

# Hyper-Elastic Contact Analysis of a Push-Button Diaphragm Seal

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## Abstract

World market pressures demand that corporations continually bring new and innovative products to market as rapidly as possible. Traditional build and test product development methods in today's competitive markets are too slow, costly, and rarely yield optimized robust product designs. Complex large deflection patterns of rubber diaphragm seals combined with non-linear contact and material behaviors are difficult to calculate utilizing classical methods. Non-linear, Hyper-Elastic contact analysis capabilities found in finite element analysis programs like ANSYS, combined with fast workstations now allow engineers to rapidly evaluate and optimize rubber diaphragm seal designs prior to committing to costly prototypes and tooling.

Presented is the non-linear finite element analysis of a rubber diaphragm seal utilized in a pushbutton design. Analysis considerations encompassed, nonlinear hyper-elastic material behavior of the rubber, large deflection analysis of seal complex motion, and contact analysis with mating parts. Design parameters of primary interest were, seal deflection patterns and seal actuation force as a function of travel.

Technologies like finite element analysis play an important role in bringing robust new products of the highest quality to global customers. Product development and analysis teams working together are applying this technology to Seal designs at Rockwell Automation.

## Introduction

Industrial controls devices such as, panel mounted sensors, indicator lights, or pushbuttons are required to meet many product standards such as IEC, NEMA and UL. These product standards define many test requirements which assure that products of this type, are designed correctly and can survive many industrial environmental conditions. Some examples of these are thermal cycling, mechanical shock, vibration, repetitive use, abuse by the user, and water or chemical splashes. In many applications, control panels with mounted indicator lights or pushbutton operator switches, house many sensitive electronic or electro-mechanical devices. These internal devices must be protected from the industrial environment, where chemical or water splashes can be an everyday occurrence.

In applications like this, pushbutton operator switches must be capable of actuating through a required travel for contact make or break, have the right tactile feel for the operator, and yet provide an adequate seal from the outside environment. Water tight seal environments for pushbutton operators are defined by NEMA/UL or IEC water ingress test standards. Tests defined by these standards, evaluate the effectiveness of a seal design, by spraying an established rate of water, on a number of devices, at a specified distance, direction and time. This test is sometimes referred to as the hose test.

A movable seal for a device such as a pushbutton, takes the form of a rubber membrane or corrugated diaphragm. The rubber diaphragm must provide an adequate water tight seal, accommodate the pushbutton operator travel, survive millions of operations, operate under varying temperature extremes, without impeding the motion of the pushbutton action or compromising the tactile feel for the user. Therefore developing a seal design, which meets all of the design requirements, utilizing build and bust development techniques can be very time consuming and costly. For this reason, computer aided design technologies in the form of ANSYS finite element analysis and fast workstations, now allow seal design engineers to evaluate and optimize design approaches prior to fabrication and testing of prototypes.

Molding rubber components like a diaphragm seal, in many cases require long processing times to allow for the curing process of rubber to occur. Because of this, it is not uncommon for a rubber mold die to have several hundred cavities based on part size and annual volume requirements. Consequently, getting the rubber part design right the first time is of major importance. Modifying a tool with several hundred cavities due to improper part design, is many times impractical and usually requires a new die or significant tooling costs to correct design errors. Major advantages of finite element modeling to develop rubber molded components, like a diaphragm seal, are to get the design right the first time, significantly reduce die rework costs and shorten time to market.

Another application of finite element modeling is to study the influence of molding variations or part tolerances on part performance. This can be very useful to the design engineer in selecting tolerances and matching process capabilities with the part performance requirements. As an example, part finite element models of maximum material condition (MMC) versus least material condition (LMC) part size variations, can be evaluated and compared with product requirements. The focus of the following investigation, concentrates on the application of Hyper-Elastic contact analysis to optimize the design of a pushbutton diaphragm sealing system, utilizing the ANSYS finite element software.

