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COMSOL® Application Builder lets end-users harness the power of numerical modeling and simulation

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Abstract

Non-destructive direct measurements of mechanical properties of biological tissue, such as that of the crystalline lens of the eye are difficult to obtain. More often indirect measurement methods are used, which then require post processing of the data to extract meaningful results which can be translated into material properties, such as the shear modulus of elasticity of the crystalline lens.

This paper will present how COMSOL® can be used as a tool for the processing step of deducing the shear modulus of the crystalline lens. Moreover, we will discuss the use of the COMSOL® Optimization module to reverse engineer the material property; as well as the use of COMSOL's® Application Builder to create a Graphical User Interface (GUI) which enables non-simulation experts to use the simulation model.

KEYWORDS: Biomechanics, Reverse Engineering, Mechanical Properties, Soft Tissue, Crystalline Lens, Optimization, Application Builder

Introduction

Kejako is developing a non-invasive solution for demanding presbyopia patients seeking to keep their quality of life through the compensation of visual accommodation decay. The company has already developed the first and proprietary 3D parametric model of the complete eye. The model combines multi-physics numerical modeling to compute the full eye's normal optical and mechanical behavior, as well as resulting impacts due to a specific eye disease. The model was first built for research and development purposes as a powerful tool for understanding, experimentation, and the numerical proof of concept of potential solutions. Kejako is currently working on the numerical proof of concept of their proposed Phakorestoration™ solution, with the goal of characterizing the effect on the lens' mechanical properties as a result of a customized treatment plan.

Theory

When we are young, the crystalline lens of the eye is soft and flexible, but as we age. **Figure 1b** shows a simplified schematic of the crystalline lens, identifying the different cellular tissue regions.

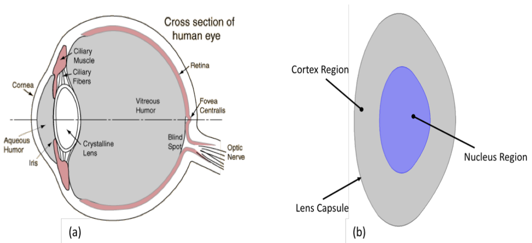

Figure 1: a) Simplified model of eye's anatomy [1], b) Simplified model of crystalline lens constructed in COMSOL® [2]

In the young lens, the nucleus is softer than the cortex, but with increasing age, there is a relatively more significant increase in the stiffness of the nucleus **[3].** As part of the visual accommodation process the lens changes its shape to adjust for a person's far and near vision as shown in **Figure 2a**. Accommodation is the process by which the eye changes optical power to maintain a clear image / focus on an object as the object's distance varies **[1]**. Change in optical power is achieved primarily as a result in the change of the lens' shape as shown in **Figure 2b**.

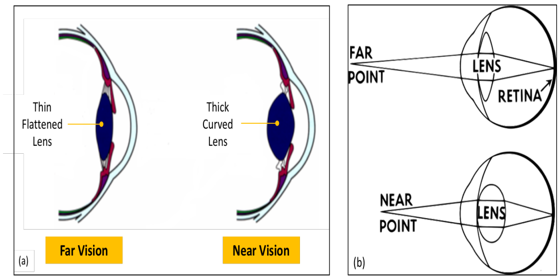

Figure 2: a) Near and far vision lens shape, b) Change in optical power in relation to lens shape **[1]**

Young flexible lenses can easily change their shape, from a flatter shape for far vision to a more curved shape for near vision. However, as the lens becomes stiffer and less deformable, as with older eyes, the lens's ability to change its form from flattened (for far vision) to curved (for near vision) deteriorates with age. There is a stiffness gradient to the lens as shown in **Figure 3 [3]**.

