Study of Feedback Controlled Variable Cone Expansion Process

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This paper will discuss a variable cone expansion of casings that is realized through a two-cone expansion system with a smaller sized, fixed cone at the front and a variable cone at the back. The variable cone can be moved between an expanded position and a retracted position. During expansion, the variable cone is enlarged to its expanded position and advanced through the casing until a restriction (e.g. smaller ID wellbore outside the casing) is reached. At the restriction, the variable cone is automatically retracted to allow passage through the restriction without incurring a large force. Once passing the restriction, the variable cone will return to its expanded position. The movement of the variable cone between its two possible positions is realized through a feedback controlled mechanism.

In this study, Finite Element Analysis (FEA) is used to investigate the potential influence of frictions between different parts within the system during the movement of the variable cone. Ways to increase the critical friction coefficient via fixed cone modification are also evaluated.

Keywords: Wellbore, feedback control, friction, critical friction, FEA

1. Introduction

Variable cone expansion technology allows a flexible one trip expansion of casing with restrictions, such as the small ID wellbore outside the casing, without inducing large expansion force. The variable cone expansion system consists of two cones, see Figure 1, one is a smaller sized fix dimension cone which is at the front and the other is a variable cone (or retractable cone), see Figure 2.

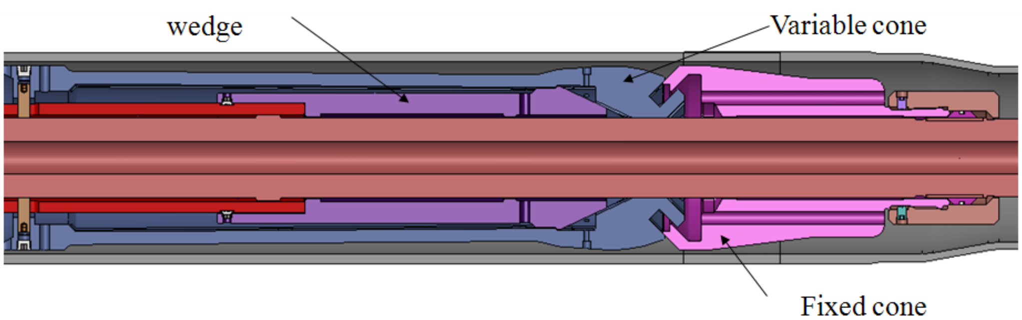

Figure 1. A Variable Cone Expansion System.

During the expansion process, the variable cone (see Figure 2) is enlarged to its expanded position and advanced through the casing until a restriction is reached. At the restriction, the variable cone is automatically retracted to allow passage through the restriction without incurring a large force. Once passing the restriction, the variable cone will return to its expanded position.

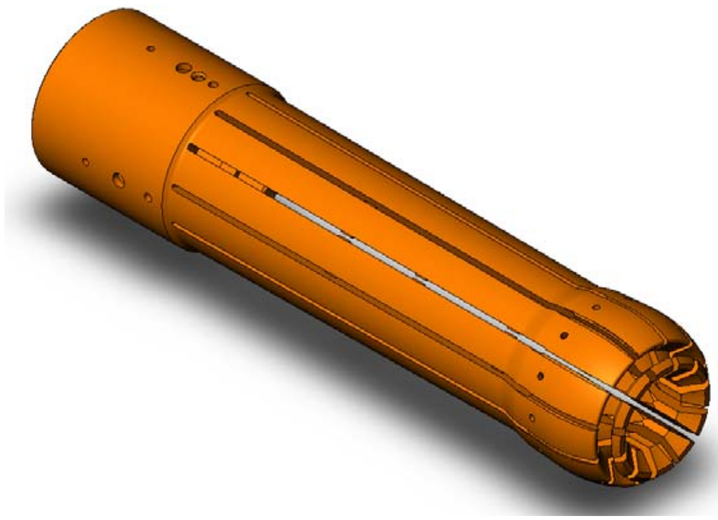

Figure 2. An example of a variable cone.

The movement of the variable cone is controlled by a feedback control system. The hydraulic feedback control process can simply be described as the force applied on the wedge, controlled by the force acted on the variable cone. When the force F1 on the variable cone is within certain range, the force applied on the wedge F2, has a certain relation to the force, e.g. F2= m F1. This will ensure that the variable is kept at its fully expanded position. When F1 is larger than the allowable quantity (Fmax), then F2 is decreased to a low value F0, allowing the variable cone to retract. The reverse is true as well: when F1 is within the range, the hydraulic feedback controller will ramp up F2 until F2=m F1, allowing the retracted variable cone to return to its expanded position once a restriction is passed.