## **Procedure**

### ***Pushbutton Operation and Diaphragm Seal Assembly***

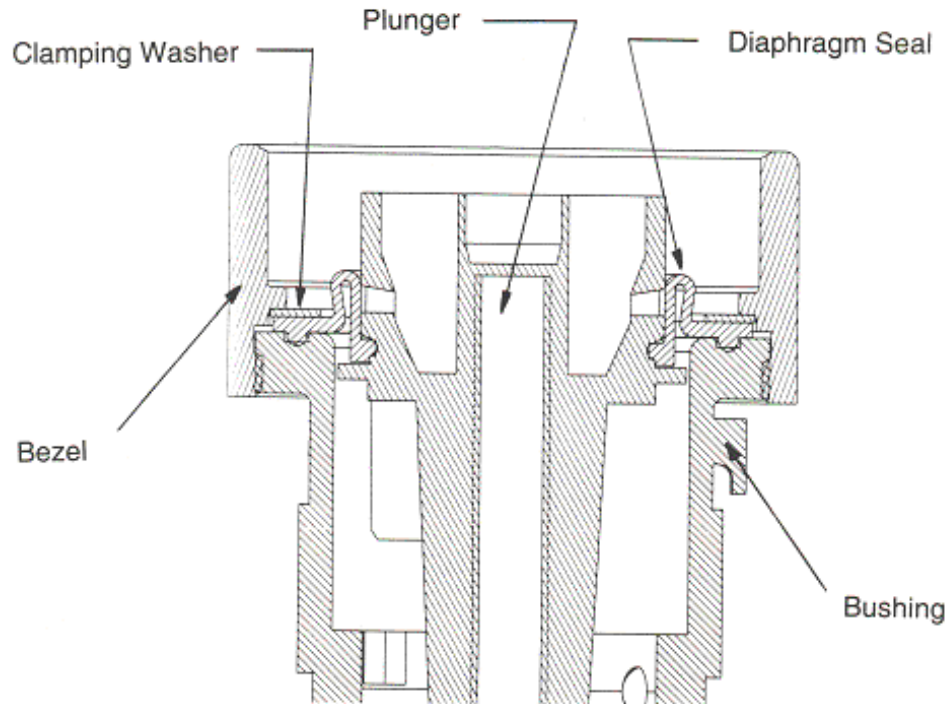
Most pushbutton operators have an external button or lever that protrudes from the control panel which is activated manually by the user based upon demand. This external protruding button or lever is referred to as the pushbutton operator. Depending on the operator function, these pushbuttons maybe lighted or color designated to allow for easy functional identification by the user. Attached to the external button is a long cylindrical internal component called the plunger. As the button is depressed, the plunger transmits translational motion to protruding contact cartridge pins in the rear of the pushbutton operator device. This movement or depressing of contact cartridge pins causes a set of double break contacts to either make or break current. At rest, the contact blocks may either be in a normally open (NO) or normally closed (NC) state, depending on the type used. Multiple contact cartridges maybe snapped into the back of the pushbutton operator to control more than one circuit at a time. Electrical connections to the contact cartridges are made inside the panel or enclosure with screw clamp terminations.

A preloaded return spring attached to the plunger assures that the button operator will always return to the original position when not depressed by the operator. The primary function of the diaphragm seal is to prevent water or chemicals from entering the pushbutton operator and into the inside of a front panel. The diaphragm must provide a reliable seal as well as allow ease of movement of the plunger over the entire range of travel. A photo of the pushbutton operator, diaphragm seal and push button cross-section are shown respectively in Figures 1-2.



Figure 1 - PHOTO OF PUSH BUTTON OPERATOR AND DIAPHRAGM SEAL

## Cross-section of Push Button Operator



**FIGURE 2 - CROSS-SECTION OF PUSH BUTTON OPERATOR**

Pushbutton operator assembly starts first with mounting the diaphragm seal onto the plunger. The seal is stretched over the plunger using a special tool so that a sealing bead lies inside the external plunger groove. This procedure is similar to stretching a balloon over the nozzle of a helium bottle. Assembly of other internal components then proceed to complete the pushbutton product.

Pushbutton operators are mounted on a panel by securing the operator housing to the panel with a tightened nut and sealing panel gasket. The diaphragm provides a seal to the external environment at a second location between the housing and a tightened external bezel washer assembly. This pushbutton installation is then completed with snapping contact cartridges into the rear of the operator and wiring electrical terminations.

### ***Diaphragm Seal Design Considerations***

The primary function of the diaphragm is to provide a moving seal between the housing and movable plunger. A raised rubber bead on the diaphragm, fits into a groove on the bushing face, to form a water tight seal. Required clamp load to form this seal is provided by an externally tightened bezel. The

robustness of this seal is influenced by several factors such as groove depth, size of rubber bead, stiffness of rubber and clamp load. A second location of diaphragm sealing is found at the movable plunger. At this location, a rubber bead on the diaphragm, is stretched over the plunger containing a groove, analogous to stretching a balloon over a nozzle. Clamp load at this sealing location, is provided by the diametrical interference between the groove, bead and resulting hoop stress.

