NISA - USER Manual : Squeeze Film Module

Ver 1.0

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i. Acknowledgements

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ii. Change Log

Sl Nos.	**Date Revised**	**Changed by**	**Comments**
1	19th Oct 2014	Anish Roychowdhury	Ver 1.0 First Draft
2	16th Nov 2014	Anish Roychowdhury	Frequency sweep and node of interest incorporated.

Contents

1 Introduction to Squeeze Film

Vibratory MEMS devices such as gyroscopes, RF switches etc., often consist of a vibrating plate like structure with a thin air film trapped between the plate and the substrate [See Fig. 1]. Under such conditions the trapped air offers back pressure on the bottom surface of the plate, thus opposing its motion. A part of this pressure acts as a damping force and is responsible for reducing the Q factor of the device. This phenomenon is known as squeeze film damping [1]. Thus accounting for squeeze film, while modelling the dynamics of such devices is essential. It is not always economically feasible or viable to have experimental structures fabricated and tested every time. Thus one has to perform numerical simulations or select appropriate analytical models which address the problem at hand from a vast set of published literature. The Squeeze Film module in NISA tries to address the problem of modelling for the squeeze film effect in MEMS structures, accounting for the plate elasticity effect as well.

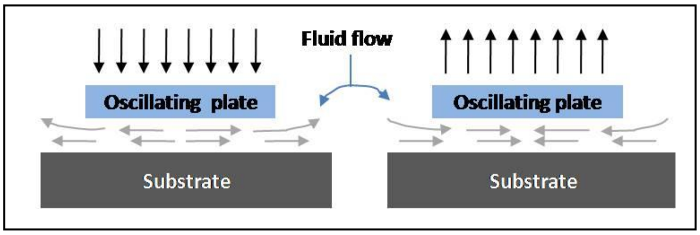

Figure 1: Squeeze flow schematic

2 Squeeze Film Module in NISA

2.1 Modelling capabilities

The current version of the squeeze film module (i.e. Ver 1.0) solves the Reynolds equation for fluid coupled with the linear elasticity equation (See Appendix A). Current capability allows for harmonic solution for the pressure distribution on the face of the moving plate exposed to the squeeze film layer. The resulting squeeze film damping and stiffness forces are also computed and comes in a data file. Nodal data for pressure and the displacement values along x y and z directions are also generated in an output data file. The NISA squeeze film module allows users to specify rectangular geometries for the structure to be modelled. It allows for material properties of the structure and the air gap to be specified. The user can specify the structural boundary conditions using existing NISA GUI. The fluid domain in this squeeze film module is the lowest layer of nodes of the structural mesh which is supposedly considered to be the "wet" surface. Thus the user has to specify the nodes which are open to atmosphere for the fluid domain by choosing the relevant nodes from the lower layer or the so called "wet " surface and specify trivial pressure boundary conditions as shown in Fig. 8. Only electrostatic actuation is considered in this model, and the user has to specify the actuation voltage for harmonic actuation. The electrostatic voltage is converted to a uniformly varying electrostatic traction for the structure surface.

2.2 Limitations

The current version of the squeeze film module (i.e. Ver 1.0) solves the Reynolds equation for fluid coupled with the elasticity equation. Current rectangular plate geometries without perforations may be modelled, accounting for plate elasticity effect. The module allows for harmonic solution with the frequency of interest to be provided by the user. A frequency sweep can be done by repetitive runs with incremental increase of frequency. only harmonic solution is allowed. The user has to input the required frequency of interest and not a range in which a sweep can occur. The solution allows for plate elasticity but perforated plates are not accounted for in the current model.

3 Overall Process Flow

The Overall process of modelling meshing and solving a squeeze film problem is described in this section, (See Fig. 2). In a broad sense the process maybe divided in the following sub-steps:

- Pre-processing in NISA
- Microsystems module data input
- Execution
  - Parsing
  - Analysis
- Post processing

4 Process Details

In this section we describe in detail each of the processes mentioned in section 3, along with relevant screen shots for the same.

4.1 Pre-processing in NISA

The pre-processing in NISA involves defining the structure geometry, creating the mesh, specifying boundary conditions and constraints for structure and fluid domain.

4.11 Creating Geometry

After launching the NISA display IV application, create geometry from the Geometry tab of the main menu. as an example for a cuboid (Geometry--> Cube--> Create--> 2 corners) will create a cuboid allowing users to specify the two opposite corners of the cube. (See Fig. 3) (Note: all dimensions are in microns).

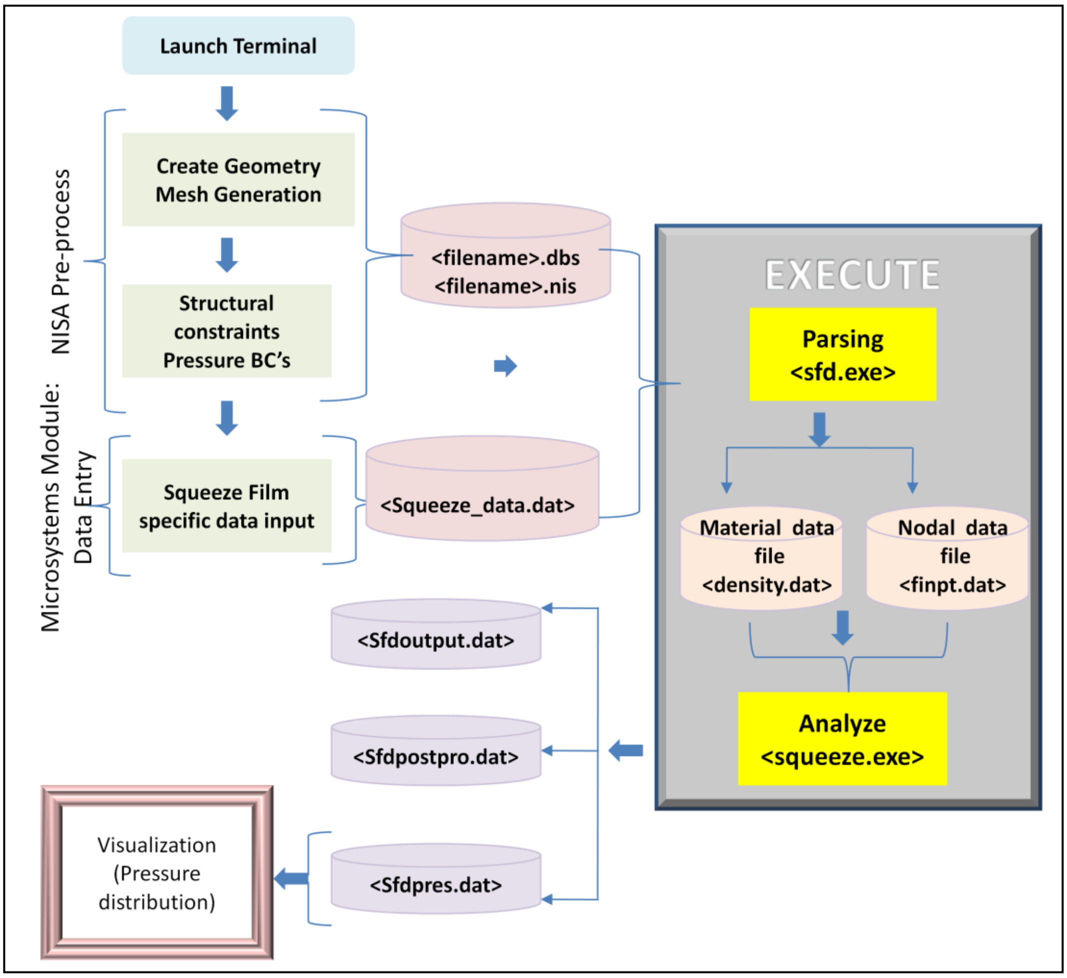

Figure 2: Overall process flow: Squeeze film module

4.12 Meshing

Once the geometry is created, the mesh is generated as follows. The cube created shows as an entity in the panel on the left (See Fig. 4). Right click on entity, select the cube created, then right click on the cube and select "extract hyperpatch", After the hyperpatch is generated the user may choose to extract lines following the same procedure and choosing "extract lines" option.