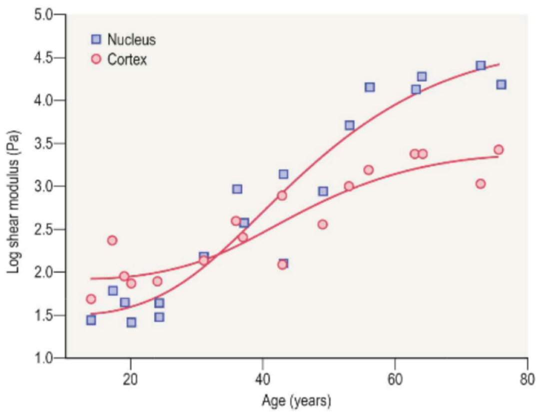

Figure 3: Nucleus and Cortex shear modulus as a function of age **[3]**

In the young lens, stiffness progressively decreases from the surface of the cortex to the center of the nucleus, whereas in older lenses the stiffness gradient increases from the surface of the cortex to the center of the nucleus.

Experimental Set-up

To determine if the treatment achieves its desired results, the mechanical properties (i.e. shear modulus gradient) of the lens needs to be accurately measured before and after treatment. This will involve the use of a test fixture (a.k.a. Lens Spinner) shown in **Figure 4** and COMSOL Multiphysics to reverse engineer the shear modulus value from lens spinning test data.

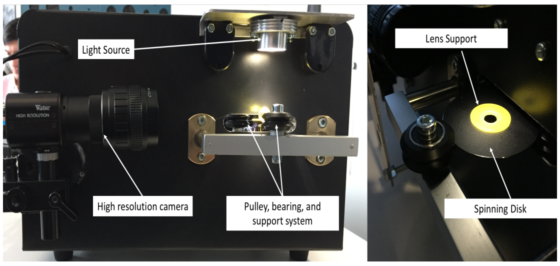

Figure 4: Lens spinner test fixture **[2]**

The lens spinner is used to simulate the in vivo forces experienced by the crystalline lens, that drives the change of lens' shape, as part of the visual accommodation process. **Figure 5** shows a highly simplified schematic of the visual accommodation system, consisting of the lens, zonula fibers, and ciliary muscle.

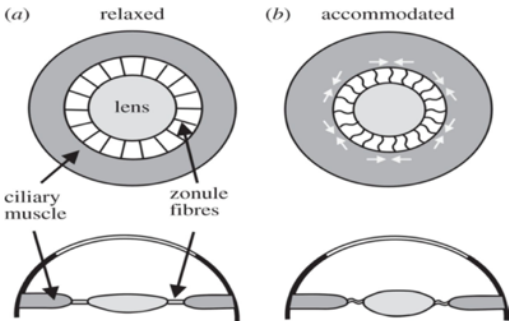

Figure 5: Simplified schematic of the visual accommodation system, images in the first row show a top view, images in second row show a side view **[4]**

When viewing a far object, the ciliary muscle relaxes allowing the lens' zonula and suspensory ligaments to pull on the lens, flattening it, as shown in **Figure 5a**.The source of the tension is the pressure that the vitreous and aqueous humour exert outwards onto the sclera. When viewing a near object, the ciliary muscles contract inward (resisting the outward pressure on the sclera) causing the lens zonules to slacken which allows the lens to spring back into a thicker, more convex form, as shown in **Figure 5b [1]**.

The lens spinning fixture was designed to mimic the force applied to the equatorial region of the lens by the zonular fibers (refer to **Figure 6**) utilizing a centrifugal force. As the lens is spun about its central axis, it experiences a centrifugal body force which is dependent upon its density (ρ), its angular speed (ω), and is equatorial radius (r) according to the relationship shown in **Figure 6 [5][6][7]**.