In addition to providing adequate water tight seals at both locations, the diaphragm must move freely without buckling and utilize a minimum amount of force. Finite element analysis is a tool that can be very helpful in optimizing bead design, determining clamp loads, evaluating diametrical interference, sizing the diaphragm loop, and visualizing the seal motion or bead clamping action.

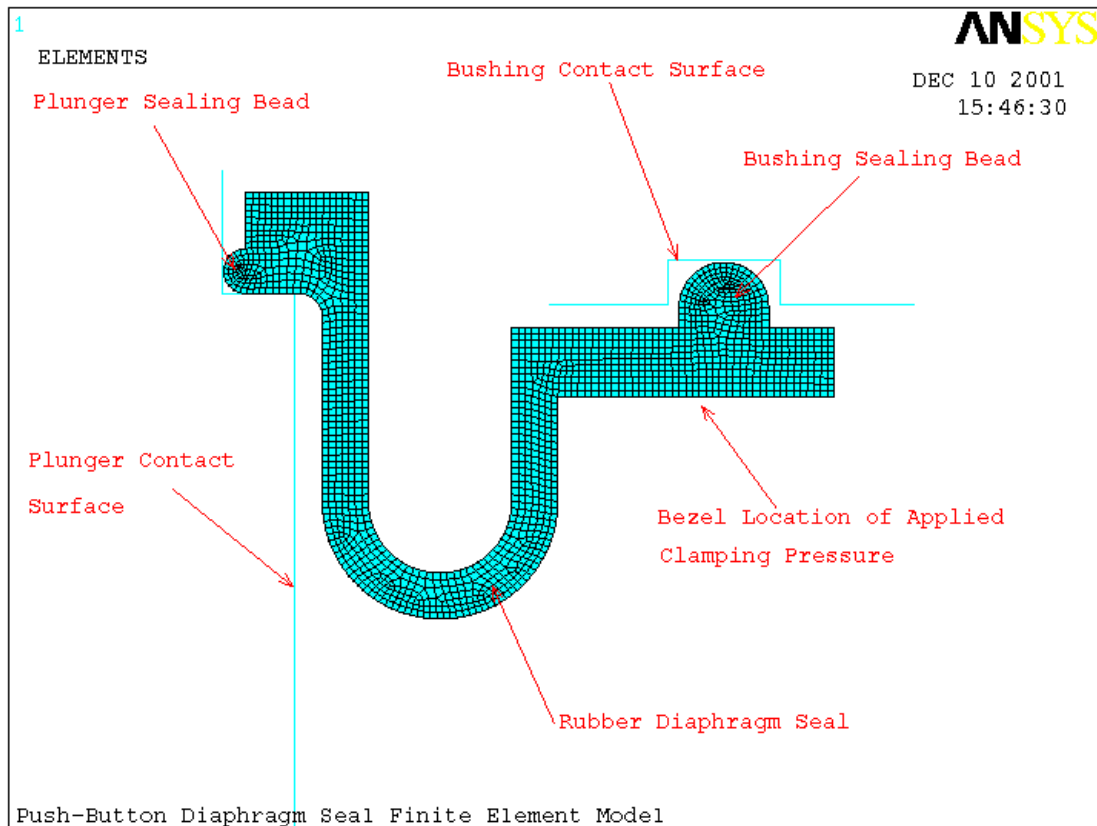
## **Analysis**

### ***Finite Element Modeling Considerations and Model Creation***

A quarter symmetry solid model of the diaphragm was initially created by the product design engineer. This solid model created in Pro-Engineer was exported to ANSYS in the form of an IGES file. One advantage of letting the design engineer create the geometry is that he or she has control over the design, obtains a more in depth understanding of the product function and can share in some of the work of model creation. The seal model geometry was created so that the axis of revolution would lie along the global y-axis which is consistent for an axisymmetric finite element model. One of the symmetry cuts for the quarter model was made along the x-y plane. By creating the solid model in this manor, allowed for one surface of the seal cross-section to be used for the axisymmetric finite element analysis directly. Based on experience of the author, a little up front communication with the design engineer in creating model geometry that is appropriate for FEA, can save a great deal of time for the finite element analyst. Another benefit is the product engineer gains an understanding of the benefits of FEA and is a part of the analysis and design optimization process.