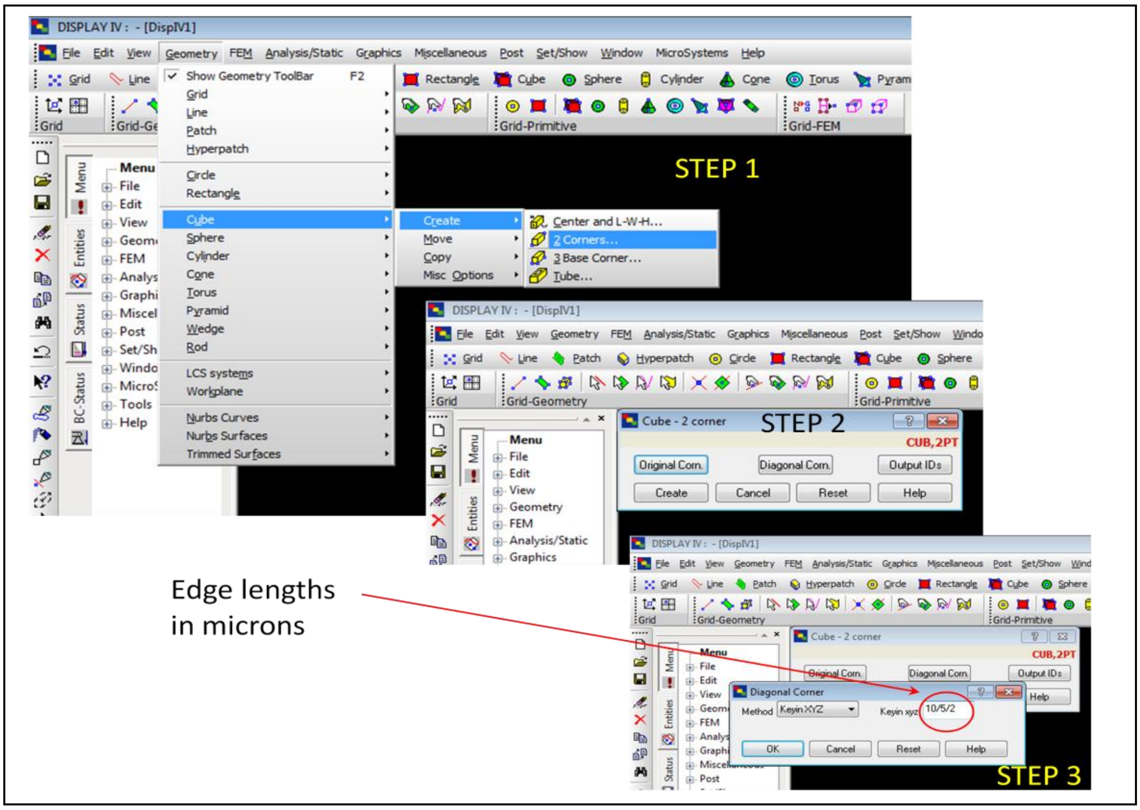

Figure 3: Geometry creation

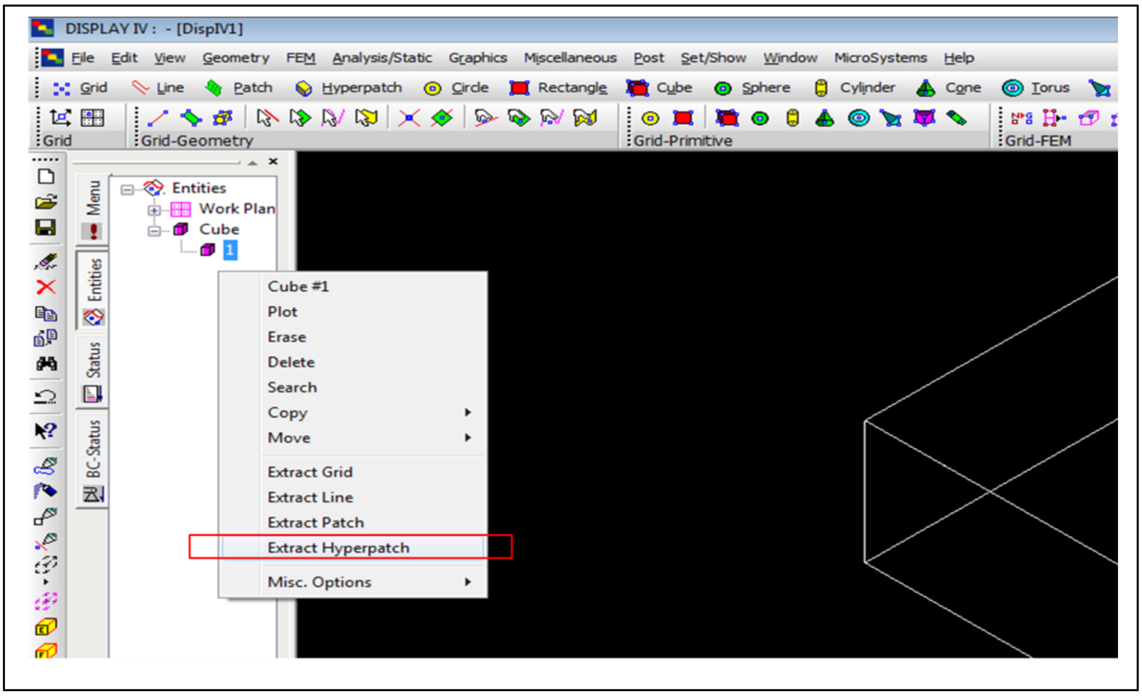

Figure 4: Extracting hyperpatch

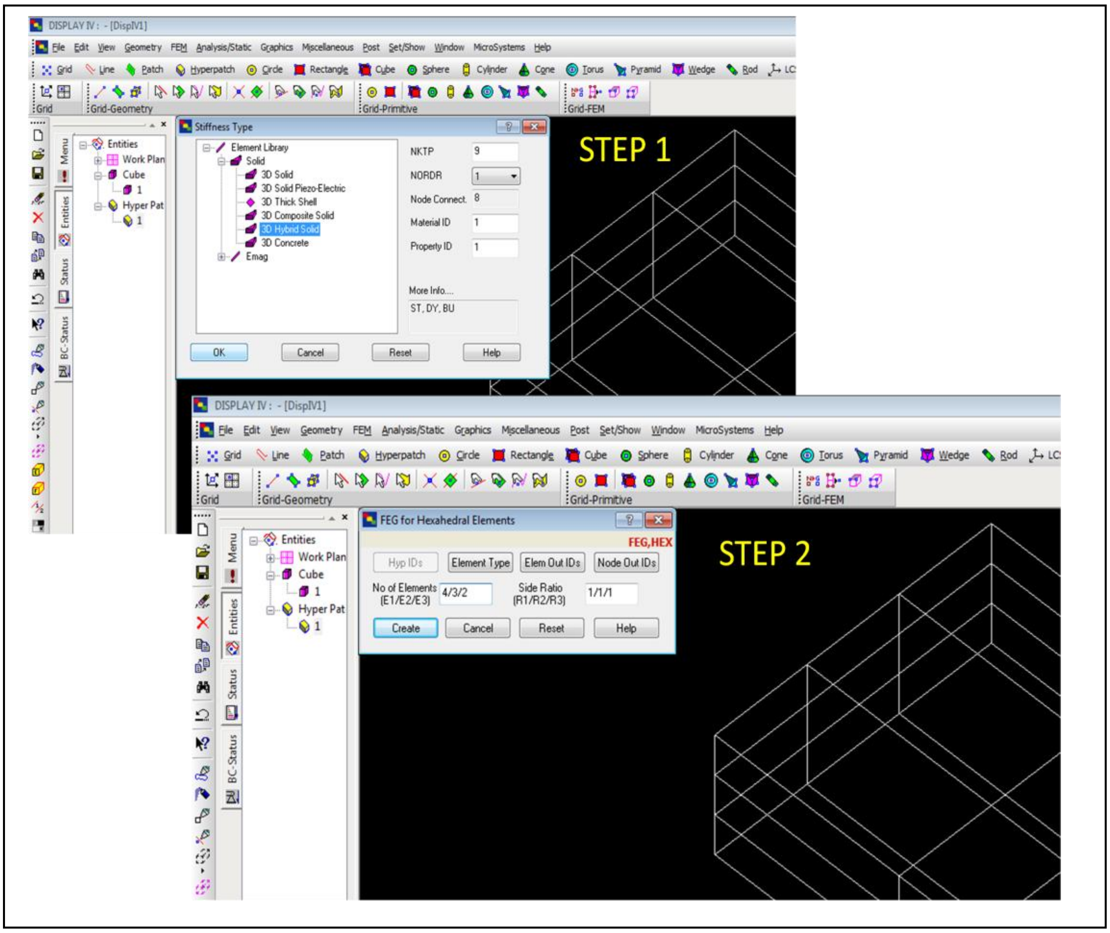

Figure 5: Meshing - element choice

Once the hyperpatch and /or lines are extracted, from the FEM menu tab in the main top panel choose Mesh--> FEG--hexahedron mesh --> element type--> 3D hybrid solid, next enter the number of elements in each of the directions (See Fig. 5) . This completes the meshing process.

4.13 Boundary conditions and constraints

Once the Meshing is complete, the next step in pre processing involves specifying boundary conditions and nodal loads. From the main menu choose FEM--> Structural BC--> Displacement --> Add to add the structural nodal constraints as shown in Fig. 6. Thus after selecting the desired nodes for a fixed end the user needs to apply Ux =0, Uy= 0 and Uz = 0. (Fig. 7 shows a cantilever geometry meshed and constrained at one end) For the fluid domain, the trivial pressure conditions for the nodes on the open edges are applied in a round about way as the NISA GUI does not have a Pressure DOF. As depicted in Fig . 8, Applying a **ROTX = 1** for the selected nodes (Lowest layer nodes on the open edges) from the GUI would result in the desired fluid BC.