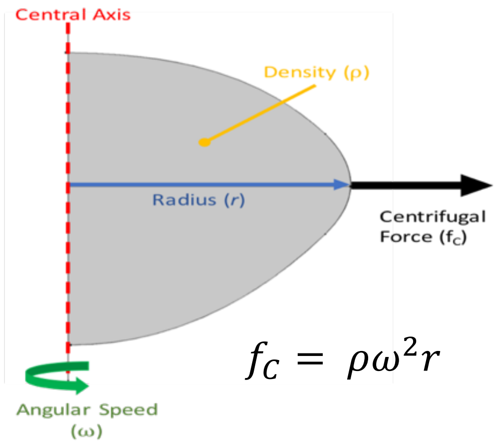

Figure 6: Axisymmetric model of lens **[2]**

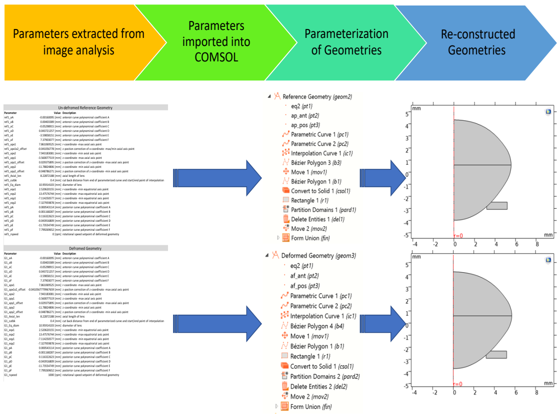

Figure 7: Reconstruction of un-deformed and deformed lens geometries from lens spinning data within COMSOL® **[2]**

When the angular speed is zero, the lens is in its relaxed non-deformed or fully accommodated state. As the angular velocity is increased, the centrifugal force develops causing the lens to deform outwards in the horizontal direction (i.e., expanding along the equatorial axis), thus increasing its equatorial radius.

However, the lens spinner test only provides data related to the resulting lens deformation, therefore an additional analysis is needed to extract and quantify the mechanical properties on the tested lens. COMSOL Multiphysics® v5.3 FEA software is used to reverse engineer the shear modulus values based on lens deformation measurement data obtained from the lens spinning test.

Governing / Numerical Model / Simulation / Methods / Use of Simulation Apps

A 2D asymmetric model representing the lens was constructed in COMSOL® from geometrical data extracted from an intermediate image analysis step following the lens spinning test for a selected porcine lens. This data is used as an input into COMSOL® for the reconstruction of the porcine lens geometry for each of the test speeds performed.

Two lens geometries are created inside of COMSOL®, the first using the extracted image analysis data set for the un-deformed reference geometry (i.e., @ 100 rpm) and a second using the extracted image analysis data set for the deformed geometry (i.e., @ 800 rpm or 1000 rpm). Both geometries are created in the same fashion, only the resulting size and form varies, which is dependent on the discrete parameter values of each geometry.

COMSOL’s® Structural Mechanics module and Nonlinear Elastic Material module are used to define the physics and associated material properties of the reconstructed porcine lens geometries as part of the development of the forward finite element analysis.

Using the reconstructed un-deformed and deformed geometries of a tested porcine lens, both a forward and an inverse finite element analysis is performed using COMSOL Multiphysics® to estimate the lens' shear modulus values of a tested porcine lens.

The forward analyses consist of two stationary studies, one for the undeformed geometry and a second for the deformed geometry. The forward analysis studies serve as a means to apply the defined boundary conditions, physics, and associated material models to the deformed and un-deformed geometries. As well the results from studies 1 & 2 are subsequently used as inputs to the inverse analysis (i.e. Study 3).

COMSOL's® Optimization module is used to perform the inverse finite element analysis, employing a geometrical comparison of a simulated lens geometry (starting from the undeformed geometry results from study 1) with that of deformed porcine lens geometry result from Study 2, to estimate the lens’ shear modulus value which will minimize the difference between the two geometries. The overall process methodology is shown in **Figure 8**.

