Application of PLM to MEMS Devices in Education

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Abstract

Industrial usage of Product Lifecycle Management software has enabled engineers to design, analyze, and manage products from conception to retirement. PLM software is currently used in the aerospace, automotive, chemical and petroleum, and electronics industries. With the increased use of PLM software product development has become more streamlined and requires engineers to be proficient with these new tools. Additionally, the increased development and usage of Micro-Electro-Mechanical Systems (MEMS) has created a need for engineers to have some knowledge of such devices. Since PLM has been successful in other industries there is no reason that the same success cannot be anticipated in the MEMS industry. Currently PLM software has no specific tools for MEMS simulation, but the design and management tools can be used in conjunction with specific MEMS analysis software.

In a university setting with an integrated PLM curriculum, the addition of some basic MEMS examples would expose students to MEMS devices and practices. Specialized MEMS software would not be necessary as the MEMS device models could be scaled so that analysis is possible using tools within the PLM system. Students could then compare their simulation results with both published experimental results and with theory taught in the curriculum. We present a series of case studies including a micro beam frequency response and a micro gear train analysis, giving students a basic understanding of MEMS applications and how PLM can be applied to the MEMS industry.

Introduction

Product Lifecycle Management (PLM) has been developed as a means for engineers to plan, design and test a product from the opening stages of product description through the design, testing and manufacture, to the retirement of the design. The PLM software suite contains a database management tool that allows all documents pertaining to the design to be stored and easily accessible. The suite also contains an integrated CAD and analysis package that allows for the modeling of the product along with analysis of the generated models. All of the models and analysis information are also stored in the database for easy access. This means that any changes to the design are documented and stored for later review. This use of a database means that all information for a given product is readily accessible to engineers allowing for more efficient product development. Additionally the usage of Micro-Electro-Mechanical (MEMS) devices has become more common, leading to the need for non-MEMS specialists to be involved in the design process. With this in mind many companies have developed MEMS design software that aids in the design and characterization of MEMS devices. While current PLM software has no design aids targeted specifically at MEMS development, the database management software can still be used for document management and the design and analysis tools may be applied in a limited amount.

Also of importance if MEMS design is to be performed by non specialists is the need to expose engineering students to basic MEMS devices and their functionalities. This would be easily accomplished in a university setting with an integrated PLM curriculum. Some basic examples to illustrate MEMS devices, along with the ability of the software to model and simulate such devices would be beneficial. Such examples would also allow students to apply concepts learned previously to a situation other than a problem out of a book in the class. The students would be allowed to demonstrate their proficiency with the modeling and analysis software along with their knowledge of the theoretical aspects of the material. After analyzing their model using the software the students would then be required to perform the necessary calculations to check for correlation between the simulation and theoretical analysis methods.

In developing these examples a series of case studies were performed to ensure that the software could accurately model and simulate the MEMS devices and that an adequate solution was developed when compared to theoretical calculations. The case studies were then used as a basis for lessons for undergraduate students. The PLM software used was CATIA V5 R12 produced by IBM, this software suite is an integrated design tool that can perform CAD operations and has integrated analysis tools [1]. For database management SMARTEAM V5, also produced by IBM was used, and this software allows the user to manage the files in an organized manner. In each case the PLM software, CATIA V5 R12, was capable of modeling the device, but scaling the device was necessary for the analysis portion of the program. The following schema was used to develop the case studies in an effort to address all of the important issues.

Case Study Schema

Each case study **must** include:

- Paper citation with
  - Explanation of device
  - Tests preformed
  - Assumptions and constants used
  - Results that can be compared to later
- Goal of case study
  - What facet of the mechanism is under scrutiny
- Details of simulation
  - Assumptions made in modeling (materials, simplifications)
  - Testing options (element type, size)
  - Difficulties in simulation (scaled model, mesh problems)
  - Results of simulation
- Comparison of published and simulation results
  - Direct comparison if possible
  - Possible to scale the results for a scaled model?
  - Does standard macro theory apply?
  - If not, why?
  - Reasons for disparity between experiment and publication
  - Solutions for fixing the simulation to improve correspondence to published results

Case Study 1

The first case study is the modeling and simulation of a micromechanical resonator. The goal is to model and perform a frequency analysis of a resonator as presented by Nguyen [2].