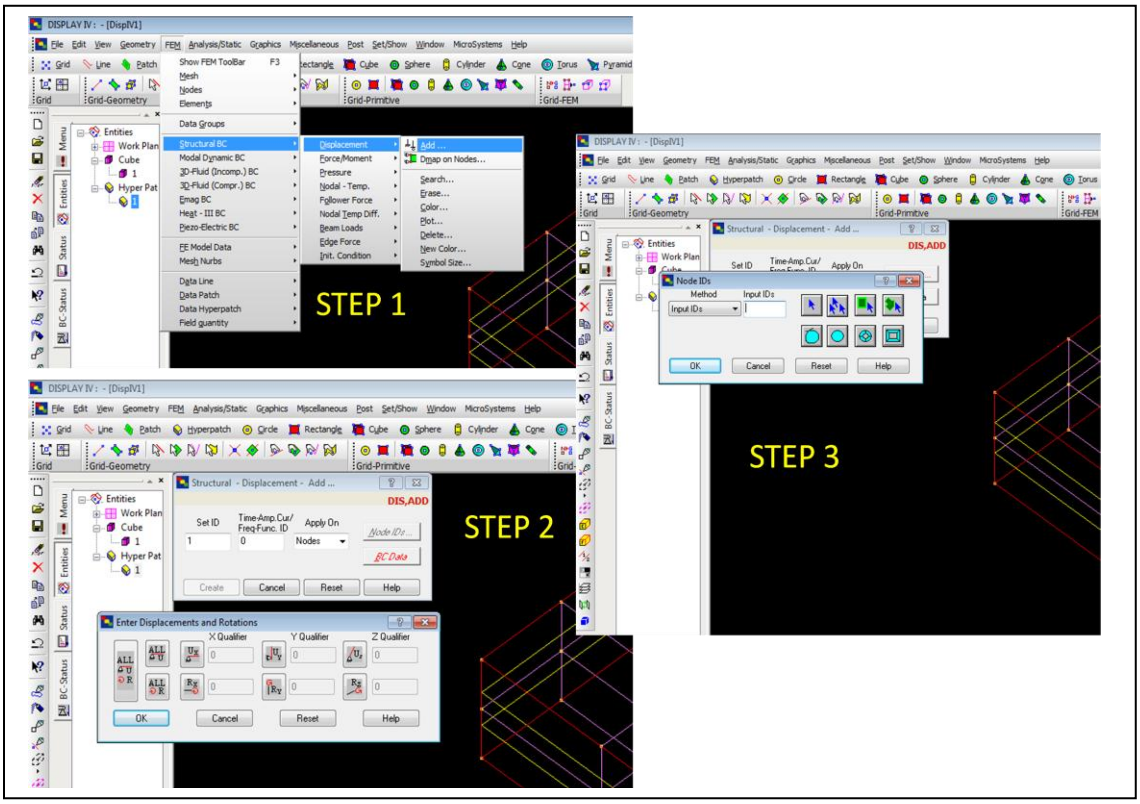

Figure 6: Adding the structural constraints

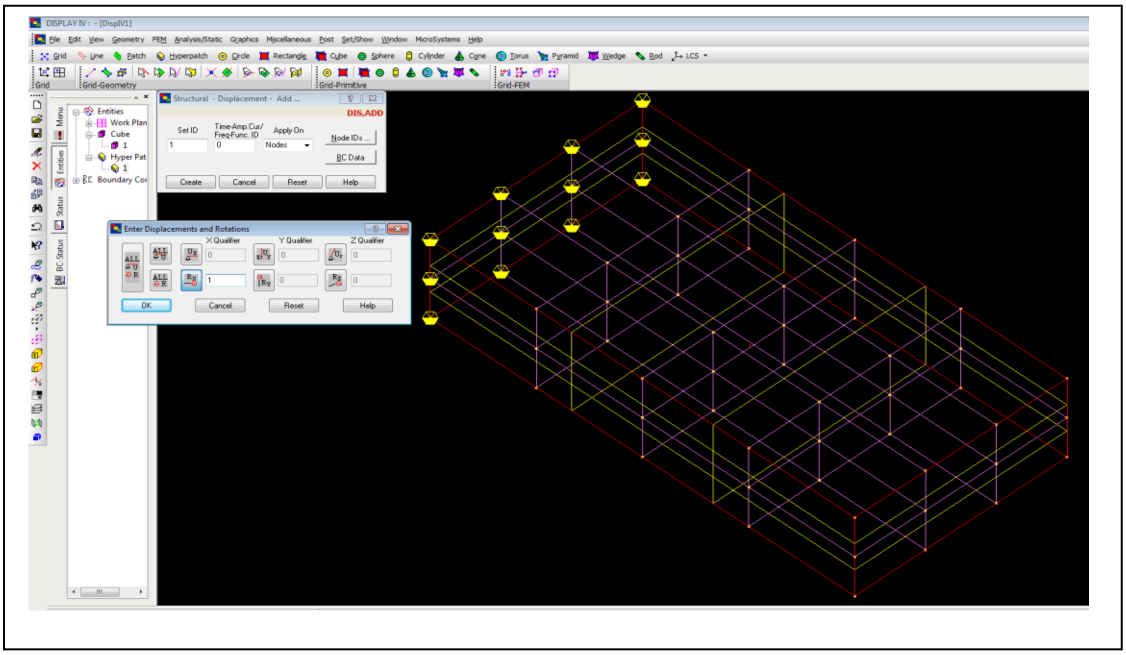

Figure 7: A cantilever model showing one end structurally constrained

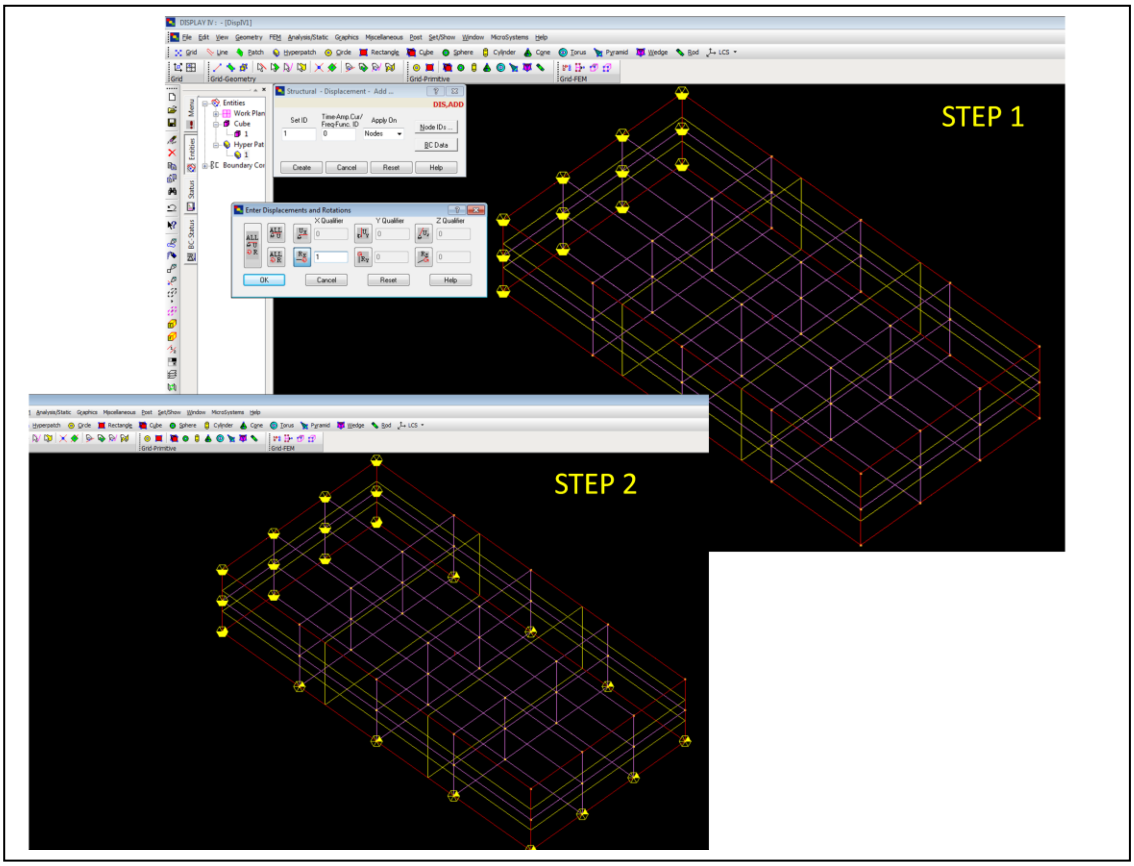

Figure 8: Applying the fluid domain BC's using ROTX DOF in NISA

4.2 Micro systems module data input

The data entry specific to squeeze film comes from a separate input panel accesses from the Microsystems tab on the main menu. Choose Microsystems-->Squeeze Film--> Harmonic--> Data Input (See Fig. 9). A data entry window then pops up allowing for entry of data specific to squeeze film. The parameter entered are as follows,

- Number of elements in X , Y and Z direction (as entered during meshing)
- Frequency (radians/second), (Start , End and Increment)
- Air gap (SI units)
- Input voltage (Volts)
- Young's Modulus of the structure (SI units)
- Poisson's ratio
- Density (SI units)
- Pressure (SI units)
- Viscosity (SI units).