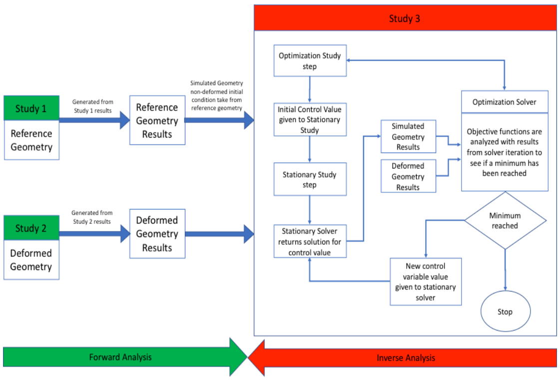

Figure 8: General schematic of Forward and Reverse analyses **[2]**

COMSOL's® Optimization module interface enables the set-up of objective functions, constraint contributions, and control variables which can be defined locally on certain geometric entities, as well as a least-squares contribution with a time or parameter dependence.

As part of the set-up of the inverse analysis, four global objectives function are created, ***gobl₁***) for the arc length of the lens , ***gobl₂***) for the area of the lens, ***gobl₃***) for the radial length of the lens, and ***gobl₄***) for the axial length of the lens, as defined by **Equation 1**. The objective functions have been normalized, which gives equal weighting to each.

$$\boldsymbol{gobj_1} = \left(\left(\frac{s(\xi)}{S}\right) - 1\right)^2, \boldsymbol{gobj_2} = \left(\left(\frac{a(\xi)}{A}\right) - 1\right)^2,$$
$$\boldsymbol{gobj_3} = \left(\left(\frac{r(\xi)}{R}\right) - 1\right)^2, \boldsymbol{gobj_4} = \left(\left(\frac{z(\xi)}{Z}\right) - 1\right)^2$$

Equation 1: Formulation of individual objective functions **[2]**

The first objective function compares the arc length (*S*) of the deformed geometry, with the arc length (*s*) of the simulated geometry which is dependent of the control variable ξ (i.e. shear modulus of the lens). The second objective function compares the cross-sectional area (*A*) of the deformed geometry, with the cross-sectional area (*a*) of the simulated geometry which is dependent of the control variable of the lens. The third and fourth objective functions compare the deformed radial length (*R*) and axial length (*Z*) respectively, with the simulated radial length (*r*) and axial length (*z*), which are also dependent on the control variable. Each objective will go to zero when a perfect match between the simulated and deformed geometries occur for that particular objective (i.e., area, radial length, axial length).

Once individual objective functions and control variables have been defined under the component node, they are now accessible to be used in an Optimization study step. To set up the inverse analysis, a third stationery studied (i.e., Study 3) was created. In conjunction with the stationary study step, an Optimization study step was added. The Optimization study node collects all settings necessary for solving the optimization problem. It serves the dual purpose of defining the optimization problem to be solved and choosing an optimization solver, as well as controlling important solver properties and solver output **[8]**.

The optimization node is also where the overall objective function gets constructed. The configuration was set up to build an overall objective function, which seeks to minimize the sum of the individual objective functions defined by **Equation 2**.

$$Q(\xi) = min[gobj_1(\xi) + gobj_2(\xi) + gobj_3(\xi) + gobj_4(\xi)]$$

Equation 2: Formulation of the Overall Objective Function **[2]**

Once the configuration is completed, the study can be launched to start the optimization solver. The optimization algorithm will run seeking to minimize the overall objective function. The algorithm will begin its search from an initial value given in the control variable node, and in turn the stationary solver will use this control variable value as an input to solve the finite element problem for that value. At every solver iteration, the optimization results will be analyzed to determine the impact on the objective function (i.e., whether an increase or decrease occurred). Based on the objective function analysis, the optimization solver will update the control value to be used for the next iteration. This iteration process will continue until the optimization solver determines that a stationary point has been reached (i.e.; objective function cannot be minimized further), and at this point the optimization will terminate.