Use of micromechanical communication circuits for low loss filtering, mixing, switching, and frequency generation make possible the miniaturization of communication devices. The most common micromechanical device for such applications is a simple flexural beam with clamped-clamped end conditions. The beams were modeled as shown in Figure 1, with L_r as the length, h_r as the height, and W_r as the depth of the beam. Nguyen presents results for free-free beams using Timoshenko methods shown in Table 1; these results will be used for comparison values [2].

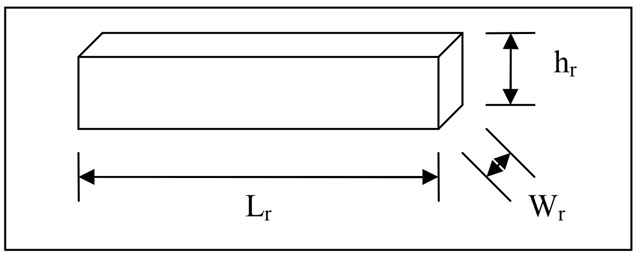

Figure 1: Micromechanical resonator beam representation

Table 1: Micromechanical resonator frequency results [2]

Freq. [MHz]	Material	Mode	h_r [µm]	W_r [µm]	L_r [µm]
70	silicon	1	2	8	14.54
110	silicon	1	2	8	11.26
250	silicon	1	2	4	6.74
870	silicon	2	2	4	4.38
1800	silicon	3	1	4	3.09
1800	diamond	3	1	4	6.16

Beam geometry is the main factor in producing a desired frequency as observed in Table 1 [2]. Such beams are manufactured using surface micromachining in order to produce varying end conditions and complex geometries.

A micromechanical resonator was modeled using CATIA V5 R12 to the specifications of the first resonator in Table 1. For the sizes of beams given in Table 1 CATIA V5 was unable to mesh and compute a finite element analysis (FEA), but was able to model and apply the material properties for the beam. All of the modeled beams were made of silicon with the following material properties: Young's Modulus $E = 1.65e^{11}$ N/m^2, Poisson's Ratio $\upsilon = 0.22$, and density $\rho = 2330$kg/m^3. The element type was a linear tetrahedron with a mesh size of 0.0001m. The dimensions of the beam were then doubled to keep the L_r-to-W_r ratio constant at 1.8175. The FEA was attempted again, this process was repeated until the first success with a beam of the following dimensions: h_r =128 µm, W_r = 512 µm, L_r =930.56 µm. After attempting to perform analysis on some beams close to this size it was found that a beam of the dimensions h_r =96 µm, W_r = 384 µm, L_r =697.92 µm is a lower limit for frequency analysis in CATIA V5. It also appears that the smallest element size allowed is 0.0001m and the smallest allowable mass is $1e^{-9}$ kg. The full frequency analysis results for both beams can be seen in Table 2. This beam as modeled is shown in Figure 2, and the beam model with the frequency analysis is shown in Figure 3.

Table 2: FEA beam frequency results

	Beam 1	Beam 2
Mode Number	Frequency KHz	Frequency KHz
1	1118.4	1542.80
2	1489.7	2178.10
3	1871.6	2579.30
4	2632.3	3715.20
5	3069.3	4432.20
6	3320.1	4454.30
7	3466.5	4949.50
8	3489.3	5147.20
9	4450	6293.20
10	4614.4	6548.90