A routine was then written as part of the ANSYS input file, to import the Pro-E IGES file and clean up the geometry such that only a cross-section of the seal geometry lying in the x-y plane remained. Since the diaphragm seal geometry and deflection behavior is axisymmetric, an axisymmetric finite element representation of the seal was used for analysis purposes. The element selected to model the rubber diaphragm seal behavior was the hyper-elastic HYPER56 axisymmetric element.

Rigid contact surfaces of the plunger I.D., plunger sealing groove, bushing sealing groove, and bushing clamping surfaces were modeled using TARGE169 rigid surface target elements. At potential regions of contact between the rubber seal and rigid contact surfaces, CONTA171 elements were added. Bezel clamping of the seal bead between the washer and bushing was accomplished by simply imposing displacements on the seal opposite the bead. The magnitude of these imposed displacements was based the Bezel tightening rotation angle and thread pitch. Shown in Figure 3 is a plot of the diaphragm seal finite element model and contact surfaces of the plunger and bushing. Convergence of contact elements with rigid target surface elements was obtained by trial and error by adjusting the stiffness and convergence criteria for the contact elements.

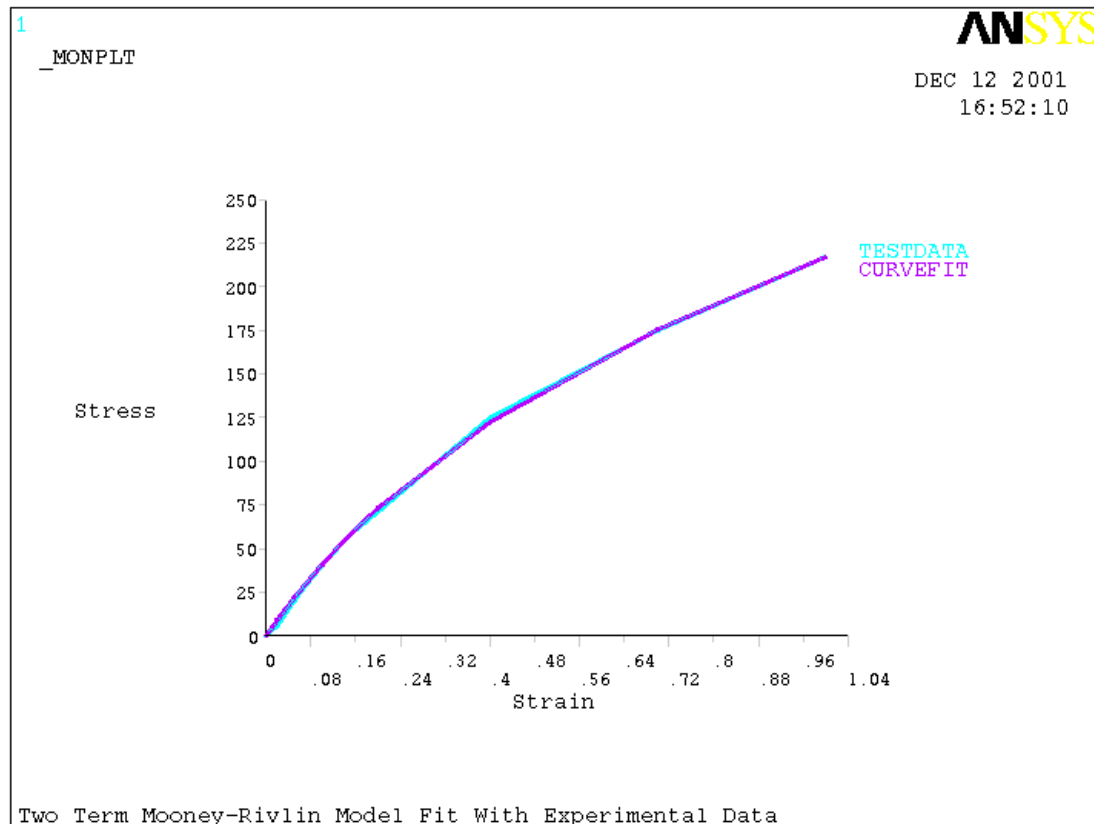


**FIGURE 3 - PUSH BUTTON DIAPHRAGM SEAL FINITE ELEMENT MODEL**

Since the rubber diaphragm undergoes significant distortion relative to the initial geometric shape, the stiffness changes as a function of deflection or seal distortion. Therefore this falls into the geometric non-linearity class of problem referred as large deflection. The large deflection feature was turned on in the seal analysis models to capture this geometric non-linear phenomenon. In addition to the geometric non-linearity of changing contact surfaces and large deflection stiffness behavior, the non-linear material characteristic of rubber was also considered.