During the development process, FEA is used to verify designs and then to help with the optimization process. The success of variable cone expansion depends on many design and operating parameters. The parameters studied in the numerical simulations are friction coefficient, cone geometry, and controller multiplier (m). Specifically, focus on the influence of friction coefficients between cone and pipe, and wedge and variable, and on determination of critical friction coefficient. The critical friction coefficient signifies a value when friction coefficient is larger than this value, the expansion system will self-lock, preventing the variable cone from reaching its designated expanded position. One way to improve and optimize the variable cone expansion system is to increase the system critical friction coefficient. The study on cone geometry and controller force multiplier is to find directions to increase critical friction coefficient.

Preliminaries on critical friction coefficient and verification of FEA representation of feedback control process are presented in Section 2. An FEA model for the variable cone expansion process is described in Section 3. Section 4 will reveal the findings from numerical simulations of the variable cone expansion process, including critical friction coefficient for a design, and influence of cone design and force multiplier on critical friction coefficient.

2. Preliminaries

Since critical friction coefficient is not a common parameter used in mechanical design considerations, the concept of critical friction coefficient is recapped in lieu of friction angle. By the same token, the modeling of a feedback controlled process is not common in the practice of finite element analysis; the method is described and verified via a simple example.

2.1. Critical Friction Coefficient

For this application, consider the scenario that an object is pushed up a wedge via a horizontal force; (see Figure 3), assuming the friction coefficient between the object and the wedge is μ.

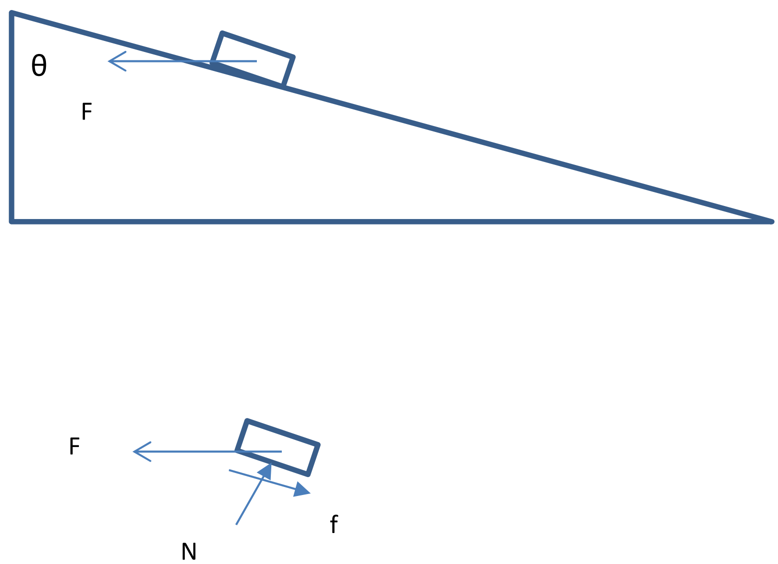

Figure 3. Illustration of critical friction concept and a free body diagram.

To push the object up the wedge, it is required that:

$$\mu F \cos\theta \le F \sin\theta \quad \text{or} \quad \mu \le \tan\theta = \mu_c$$

For this case, when friction between the object and the wedge is smaller than critical friction coefficient, the object can be pushed up the wedge by a horizontal force. Otherwise, it does not matter how large F is, the object cannot be pushed up the wedge, and the system is self-locked.

It is noted that the critical friction coefficient is a structural property. In this example, the larger the angle θ, the larger the critical friction coefficient is.

For the variable cone expansion system, there are four objects in contact with each other, and there are two forces (F1, F2) applied to the system, so the critical friction coefficient cannot be calculated by a simple formula as in this example. The concept helps to identify qualitative direction for design changes.