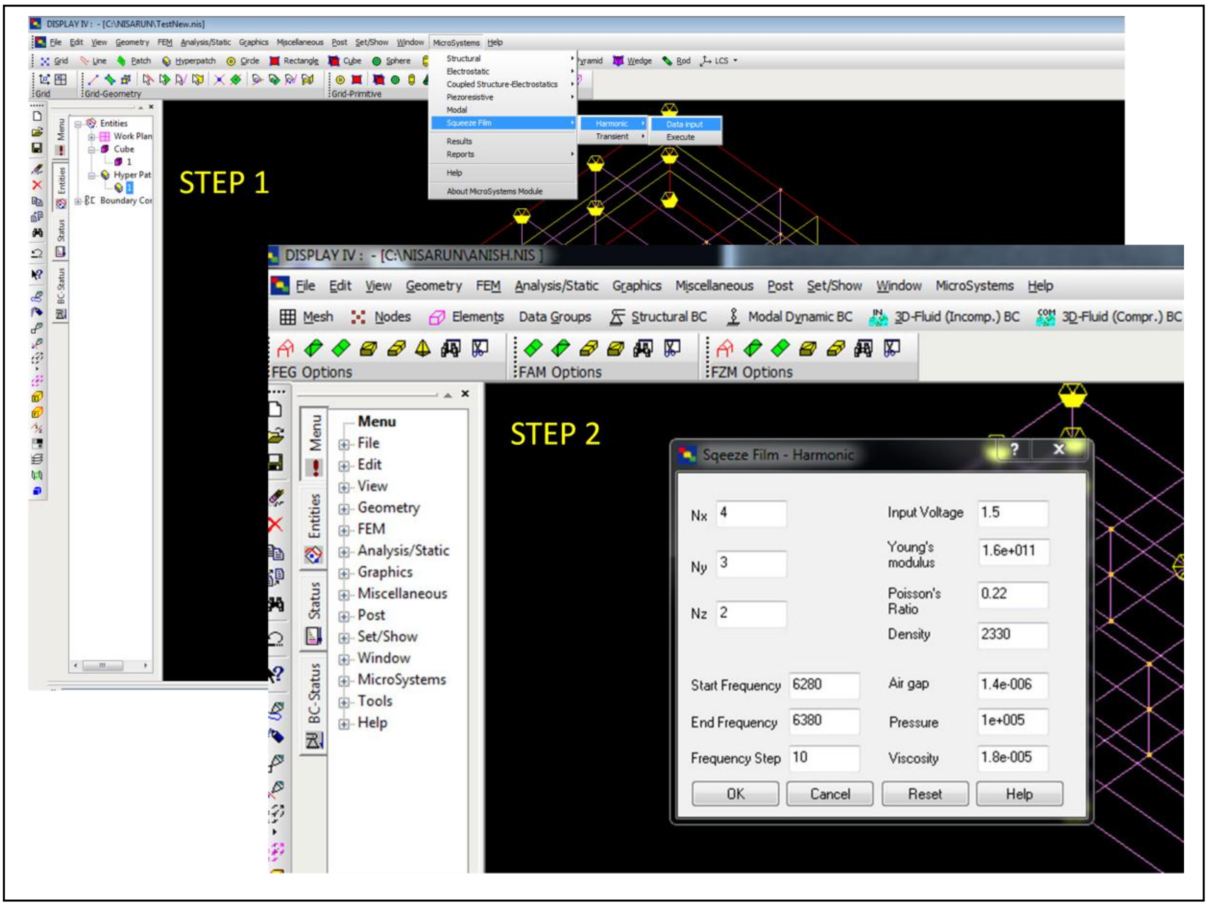

Figure 9: The squeeze film data input selection

The data needs to be saved in two formats after the data entry process is complete. Thus one need to save the data **first** as a "<filename>.nis" file **and then** as a "<filename>.dbs" file before proceeding further.

4.3 Execution

The solver is invoked using the execute button (see Fig. 2) in Main Menu --> Microsystems --> Squeeze Film --> Harmonic --> Execute option in the main menu. (See Fig 10.). The node of interest needs to be specified at the time of execution. a Right click on the geometry over a node will enable one to determine the node number which has to specified at execution time. (See Fig 11). The execute operation works internally in two steps. Firstly a parsing operation is performed on the raw data files generated by data entry by the user from the GUI, secondly the parsed input files are then input to the solving modules which after successful execution generates three output files discussed in section 4.4.