### ***Characterization of Rubber with Moody-Rivlin Material Model***

Test data for various rubber molding compounds was provided by the molding manufacturer in the form of stress-strain curves. The stress-strain data was curve-fitted to a simplified two term Moody-Rivlin material model to characterize to hyper-elastic behavior of rubber. This curve-fitting of data was accomplished utilizing the Moody-Rivlin curve fitting routine within the ANSYS prep7 portion of the program. Depicted in Figure 4 is a plot showing the excellent two term Moody-Rivlin material model fit to the original stress-strain curve data. Since rubber is an incompressible material with a poisson ratio equal to .5, to avoid numerical instabilities a value of .49 was utilized in this analysis. To serve as an additional check on the material model fit of data, a simple axisymmetric test bar model was constructed and loaded through the same strain range as the vendor material data provided.



**FIGURE 4 - MOONEY-RIVLIN RUBBER MATERIAL MODEL FIT**

An area of primary interest, was bending of the diaphragm seal loop as the push button plunger moves through the required range of motion. In the seal loop area region, the stress-strain levels fall almost in the linear range of the rubber stress-strain curve. Therefore having test data and a perfect fit in the highly non-linear region of the rubber stress-strain curve was of less importance. The major emphasis for this investigation was correctly predicting the force required to move the seal through the required range of motion. This force was mainly influenced by the seal loop bending stiffness and boundary conditions at the two sealing bead locations.

### ***Finite Element Model Loading Sequence***

The sequence of loading the seal progressed as a three step process. Step one was to mount the inner sealing bead on the plunger and inside the plunger groove. In practice this is done by stretching the seal bead with a special tool over the plunger and mounting surface. From a modeling standpoint this was done by starting the plunger surface target elements out at a small radius and moving them radially to a position equal to the plunger O.D. which picks up the appropriate sealing surfaces in the process. This action produces a hoop stress on the diaphragm sealing bead and is analogous to stretching a balloon over a nozzle. Step two of the loading sequence progresses with clamping the outer sealing bead between the bushing and bezel. This is accomplished in the product by tightening the bezel to some predetermined tightening torque. From a modeling standpoint this was conducted by deflecting nodes on the seal adjacent to the load washer an amount equal to the squeezing deflection typically found in the product. And lastly,



step three progressed with translational motion of the plunger resulting from a user pushing the external button. This loading action was modeled by translating the plunger target elements in the axial or vertical direction of the finite element model.

## ***Factorial Experimental Design Parameter Evaluation***

In the last 10 to 15 years there has been an upsurge of interest in fractional factorial experimental designs with the introduction of Taguchi Methods by Dr. Genichi Taguchi. A noted Japanese technical specialist, Dr. Taguchi promoted a renewed interest in the application of experimental design techniques for making product quality improvements [6]. He developed a simple method for constructing orthogonal experimental design arrays and linear graphs to evaluate factor interactions. Factorial or fractional factorial experimental design arrays are used to help identify significant manufacturing or design factors which have the most influence on variation of product performance. Factorial experimental designs are not a new technology, but were first introduced in the 1930's by Frank Yates, as the famous Yates tables [7] to study and improve yields in the field of agriculture.