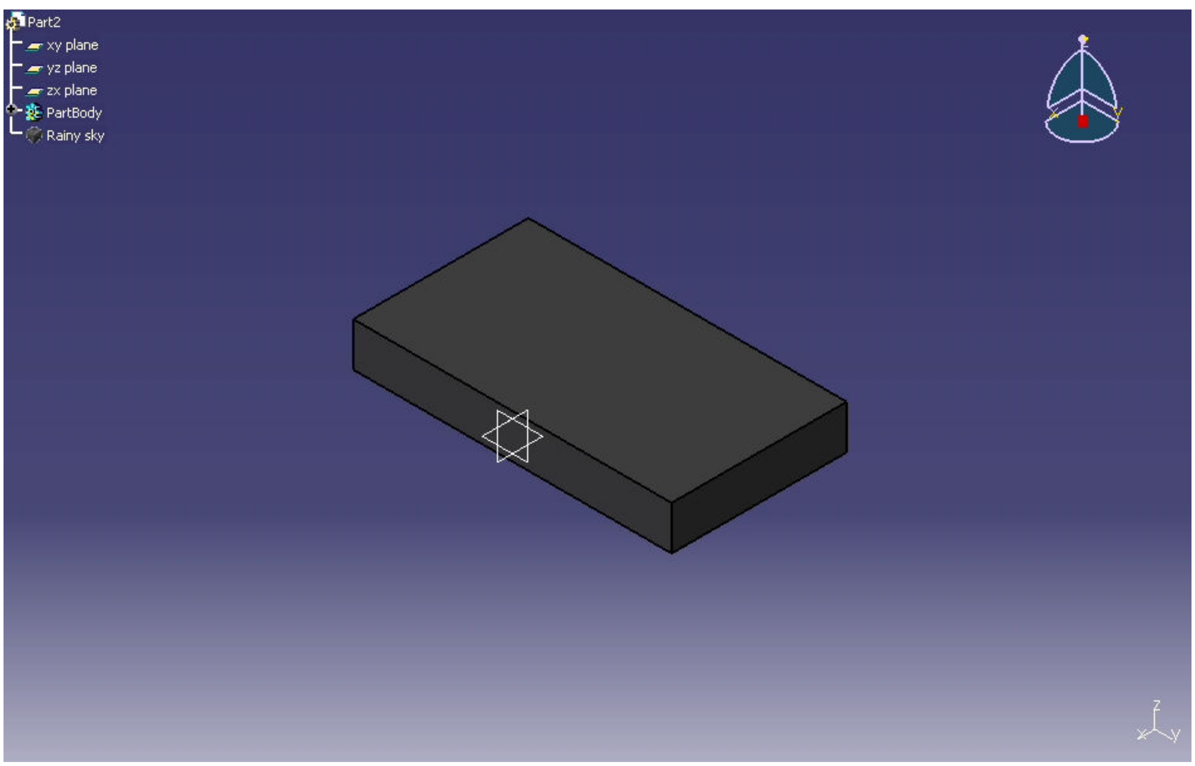

Figure 2: Micromechanical resonator beam model

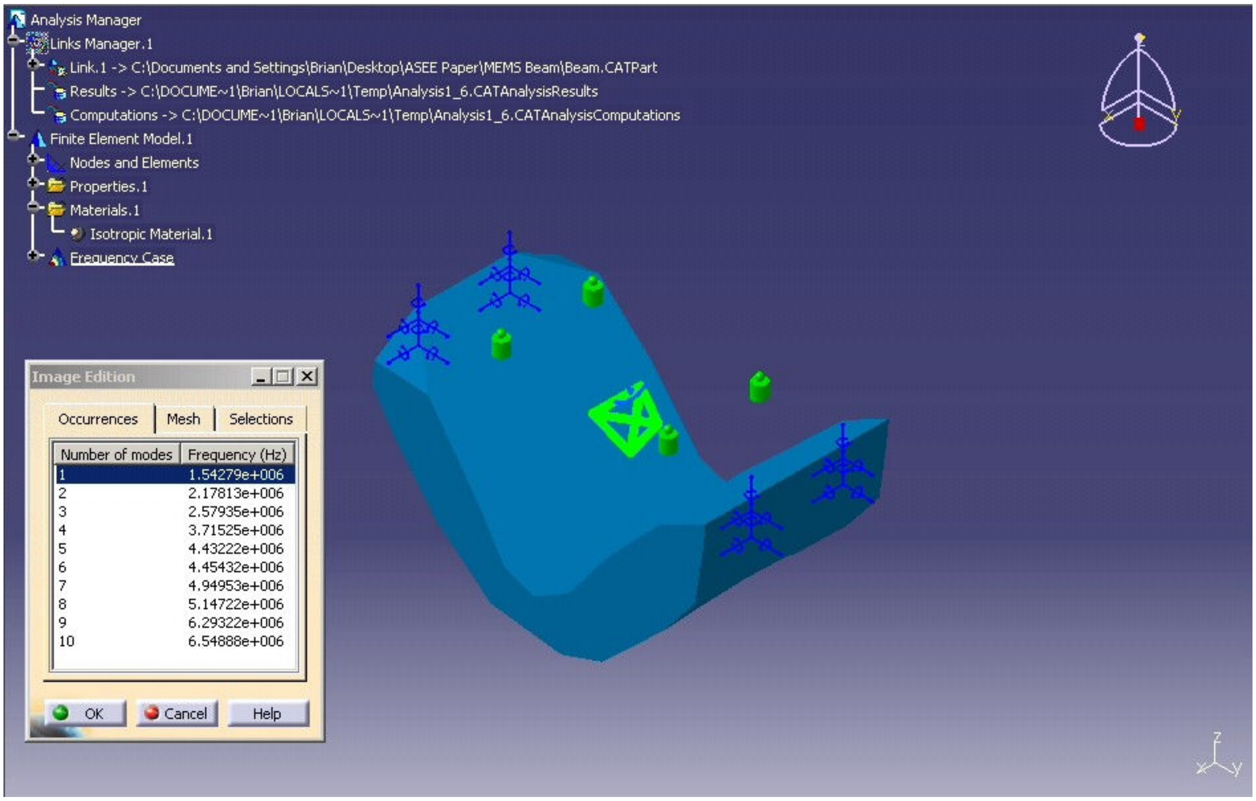

Figure 3: Micromechanical resonator beam frequency response

A result of the scaling to enable FEA analysis is that direct comparison to published results was not possible, but calculated results were found for comparison. Standard beam theory is not the best possible solution for the beams in question because of their L_r-to-W_r ratio. It is better to use the popular Euler-Bernoulli equation for a beam [3]. A simplified version of this equation that neglects stress and width effects is [4]:

$$f_o = \sqrt{\frac{k_r}{m_r}} = 1.03\sqrt{\frac{E}{\rho}}\frac{h}{L_r^2} \quad (1)$$

Where E is Young's Modulus, ρ is density, and h and L_r are beam dimensions. Using this formula for comparison the FEA results were found to be reasonable, with the results tabulated in Table 3, along with the dimensions of all the beams that were modeled.

Table 3: FEA results and comparison to calculations

h_r [μm]	W_r [μm]	L_r [μm]	Mass (kg)	Calculated Frequency (mode 1) kHz	FEA Frequency (mode 1) kHz
2	8	14.54	5.42E-13	81997.84	No mesh, zero mass in model
4	16	29.08	4.34E-12	40998.92	No mesh, zero mass in model
8	32	58.16	3.47E-11	20499.46	No mesh, zero mass in model
16	64	116.32	2.78E-10	10249.73	No mesh, zero mass in model
32	128	232.64	2.22E-09	5124.87	No mesh
64	256	465.28	1.78E-08	2562.43	No mesh
128	512	930.56	1.42E-07	1281.22	1118.37
96	384	697.92	5.99E-08	1708.29	1542.79

With the limitation on mesh size it is not possible to model and analyze the smaller resonators, but the calculation results could be improved using Timoshenko methods which require the simultaneous solution of coupled differential equations [3].