Experimental Results / Simulation Results / Discussions

A pair of porcine lenses which came from a ~6-month old pig and taken right after death were tested on the lens spinner within three hours following the death of the pig. Each of the extracted lenses were labeled with a unique identifier 1P1 (for the first lens) and 1P2 (for the second lens). The pair of lenses were maintained at a temperature of 4°C just prior to testing on the lens spinning rig, and each lens was spun at 800 and 1000 rpm, multiple successive times. The resulting estimated shear modulus values for the pair of lenses were deduced from the lens spinning data using the previously described forward-reverse FEA analysis. The FEA analysis was ran using both a Hyper Elastic as well as a Liner Elastic material model to estimate the shear modulus of porcine lenses. The estimated shear modulus values are shown in **Figure 9**.

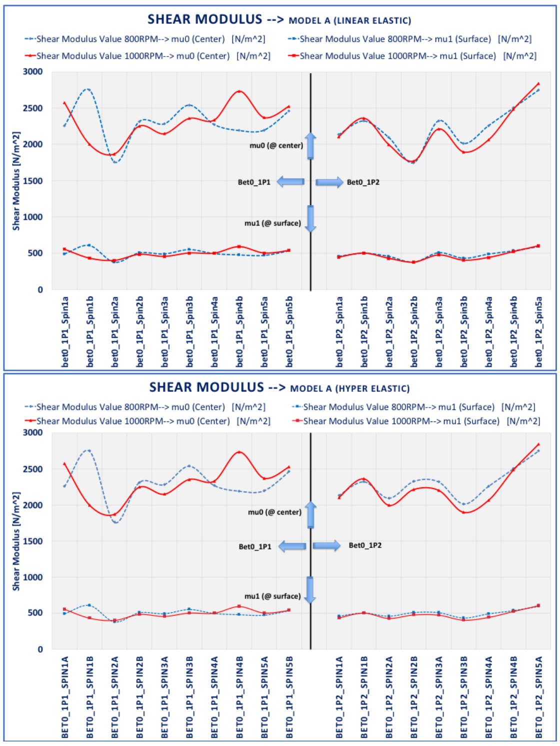

Figure 9: Estimated shear modulus values using model A **[2]**

From the graphs shown in **Figure 9**, we can see that both the Linear Elastic and Hyper Elastic models give comparable results. The dashed blue lines show the estimated shear modulus *mu0* (@ center of the lens) and *mu1* (@ surface of the lens) for the 800 rpm lens spinning data sets. The solid red lines show the same for the 1000 rpm lens spinning data sets. Although some variation between runs is observable for each lens, the estimated shear modulus values derived from the 800 rpm (dashed blue Line) and 1000 rpm (solid red line) data sets are comparable. Moreover, the average shear values for each lens are comparable with the 1P1 lens showing an average *mu0* = 2273 N/m^2 and *mu1* = 493 N/m^2 compared to the 1P2 lens with an average *mu0* = 2239 N/m^2 and *mu1* = 484 N/m^2.

Discussions

As shown as part of this work, it was feasible to use COMSOL® to create an FEA module which can be used to reverse engineer the shear modulus values from Lens spinning data. However, the accuracy of the model to predict the true shear modulus values of a crystalline lens still needs further evaluation. Furthermore, the use of the FEA simulation model requires the user to have a good level of simulation expertise. More specifically a good level of knowledge using COMSOL Multiphysics® to be able to input the discrete geometrical values obtained from the lens spinning test which are needed for the reconstruction of the lens geometries. As well as switching between different material models, for example Linear Elastic or Hyper Elastic. In addition, able to use the derived value operations to extract specific geometrical parameter data from the results from the forward analysis studies 1 & 2, which needs to be manually saved as additional global parameters so that they can be accessible and used during the optimization Study 3. Even if the user does have a sufficient level of expertise using COMSOL®, the redundant manual data operations and manipulations are pronged to induced errors and well as being timing consuming when several sets of lenses spinning data is to be tested.