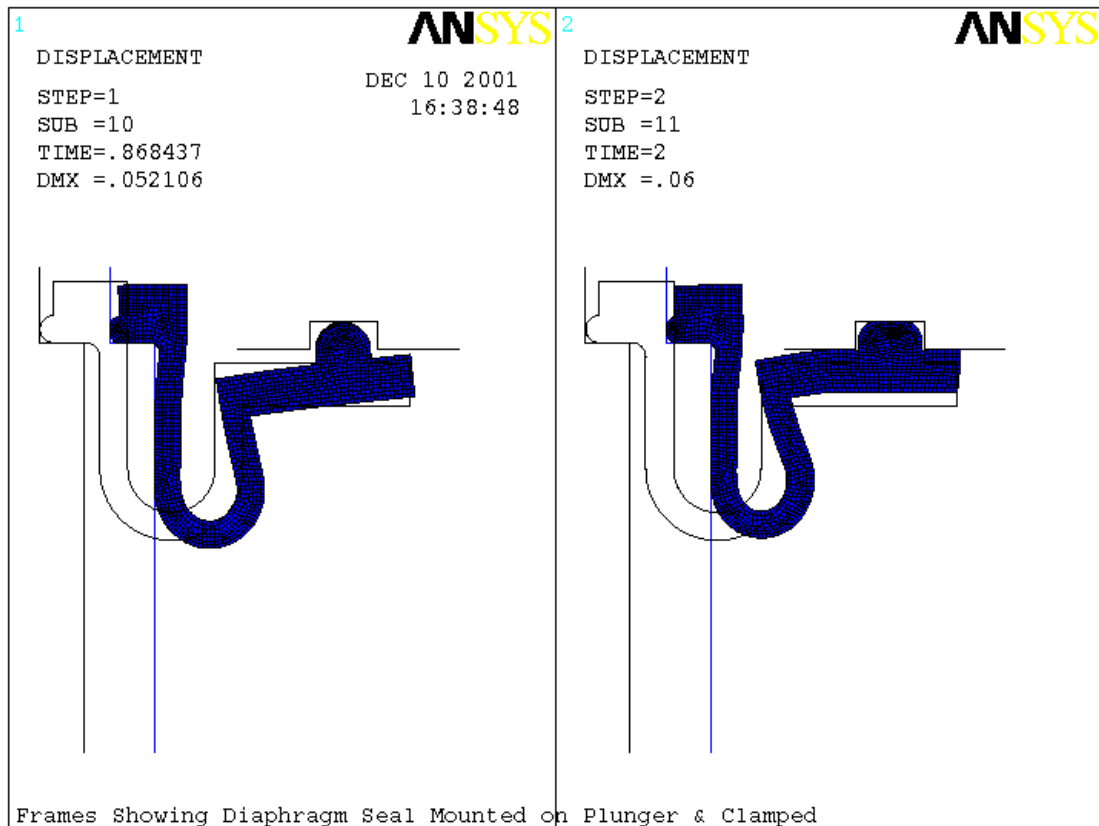
An advantage with using the fractional factorial design approach is that the influence of many design factors can be examined without having to test for all the possible design factor combinations. Generally factorial design factors or main effects selected for evaluation are, set at two levels, high or low. The magnitude of these levels is somewhat arbitrary and may be based on manufacturing process or engineering defined tolerances. These factor levels are designated within the experimental design layout as numbers 1 or 2. Traditionally factorial experimental design investigations are conducted by physically testing samples fabricated or manufactured to the factor levels by the experimental design array. Rather than physically testing prototypes, factorial experimental design investigations can be conducted by utilizing the computer simulation capability of the ANSYS finite element program. The peak actuation force of the pushbutton diaphragm seal, as influenced by several factors, was selected for such an investigation.

Some examples of factors which can influence the seal actuation force are as follows: rubber molding compound, diaphragm loop wall thickness, length of seal loop, initial stretch or hoop stress in the seal I. D. and or bezel clamping pressure. To preserve the confidentiality of results, three of these factors were selected for factorial design investigation and will be referred to as factors A-C. Factor levels were established based on product usage, manufacturing tolerances, and product design. Each factor was set at two levels defined as 1-high and 2-low. The L8 factorial experimental design array consisting of 8 combinations of main factors is shown in Figure 8. Since only three factors were selected, a full factorial experiment was constructed allowing all interactions between factors to be completely represented, without any errors introduced due to factor confounding.