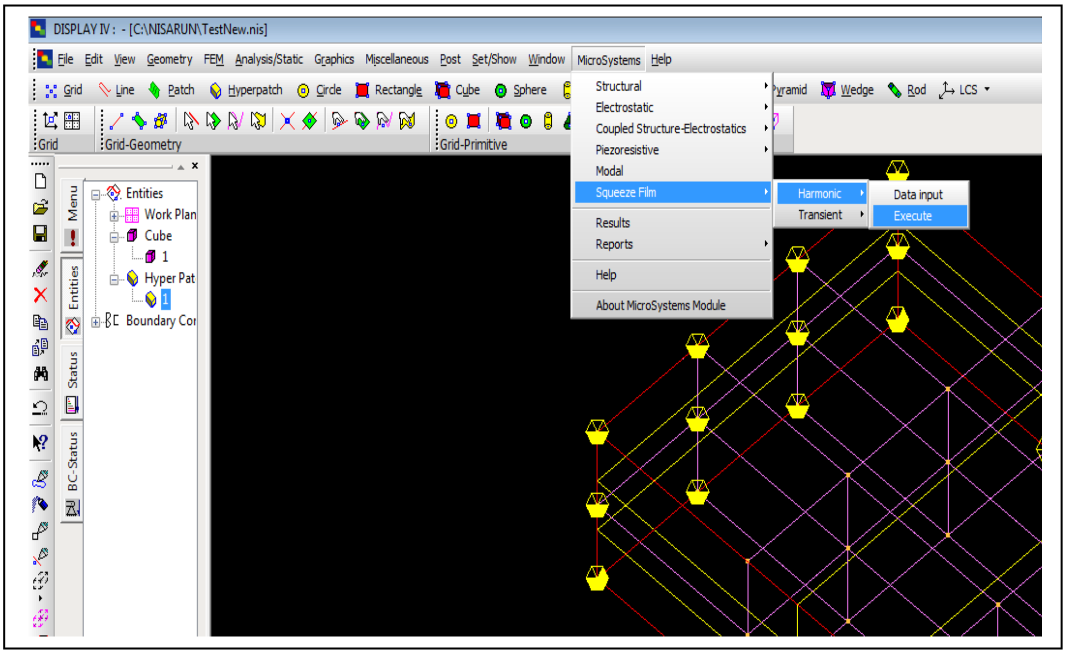

Figure 10: The execute button

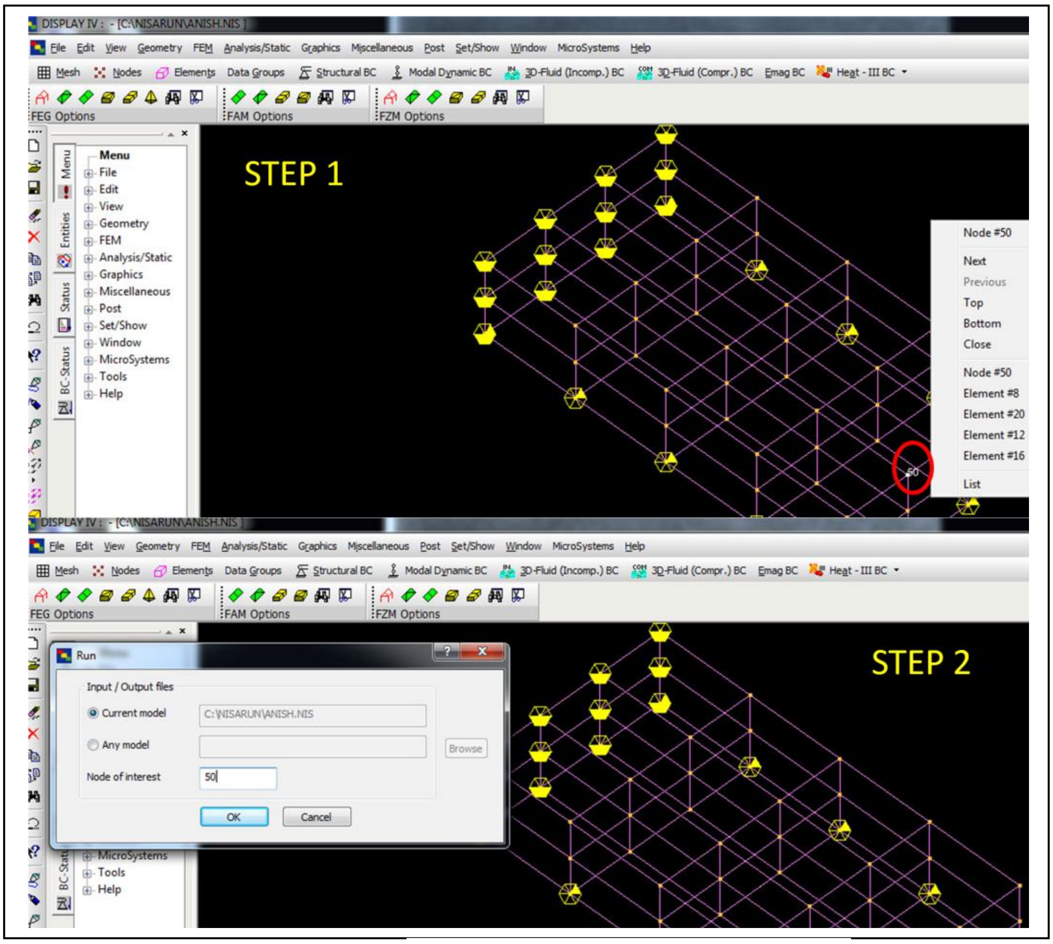

Figure 11: Node of interest

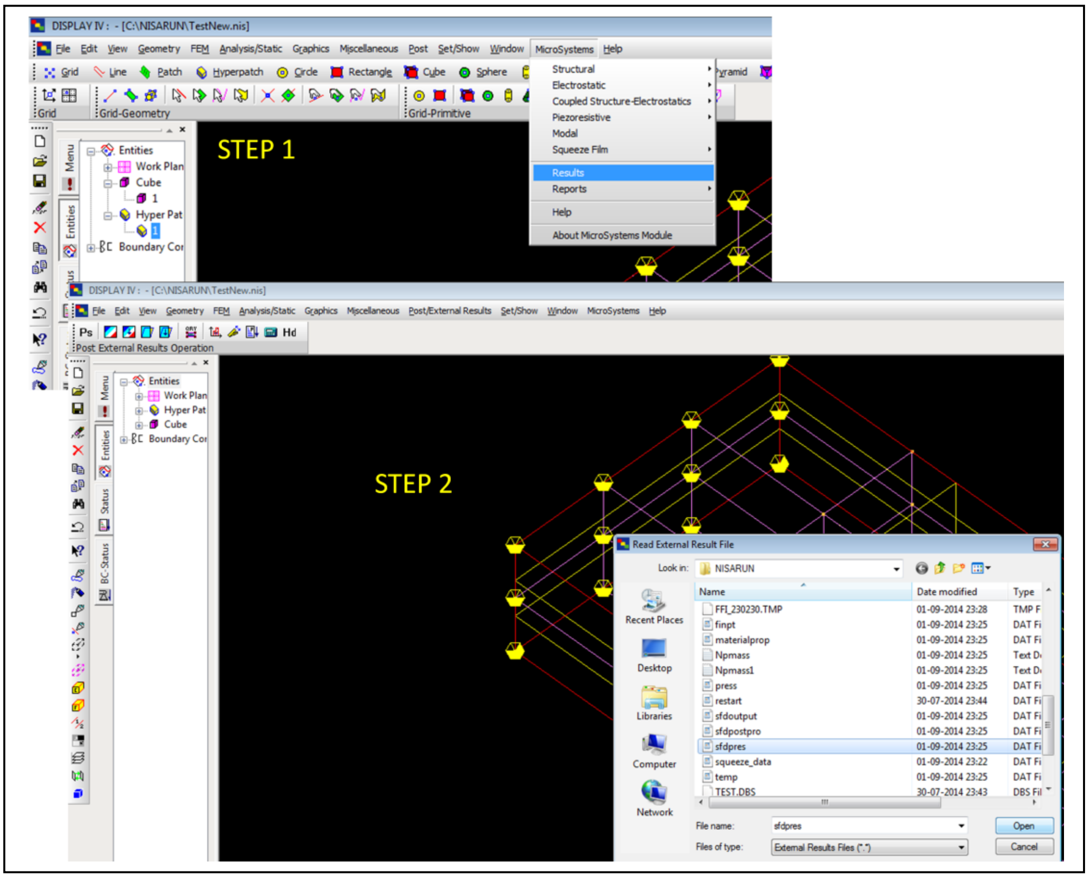

Figure 12: Choosing the results file

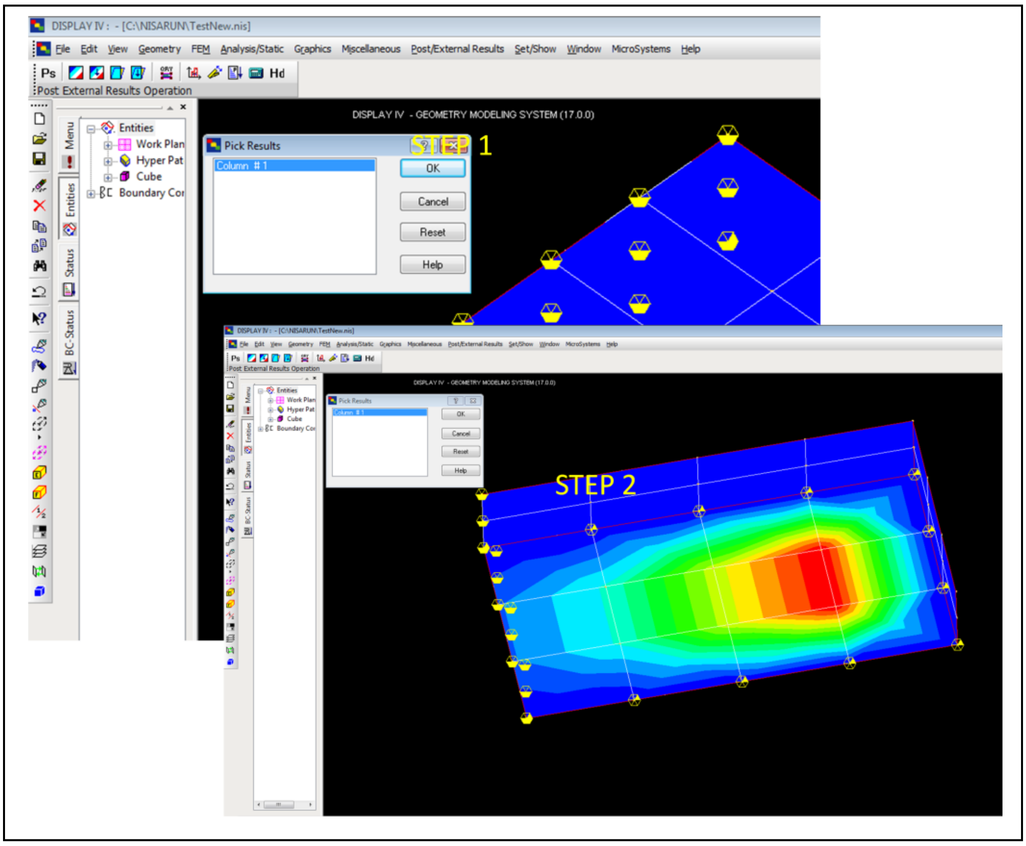

Figure 13: Pressure variation plot

4.4 Post processing

Current capability of post processing allows the user to either view the pressure distribution and/or use the nodal solutions generated as one of three data files.

4.41 Pressure and forces nodal data

The file <sfdoutput.dat> has nodal results for pressure and the displacements in the x, y and z direction. ***The data set present is that for the last frequency executed.*** The file <sfdpostpro.dat> has the resulting spring and damping forces computed by integrating the resulting pressure distribution over the wet surface to get the force on the moving plate. The 'z' displacement for the node of interest as well the corresponding frequency in radians is also present as output. The squeeze film spring and damping forces are obtained from the real (Rf) and imaginary (If) component of the resultant force respectively.

4.42 Pressure distribution visualization

The file <sfdpres.dat> has the pressure solution separately for each of the nodes and is used by NISA for visualising the pressure distribution. In order to visualize the results one needs to choose from the main menu Microsystems --> Results--> <corresponding nodal file> (see Fig 12) . Thus if one chooses to visualize the pressure solution then one can choose the <sfdpres.dat> file and select column 1 for visualization. If on the other hand the user wants to visualize the "z" direction displacement results, then the file <sfdoutput.dat> needs to be selected and column 3 needs to be chosen for visualization. For the pressure solution one needs to rotate the figure to see the bottom wet surface to see the squeeze film pressure pattern (See Fig. 13) . ***Note, only the last frequency run data will be displayed for the pressure distribution. If the user wants data for any particular frequency then that frequency must be the end frequency.***

5 Test cases

Two example test cases have been (See Appendix B) provided for the user to check the validity of the solution from this module for squeeze film. In the first case we model a cantilever resonator and compare the first three Q factors with that from published literature. In the second test case we vary the beam dimensions and compare the first Q factor of each of the beams with those from published experimental data. For generating the test data the user has to execute the model repeatedly with the range of frequency values provided and follow the procedure mentioned in section 5.1 .