Luckily COMSOL's® Application Builder provides graphical tools and editors, as well as built-in language elements and Java code to tailor an application with the user inputs, design, and results that you want to include **[9]**. Using the Application Builder, custom applications can be created on top of existing COMSOL Multiphysics® models created by an experienced simulation engineer, which can simplify the use of the simulation for less experienced engineers. In addition to COMSOL® users, being able to run applications within COMSOL Multiphysics®, COMSOL® users can also make their COMSOL® applications available for colleagues and customers who do not use COMSOL Multiphysics® by letting them connect to a COMSOL Server™ **[9]**. The COMSOL Server™ can be installed in a central location on your network or in the cloud. Colleagues and customers can then run apps on a COMSOL Server™ through a web browser or a COMSOL® Client **[9]**.

Figure 10 shows the main page of the Lens Spinner v 2.0 simulation application GUI, which users will see when the application is launched. The custom GUI interface enables users to run a simulation and obtain results, regardless of their level of expertise in FEA simulations.

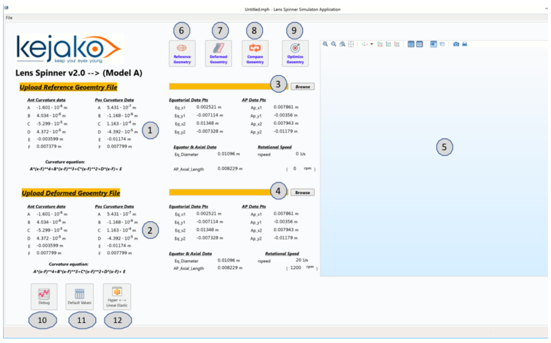

Figure 10: Lens Spinner v2.0 Application GUI – Main Page **[2]**

Callout 1 and 2 mark the sections which display a listing of the parameters which were extracted from the image analysis of the lens spinning test for the reference geometry and deformed geometry respectively. File browser pop-up dialogs (marked as callouts 3 and 4) are used to upload CSV data files which contain the parameters extracted from the image analysis of the reference and deformed geometries. The reconstructed 2D reference geometry and deformed geometry can be plotted to the graphics window (i.e., marked as callout 5), using the Reference Geometry and Deformed Geometry buttons at the top of the GUI (marked as callouts 6 and 7 respectively). The Compare Geometry button (marked as callout 8) launches the forward analysis Studies 1 and 2 respectively, and then plots the results in the form of a line graph to the graphics window, showing an overlay of the reference geometry and deformed geometries.

The Debug button (marked as callout 10) launches a debug dialog pop up, which allows specific parameters values to be changed, enables/disables specific software features, etc. However, usually this would not be used by the user, but instead used in the devolvement and testing of the software.

The Defaults Values button (marked as callout 11) populates the Reference and Deformed Geometry Parameters (i.e.; callouts 1 & 2) with a set of defaults values, allowing the user to verify that the Application and Optimization are functioning correctly. The user can use these default values to run the Reference Geometry and Deformed Geometry construction and plots (i.e.; callouts 6 & 7). Also, to verify the Compare Geometry (i.e.; callout 8) forward analysis studies 1& 2 and resulting plots are functioning correctly. Finally, the optimization study functionality using the Optimize Geometry button (i.e.; callout 9) can be run, which will return results of a perfect matching between the Simulated and Deformed Geometries (all QFs = 1), indicating the optimization algorithm is functioning correctly.

The Hyper -- Linear Elastic toggle button (marked as callout 12) allows the user to switch between using a Model A Hyper elastic or Model A Linear elastic material model for the lens. By default, the hyper elastic material model is activated, pressing the button enables the linear elastic model (disabling the hyper elastic model). Pressing the button again deactivates the linear elastic model (re-enabling the hyper elastic model). All of the functionality of the software functions the same whether using the hyper elastic or linear elastic material model.