Lesson Plan 1

Having completed the first case study a lesson plan for junior level engineering students was created. This lesson is aimed toward junior level mechanical engineering students as they would have already completed a mechanics of materials class, have the CAD skills necessary and had some exposure to FEA. The lesson would consist of:

- An introduction to MEMS devices with uses and the multidisciplinary nature of designing such devices with an emphasis on resonators
- Introduction of fabrication issues involved with MEMS devices for example production is similar to IC fabrication but must have stricter tolerances
- Common Production techniques
    - Surface milling
    - Wet bulk micromachining (etching)
    - Surface micromachining
    - LIGA (X-ray lithography, electrodeposition, and molding)
- A brief review of standard beam theory and the presentation of the applicable macro theory calculations that would be used in performing an analysis of the frequency response of a beam
- The reasoning for using the Euler-Bernoulli and Timoshenko methods would be explained relative to the length to width ratio of the beam
- The simplified Euler-Bernoulli equation, (1), would be introduced as it is adequate for this example
- The students would then model a beam, simulate it using the software and then perform calculations using both standard beam theory and the Euler-Bernoulli equation
- Using these calculations the students would be able to observe the inaccuracy when using standard beam theory. Additionally the students would perform an exercise where the desired frequency response is known and having a set of minimum dimensions the

students would first calculate using (1) and then model and simulate to check their results.

Case Study 2

The second case study is of a gear set as attached to an electrostatic wobble motor as described by Paratte[5]. As with the first case study the goal is to model, simulate and compare the results to those of theoretical calculations.

A gear train for an electrostatic wobble motor is to consist of two gears with a gear ratio of 2.3. The pinion and gear have 14 and 32 teeth, respectively and will be made of brass. The given tooth height is 115µm, and the tooth width, b, was calculated using the formula [5]:

$$b = \frac{2C}{\sigma_{0.2} m \varphi r} \qquad (2)$$

Where C is the applied torque, $\sigma_{0.2}$ is the elastic limit stress (0.2% of plastic deformation), m is the tooth modulus, φ is the fatigue factor, and r is the gear radius. The gears are to be supported on axles made of steel of diameters 160 and 100µm for the gear and pinion respectively, both with synthetic ruby bearings. Using this formula minimum tooth widths for the desired 1µNm torque are between 0.5 and 8µm [5]. Due to fabrication constraints a minimum attainable width of 200µm is possible and this width was used in this study.

The micro-gear train was modeled and analyzed in CATIA V5 for a loading condition dictated by gear width, using equation (2). The results of the FEA solution were compared to the materials, in this case brass, yield strength to ensure that the yield strength was not exceeded.

The first model produced was a recreation of the brass gears as described above using a tooth width of 200µm. In order to model the gears some assumptions were made, the most significant was the gear type used, as it was not mentioned in the publication. To simplify the modeling and calculations necessary to model the gear, a standard spur gear with a 20˚ pressure angle was modeled using equations given by Paratte[5]. This validity of this assumption was strengthened when the calculations returned a whole depth (tooth height) value of 115.71µm which is nearly identical to the given value of 115µm. The values used in modeling this gear set are summarized in Table 4. The next assumption made was in calculating the fatigue factor (φ) used for the published results, as the elastic limit stress ($\sigma_{0.2}$) was not given the yield strength of brass, 350MPa was substituted. Using a width of 2µm with a motor torque of 1µNm given in [5] a fatigue factor of φ = 0.1543 was calculated using equation (2). This fatigue factor will be used in later maximum load calculations. This gear set was modeled and analyzed with a torque of 1µNm, but the model and element sizes were too small, and CATIA V5 was unable to create the mesh. The model was constrained in translation in all directions and in rotation in all directions except about the axle location. The model was meshed using the default element, a tetrahedron, with the default element size in each case. After this failure the diameters were then enlarged by a factor of 2 while retaining the gear ratio of 2.3 by keeping the pinion and gear teeth set at 14 and 32.

