are the mass and stiffness matrices, respectively.

The coefficients \(\alpha\) and \(\beta\) are given by

\[
\alpha = \frac{2 \xi \omega_1 \omega_2}{\omega_1 + \omega_2}, \quad \beta = \frac{2 \xi}{\omega_1 + \omega_2}
\]

where \(\omega = 2 \pi f\) is the “circular” frequency corresponding to frequency \(f\).

(Mass damping \((\alpha)\) can generally be ignored, but is included here.)

Obtaining \(\alpha, \beta\) as above is based on the assumption that \(\xi = \frac{\alpha}{2 \omega} + \frac{\beta \omega}{2}\) is nearly constant over \([ f_1, f_2 ]\) as seen at right. →

Here we have used \(f_1 = 18.6\ kHz\) (suspension beam torsion/rotation mode [#1]) and \(f_2 = 53.6\ kHz\) (vertical flexure mode [#3]).
Transient Analyses with Assumed Values of $\xi(\alpha, \beta)$

Various values of the critical damping ratio $\xi(\alpha, \beta)$ are assumed and transient structural analyses are performed using the corresponding values of $\alpha$ and $\beta$ from Rayleigh theory.
Damping Ratio via Disp. Amplitude Ratio

Plot a displacement amplitude ratio – \( \max(uz(\alpha,\beta)) / \max(uz(FSI)) \) – vs. assumed critical damping ratio \( \xi(\alpha,\beta) \) and determine value of \( \xi \) for which this ratio = 1.

- Solving the trendline fit equation gives: 
  \[
  \xi = e^{\frac{(r - 0.3170)}{0.079}} = 1.757e^{-4}.
  \]
Air Damping vs. Rayleigh with $\xi(\alpha,\beta) = 1.757 \times 10^{-4}$

- For other similar geometric configurations we can now substitute damped transient structural analyses for the more expensive full FSI analyses.
Please join OEI for Happy Hour immediately following the conference.

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Directions:
Right on Tasman Dr.
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2nd Right into OEI parking lot.
(We’re very nearby!)
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