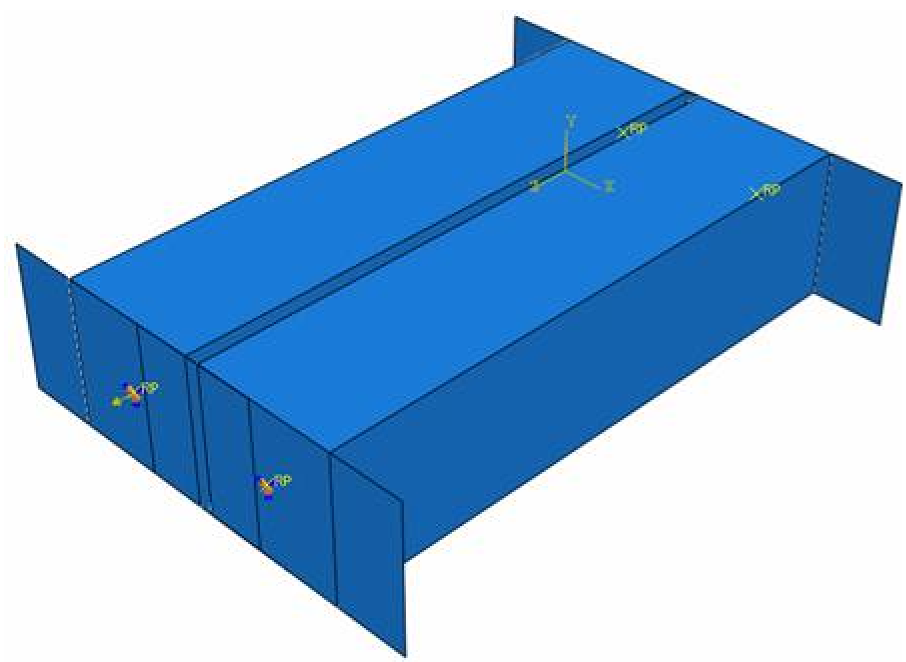

Figure 4. A simple model to verify feedback control function.

2.2 Verification of feedback control in FEA model

This work was performed before a user defined sensor was available in ABAQUS, and a user element was developed to achieve the feedback control. The function of the user element, however, is achieved via a user defined sensor. Thus the details of the user element are not presented. Only the verification of the feedback control function is given. It is noted for the user defined sensor, one still needs to write a user subroutine to relate controlled load to active load.

The verification is performed on a very simple model. Figure 4 consists of two separate rectangular blocks, the force on block F1, is applied, the controlled force F2 is applied on the other block. The control scheme is:

F1= 0 to 9196.25lb

F2= 1.32*F1 if F1< 8539.38lb

F2= 3120.16 if F1 >= 8539.38lb

The active load is applied as follows; it is first ramped up to 10,000 lb., and then ramped down to zero. It is ramped up again to 10,000 lb., and is kept there.

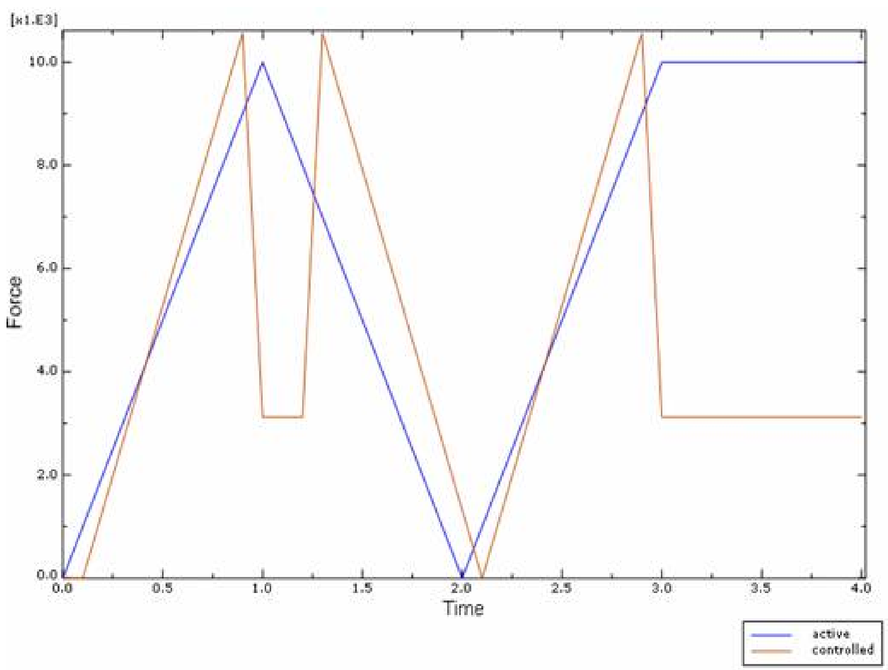

Figure 5. Variation of F2 per the assumed F1 and the control scheme.