6 Special features

6.1 Node of interest selection

The user would be allowed to pick a node of interest after creating the geometry, this would be available as input data to the squeeze film module. The node of interest is used to compute the z displacement for that particular node and is available as output data along with spring and damping forces and frequency for all the frequencies run.

6.2 Frequency sweep

User input for a range of frequency and increment step is incorporated. This allows the software to provide in an output file <sfdpostpro.dat> nodal data for all frequencies for the node number of choice which ahs 'z' displacement value, frequency, spring and damping forces.

6.3 K (stiffness coefficient) C (damping coefficient)

The stiffness coefficient and the damping coefficient maybe evaluated from the spring and damping forces using the 'z' direction displacement (u_z) for the node of interest and for each frequency as follows: $K = \frac{F_s}{u_z}$, $C = \frac{F_d}{\omega u_z}$.

6.4 Plotting FRF curve

Once the nodal data for the node of interest has been generated for the entire frequency range, that would be used to plot either normalized displacement Vs frequency graph or normalized velocity Vs frequency graph (normalized with input voltage). The data in the file <sfdpostpro.dat> maybe further processed by the user to plot FRF graphs and hence obtain Q factor using 3dB bandwidth method.

Appendix A: Theory

The NISA squeeze film module solves the coupled fluid structure problem of squeeze film and linear

plate elasticity. The fluid domain is modelled using the linearized Reynolds equation given as follows [2],

$$\frac{h_a^3}{12\mu_{\text{eff}}}\left(\frac{\partial^2 \hat{p}}{\partial x^2}+\frac{\partial^2 \hat{p}}{\partial y^2}\right)=\frac{h_a}{P_a}\frac{\partial \hat{p}}{\partial t}+\frac{\partial \hat{h}}{\partial t} \tag{1}$$

where μ_{eff} is the effective viscosity, h_a is the initial air gap, P_a is the ambient air pressure, $\hat{p}$ is the fluid pressure (perturbed about P_a) and $\hat{h}$ is the air gap (perturbed about h_a). The structural domain is modelled using the dynamic structural equation (Eq. 2) [3],

$$\boldsymbol{\rho}\ddot{\boldsymbol{u}} = \boldsymbol{\nabla}.\boldsymbol{\tau}+\boldsymbol{b} \tag{2}$$

where 'ρ' is the density of the structure and 'b' represents the body force per unit volume. The squeeze film module in NISA solves the equations (1-2) using a coupled finite element methodology using 8 node 3D elements with a hybrid formulation for the structural domain. The procedure for the coupled formulation may be found in [4]. The methodology to implement hybrid elements is explained in [Jog 2005 , 2010].

Appendix B: Test cases

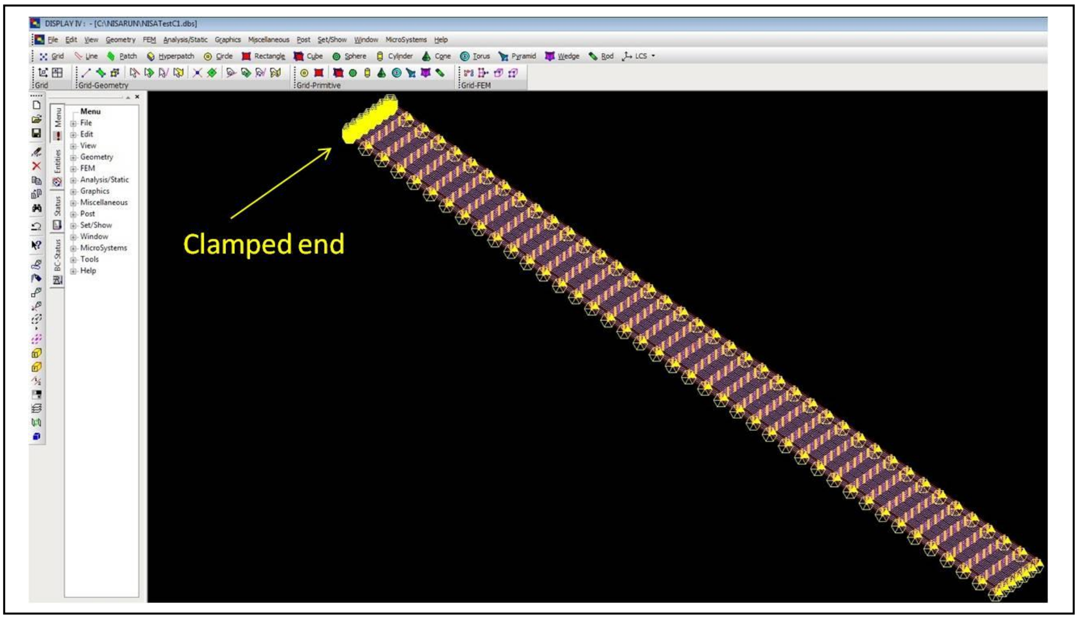

Figure 14: A cantilever beam with applied nodal constraints, with mesh : Nx = 40, Ny = 6, Nz =4.

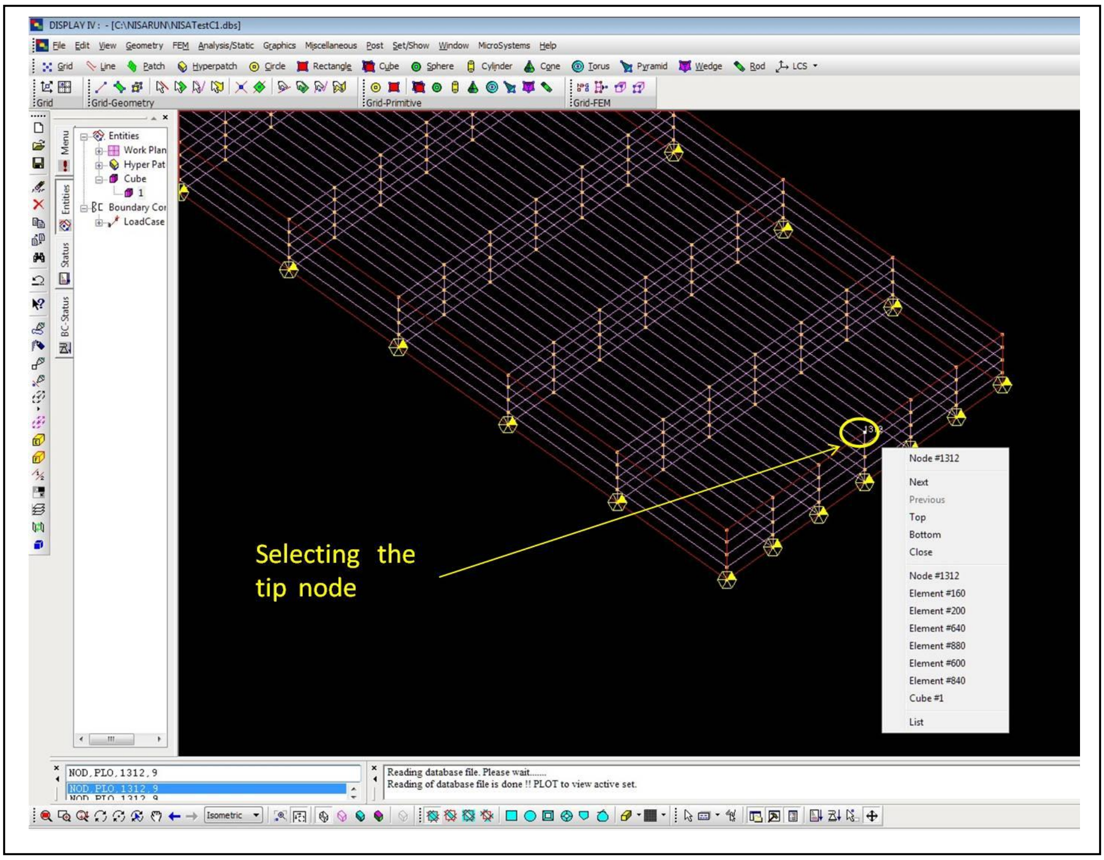

Figure 15: Tip node selection

Test Case1:

We choose to model a Si, cantilever beam as described in [7]. The simulation parameters are shown in Table 1. The beam is meshed with a converged mesh of (Nx = 40, Ny =6, Nz = 4) elements. Figure 14 shows the meshed model of the beam in NISA, with the constraint boundary conditions applied. The simulations are run for the frequencies between 1e4 Hz to 1e5 Hz in small incremental steps of 1e3 Hz. The vertical displacement (u_z)for the Tip node of the beam (See Fig. 15) is noted for the range of frequencies. The corresponding value of velocity is obtained from Eqn. 3.

$$V_{tip} = Frequency * u_z \qquad (3)$$

From the plot of normalized velocity (with input voltage) Vs frequency the Q factor is obtained using 3db method (See Fig 15) . The computed Q factor is compared with reported values from experiments and from ANYSYS [7] (See Table 2). Thus we see our squeeze film module computed Q factor compares well with experimental and numerical data from published literature.

Table 1. Simulation parameters for Test Case 1

Simulation parameters - Test Case 1	Values
Young's Modulus (Si)	160 GPa
Density	2330 Kg/m^3
Poisson's Ratio	0.22
Density air	1.2 Kg/m^3
Viscosity	1.8e-5 Ns/m^2
Air Gap	1.4 µm
Length	350 µm
Breadth	22 µm
Thickness	4 µm
Actuation Voltage	1.5 Volts

Table 2. 1st mode Q factor compared with published data [7].

Q- NISA	Q-Exp [7]	Q-ANSYS [7]
1.13	1.20	1.11

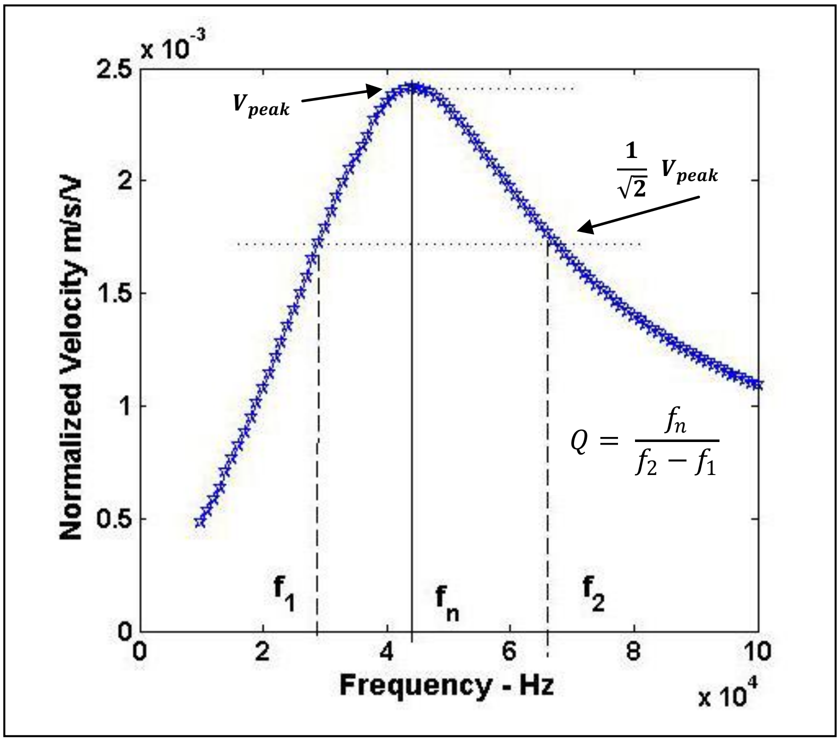

Figure 15: Q factor computation using 3db method from data from Velocity Vs frequency data from NISA squeeze film module for a frequency seep from 1e4 to 1e5 Hz

Test Case2:

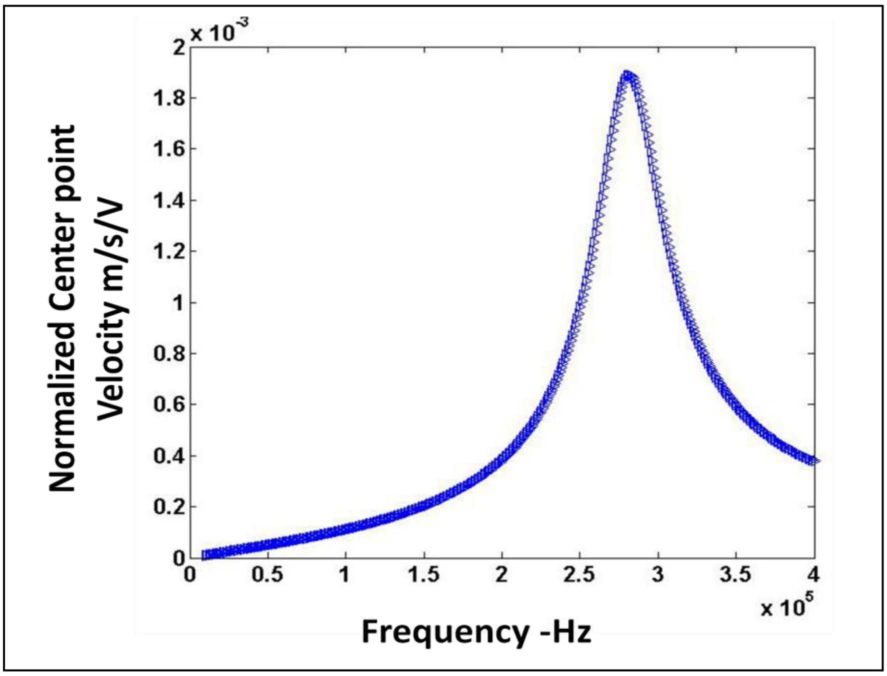

Figure 16: Frequency response graph for a fixed fixed beam with the same dimension as that of the cantilever described in Test Case 1

For the second test case we model the same beam with two opposite sides fixed as opposed to the one end fixed cantilever boundary condition modelled in the first case. As the Test case 1 model was already validated we choose the same mesh size as before and plot the normalized velocity of the plate centre Vs frequency. Proceeding in the same manner as Test case 1 we get the following dynamic characteristics (See Table 2), obtained from the frequency response plot (See Fig. 16).

Table 2. Dynamic characteristics of a fixed fixed beam as obtained via simulations.

Q- NISA	**Fn1**
6.89	282 kHz

References

[1] **Griffin W.S.; Richardson H. H. and Yamanami S**. ,: A study of squeeze film damping, ASME Journal of basic engineering, pp. 451-456, June 1966.

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