## **Analysis Results & Discussion**

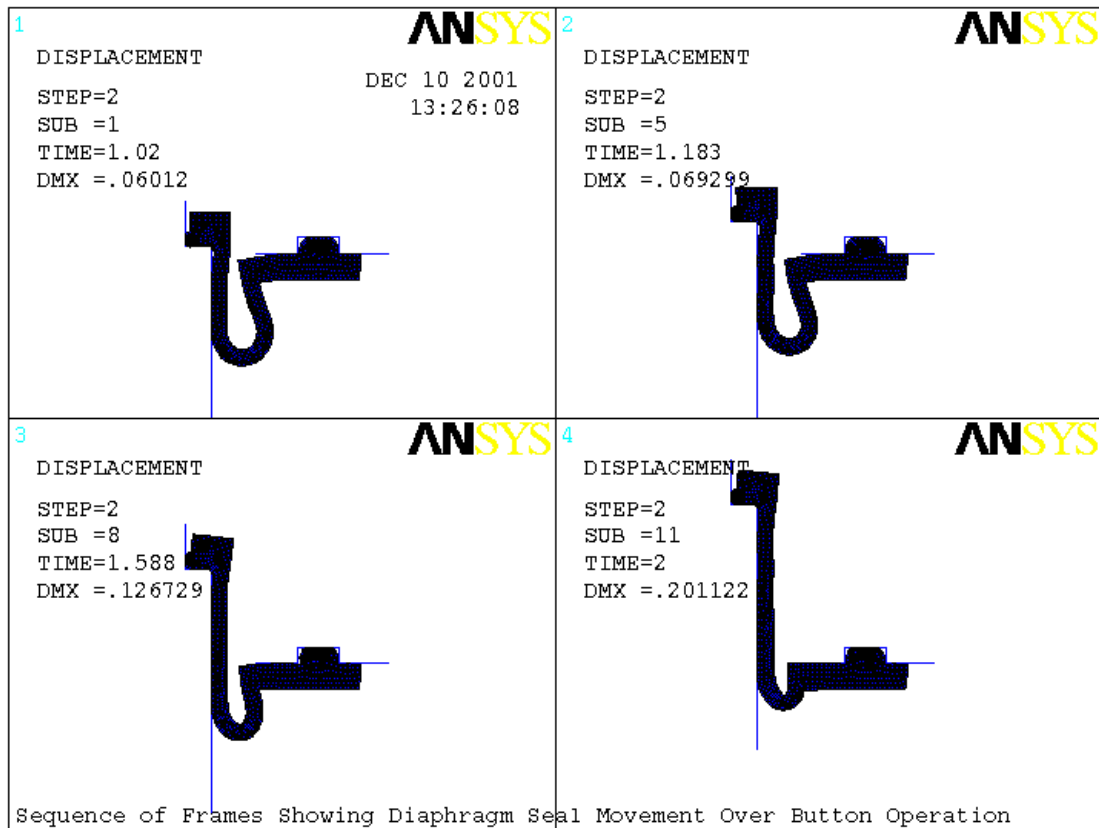
As indicated previously, the seal finite element model loading sequence, progresses as a three step loading process. Shown in Figure 5 are finite element plots showing typical seal deflection patterns when stretched over the plunger and clamped by the bezel/washer assembly. A flat spot on both plunger sealing bead and bushing sealing beads can be noted as a result of the rubber stretching or clamping action. It can also be shown that the diaphragm seal I.D. surface has conformed to the rigid plunger contact surface.



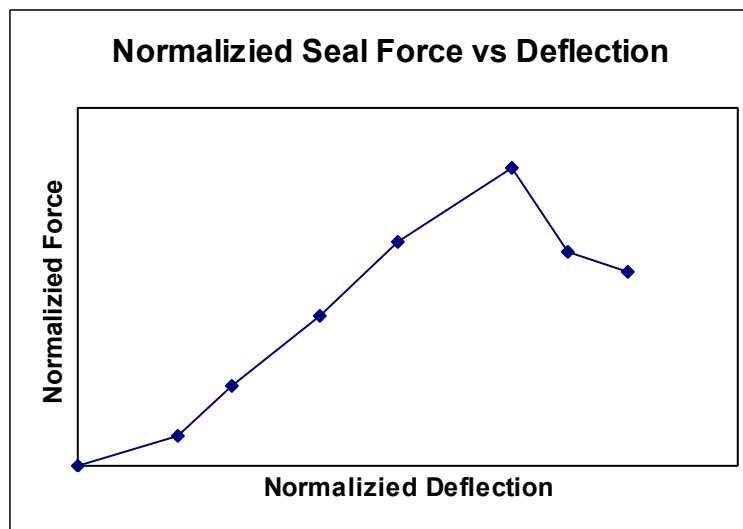


**FIGURE 5 - FEA PLOTS SHOWING DIAPHRAGM SEAL MOUNTED AND CLAMPED**

Once the diaphragm seal is mounted and clamped, the last loading consideration is a translational of the pushbutton plunger and diaphragm seal. This translation is depicted in Figure 6 with a sequence of four frames from start to finish. As the seal transitions through this travel, one can see from the FEA deflection plots how the loop rolls up the side of the plunger outer wall. A typical force versus deflection plot of this seal translational motion is shown in Figure 7. Very good correlation was obtained between finite element model predicted seal actuation force levels and Instron machine measured force levels.