Table 4: Given gear set dimensions

Gear Set 1, All Units mm except tooth numbers				
fillet radius (rf)	0.0158		Gear Ratio	2.2857
tooth width	0.2000		Center to Center	1.1829
Pinion min. tooth width	0.0020		Gear min. tooth width	0.0009
Load (Nm)	0.0000			
Pinion			Gear	
Number of Teeth	14		Number of Teeth	32
Diameter (D)	0.7200		Diameter (D)	1.6400
Axle Diameter	0.1000		Axle Diameter	0.1600
Circular Pitch (p)	0.1616		Circular Pitch (p)	0.1610
Outside Dia. (Do)	0.8229		Outside Dia. (Do)	1.7425
Addendum (a)	0.0514		Addendum (a)	0.0512
Dedendum (b)	0.0643		Dedendum (b)	0.0641
Root Dia. (DR)	0.5914		Root Dia. (DR)	1.5119
Whole Depth (ht)	0.1157		Whole Depth (ht)	0.1153
Circular Thickness (t)	0.0808		Circular Thickness (t)	0.0805
Clearance	0.0129		Clearance	0.0128
Clearance Dia. (Dc)	0.6171		Clearance Dia. (Dc)	1.5375

The tooth width and applied torque were also simply multiplied by a factor of 2. The model was then created and analyzed again to find that the element size was too small again resulting in mesh errors. The third and successful attempt to model and perform an FEA analysis of the gear set was a gear set that was 4 times as large as the original. The details of this gear set can be seen in Table 5, as before the gear ratio, the number of pinion and gear teeth remained constant.

Table 5: Successful gear set dimensions

Gear Set 3, All Units mm except tooth numbers	size factor	4		
fillet radius (rf)	0.0375		Gear Ratio	2.2857
tooth width	0.8000		Center to Center	4.7314
Pinion min. tooth width	0.0005		Gear min. tooth width	0.0002
Load (Nm)	0.0000			
Pinion			Gear	
Number of Teeth	14		Number of Teeth	32
Diameter (D)	2.8800		Diameter (D)	6.5600
Axle Diameter	0.4000		Axle Diameter	0.6400
Circular Pitch (p)	0.6463		Circular Pitch (p)	0.6440
Outside Dia. (Do)	3.2914		Outside Dia. (Do)	6.9700
Addendum (a)	0.2057		Addendum (a)	0.2050
Dedendum (b)	0.2572		Dedendum (b)	0.2563
Root Dia. (DR)	2.3657		Root Dia. (DR)	6.0475
Whole Depth (ht)	0.4629		Whole Depth (ht)	0.4613
Circular Thickness (t)	0.3231		Circular Thickness (t)	0.3220
Clearance	0.0514		Clearance	0.0513
Clearance Dia. (Dc)	2.4686		Clearance Dia. (Dc)	6.1500

Again the pinion and gear diameters, tooth width, and applied torque were multiplied by 4. For this gear set a minimum tooth width of 0.5µm for the pinion and 0.22µm for the gear were calculated. With a tooth width of 800µm there would be little chance of exceeding the yield stress of the brass gears. For this gear set CATIA V5 was able to complete a FEA analysis for the static case with an applied torque of 4µNm. As with the previous 2 attempts the gears were constrained for translation in all directions and constrained in rotation except for about the axis perpendicular to the gear face. The constraint was applied at the hole in the gear for the axle, and the torque applied to the gear face. The maximum Von Mises stress for the pinion and gear were 136.73kPa, and 26.95kPa, respectively. These are both well below the yield stress of brass, 350MPa, these models are shown in Figures 4 and 5.