The Optimization Geometry button (marked as callout 9) launches a pop-up dialog screen (marked as callout 10) which is used to start the inverse analysis Study 3, as shown in **Figure 11**.

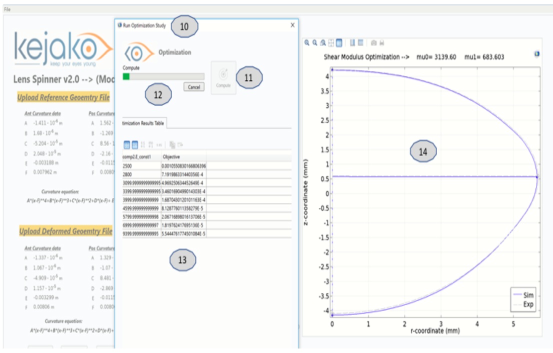

Figure 11: Lens Spinner v2.0 Application GUI -- Run Optimization Study dialog and graphics window **[2]**

The optimization study is launched once the Compute button (marked as callout 11) is pressed. As the inverse analysis is running the user can see the status of the analysis from the progress bar (marked as callout 12), as well interrupt the study with the Cancel button if necessary. Also, the user can see as each iteration is completed, the control variable value that was used and the resulting objective function value shown in the results table (marked as callout 13). Furthermore, the user can see the calculated shear modulus values (i.e.; mu0 & mu1) and a 2D Overlay Plot of Simulated Geometry vs. Deformed Geometry in the graphics window (marked as callout 14) at every iteration of the optimization, as shown in **Figure 11**.

Once the Optimization Study has terminated, an Optimized Results dialog screen pops up showing a summary of key results and values from the optimization at the top of the dialog page (marked as callout 15) as shown in **Figure 12**. As well addition results are provided in the Tabbed Page list (marked as callout 16). This example shows the Optimized Results Table (marked as callout 17) from the Optimization Study 3.

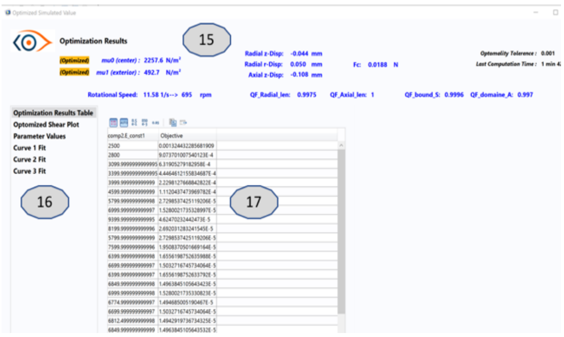

Figure 12: Optimization results summary page **[2]**

Conclusions

Using COMSOL's® Application Builder to create a custom application GUI is relatively easy and straightforward. Even for those who are not programming geniuses; using the Application Builder's graphical interface, allows even a novice to create a professional looking GUI. This tool is part of COMSOL's® standard modules package and makes the potential for sharing simulation models much easier, especially with potential end users that have no experience in FEA modeling and simulation. Building a GUI on top of the simulation lets the simulation engineer decide and control what potential users can view and how they can use the simulation application.

As part of COMSOL's® product suite, it offers a COMSOL Server™ license. A significant advantage of using a COMSOL Server™ is that it is a multiuser service that can be run continuously on the host computer allowing up to four applications to be run simultaneously through a single COMSOL Server™ license **[10]**. As a result, more users can access and use the apps with fewer licenses.

Even if there are no plans by a COMSOL® user of sharing their simulation model with others, there are still advantages for COMSOL® users to build GUIs for their models. A simple GUI can be quickly designed and implemented, thus allowing the COMSOL® user to efficiently and rapidly automate specific tasks or sequences, get or set parameter values, enable or disable different elements within the model, store derived values and results to variables, easily implement logical decision making, and easily interface with external resources.

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