**FIGURE 6 - DEFLECTION SEQUENCE OF DIAPHRAGM SEAL OVER PUSH BUTTON MOVEMENT DURING OPERATION**



**FIGURE 7 - NORMALIZED SEAL FORCE VS DEFLECTION TRAVEL**

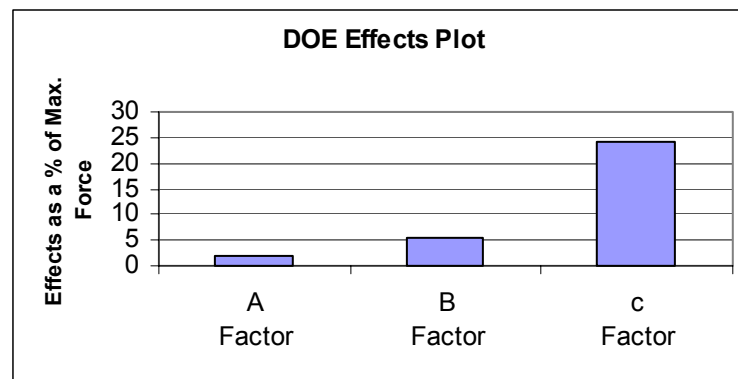
The required seal actuation force, was selected for detailed study, utilizing an L8

factorial experimental design. Since only 3 main effects were evaluated, a full factorial experimental design which considers all possible combinations, was selected for evaluation of factors A-C. Results of the 8 different runs along with factor designated levels are shown in Figure 8. It can be seen that the highest actuation force level was obtained in run 4 with Factor A = 1, Factor B=2, and Factor C=2. From results of an experimental design like this, factors having a major influence on a parameter like actuation force, can be easily identified. The factor having the most influence on actuation force was identified as Factor C and is shown in Figure 9, the main effects plot. Analysis of variance or ANOVA is a statistical technique that is used to determine which factors or interactions of main factors are statistically significant. As shown in the ANOVA table, Figure 10, only factors B and C are statistically significant and pass the F-statistical test. Factorial experimental design methods, as shown, can be useful in identifying the key design or process control factors influencing product performance and variation.

**L8 Factorial Experimental Design Layout**

Run Number	Factor A	Factor B	Interaction AxB	Factor C	Interaction AxC	Interaction BxC	Interaction AxBxC	Normalized Force
1	1	1	1	1	1	1	1	0.38
2	1	1	1	2	2	2	2	0.85
3	1	2	2	1	1	1	2	0.46
4	1	2	2	2	2	2	1	1
5	2	1	1	2	1	2	1	0.39
6	2	1	1	2	2	1	2	0.77
7	2	2	1	1	1	2	2	0.43
8	2	2	2	1	2	1	1	0.95

**FIGURE 8 - FACTORIAL EXPERIMENTAL DESIGN LAYOUT**



**FIGURE 9 - DESIGN OF EXPERIMENTS EFFECTS PLOT RELATED TO FACTOR INFLUENCE ON SEAL ACTUATION FORCE**

## Seal Activation Force- ANOVA Table

Source of Variation	Degrees of Freedom	Sum of Sq. as % of Factor C	% of Total Variation	F-statistic
Factor B	1	5.3	5	22
Factor C	1	100	93	402
Interaction BxC	1	1.3	1	5.3
Pooled Interactions	4	1	1	

F=7.71 at 95%  
confidence

**FIGURE 10 - SEAL ACTIVATION FORCE ANALYSIS OF VARIANCE TABLE**

## Conclusion

Hyper-Elastic finite element analysis capabilities within the ANSYS program, allow engineers to rapidly evaluate and optimize complex non-linear material and contact behavior of rubber diaphragm seals prior to fabrication of costly proto-types and tooling. Hyper-Elastic seal analysis used in conjunction with factorial experimental design studies also help identify key design factors which contribute most significantly to product variation. Product development and analysis teams working together are applying this technology to bring robust seal designs and pushbutton products to Rockwell Automation customers.

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