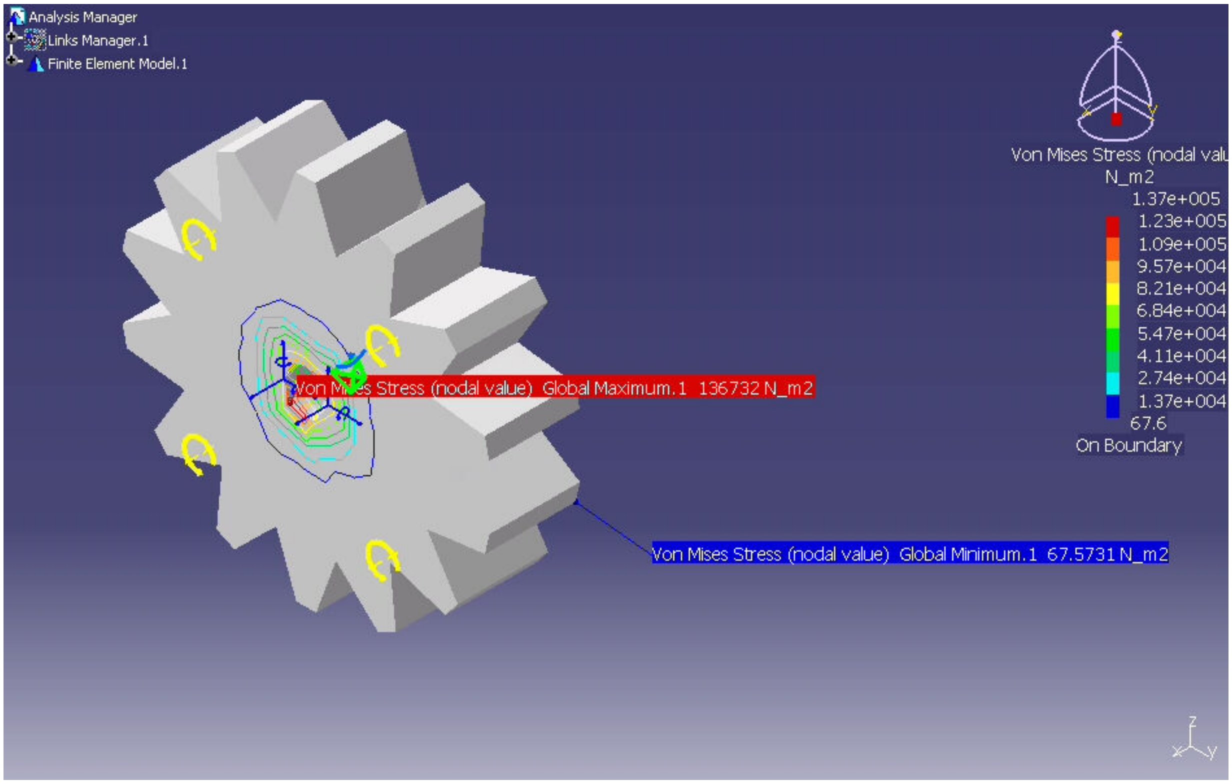

Figure 4: Pinion FEA result

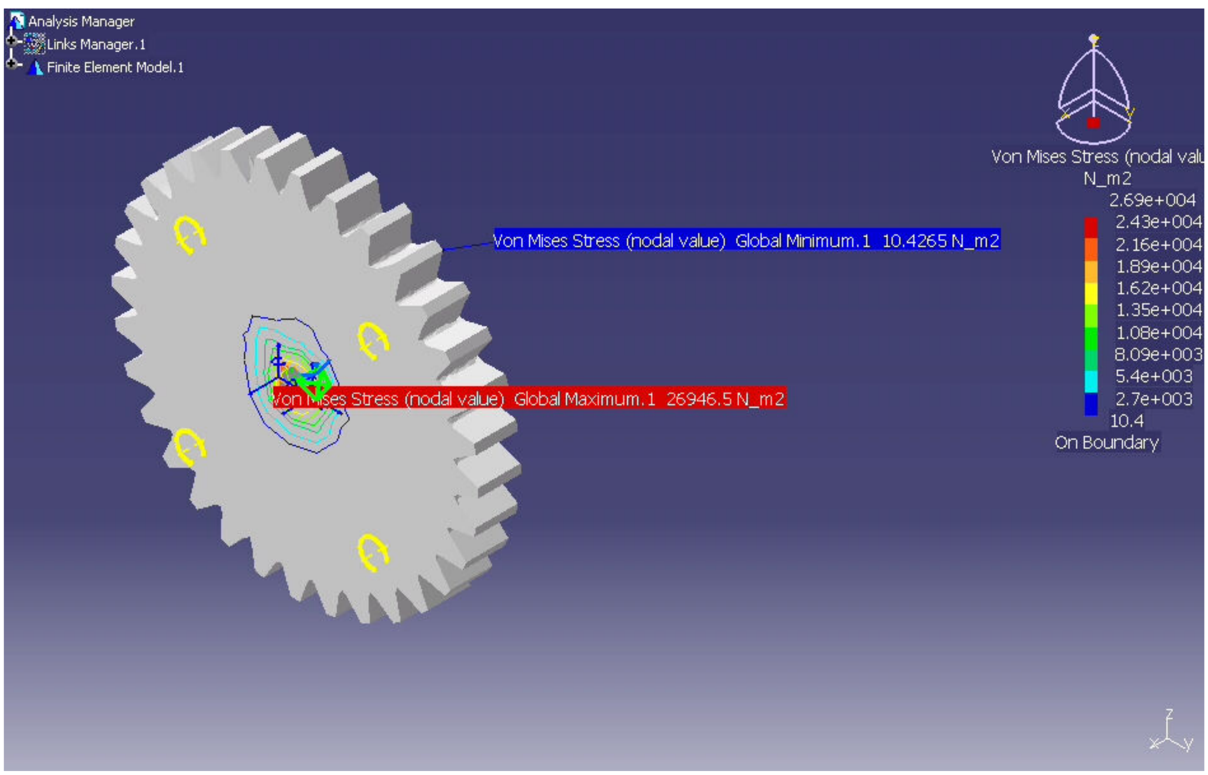

Figure 5: Gear FEA result

An attempt was made to reduce the gear thickness to the minimum calculated value, 0.22μm, but such a small thickness was not allowed by the software. In order to test the FEA solution the load was increased to the maximum allowed for the thickness, using equation (2) rearranged to become:

$$C = \frac{b\sigma_{0.2} m \varphi r}{2} \qquad (3)$$

As with equation 2, C is the applied torque, b is tooth width, $\sigma_{0.2}$ is the elastic limit stress (0.2% of plastic deformation), m is the tooth modulus, φ is the fatigue factor, and r is the gear radius. Using (3) the calculated maximum allowable applied torque, using the pinion dimensions, is C = 6377μNm. For this loading condition the maximum Von Mises stress in the pinion and gear, respectively, were 217MPa and 43Mpa, both still below the yield stress of the brass used in the models.

As with the previous case study of the micro-resonator, direct comparison of the analysis to published results was not possible due to the need to scale the device. Improvements in the software's analysis package could possibly enable the simulation of true micro scaled devices. Regardless of the software's limitations, using the scaled model and the theoretical results, correlation can be observed. The theoretical maximum load based on the yield stress is less than can be applied using the FEA model; this is acceptable as many theoretical calculations are conservative estimates.

Lesson Plan 2

The second case study was used to produce a second lesson involving the use of PLM in MEMS design. Again the lesson was aimed toward junior level mechanical engineering students as in addition to the CAD and FEA skills needed a course in machine design is a prerequisite. The second lesson would consist of:

- Introduction to micro gearing and uses
- A review of gear design, with emphasis on actually modeling gears, and relevant calculations
- The students would complete an exercise in just modeling to familiarize them with the necessary calculations and modeling steps
- Using equation (3) the students would complete an exercise given a range of both gear diameters, a set gear ratio, and loading requirement and be required to first calculate for necessary gear thickness and then model and perfume FEA to check their calculations

Conclusion

Using these case studies an exposure to MEMS devices could be easily added to a curriculum in which PLM has been integrated. By modeling and simulating the MEMS device knowledge of the software will be reinforced. The theoretical calculations would serve to reinforce the concepts from other courses, like mechanics of materials and machine design, and help students to see the practical applications of such courses. The interdisciplinary nature of MEMS devices is idea for teaching students not only the basics of MEMS Technology and uses, but also serves as a means to demonstrate to the students the association between many of their other courses. Using simple MEMS devices for the two case studies lessons can be developed that build off of prior knowledge of standard devices and then introduce concepts necessary for designing the micro sized devices. The result of adding MEMS to an integrated PLM curriculum would be graduates prepared to meet the needs of future MEMS products using the latest methodologies for efficient design.

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Biography

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