Variation of F2 per the assumed F1 and the control scheme is shown in Figure 5. The blue curve is the active load; the brown curve is the controlled force. There is a delay in controlled force magnitude. The controlled force varies as specified per the control scheme except it has a time delayed response. The delay, of course, is expected for a hydraulic controller. It is noted that the delay can be reduced by a decreased time increment in the FEA model.

3. The model for variable cone expansion process simulation

For the purpose of this study, the geometry of the variable cone expansion system (Figure 1) is simplified in several aspects. Simplification is mainly made on the variable cone. The real variable cone is connected to tubing via long slender arms. In the FEA model, the long arm is neglected and represented as the following in Figure 6. The restriction on the variable cone axial motion is approximated by additional ledger on the wedge. Some small features, such as drainage holes, etc. are removed. Due to these simplifications, the geometry of the expansion system has symmetry, only 1/24 of the model is needed for the numerical simulation. The simplified 1/24 model is shown in Figure 7.

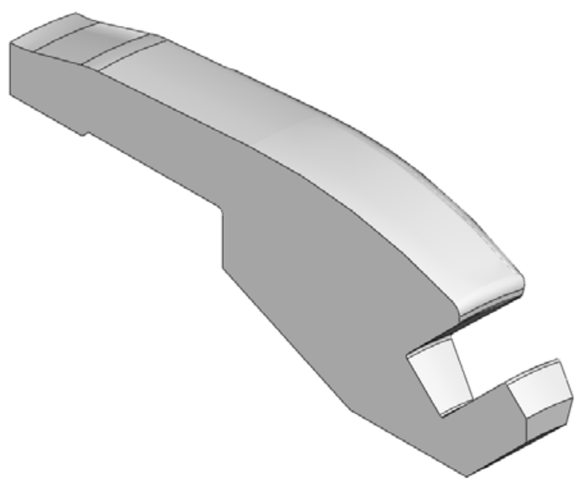

Figure 6. Simplified variable cone - shown one branch only.

Figure 7. FEA model for the simplified variable cone expansion system.

To simulate the loading conditions accurately, the variable cone is fixed axially by a rigid surface but can move radially, the active load is the force pulling the casing. The wedge is pushed under the controlled load.

The control scheme is as follows:

F2=1.32 F1 when F1 < 205kips

F2= 74.9kips when 205kips < F1 < 220.7kips

System load is capped at 221kips

The base design has a fixed cone with a 7 degree angle, and 7.10" OD, the expanded variable cone has a maximum OD of 8", and the pipe material is 316L. The original pipe is7" OD.

4. Study of Friction Effect on Variable Cone Expansion Process

As discussed earlier, the success of variable cone expansion depends on many design and operating parameters. The parameters studied in the numerical simulations are friction coefficient, cone geometry, and control multiplier (m). Specifically, we focus on the influence of friction coefficients between cone and pipe, wedge and variable, and on determination of critical friction coefficient.

4.1 Determination of Critical Friction Coefficient for the base design

The cone/pipe friction coefficient is different from those of cone/cone and wedge/cone friction coefficients. The cone pipe friction coefficient is typically very small due to coating on cone OD; the cone/cone, and cone/wedge friction coefficients are assumed to be same.

The critical friction coefficient is determined straight forward, the wedge/cone friction coefficient is varied from low to high to see when a variable cannot reach its fully expanded position (i.e. 8" OD).

The cone/pipe friction coefficient is determined to be around 0.05; the wedge/cone friction varies from 0.15 to 0.2 and 0.25. For μ=0.2, Figure 8 shows the configuration of the expansion system at a steady state stage: the variable cone reached the axial restriction represented by the ledge, thus the variable cone is at the desired expanded state with an OD of 8"; when μ = 0.25, the variable cone did not reach the axial restriction represented by the ledge (see Figure 9), thus the variable cone OD is smaller than 8", the pipe is under expanded. The full expansion and under expansion at the two conditions are illustrated in Figure 10, which shows the expansion force – stroke curves for the two cases. It is obvious that the expansion force for 0.25 friction case is substantially smaller than that of 0.2 friction case due to under expansion. A comparison of variable cone OD change for μ=0.15, 0.2 and 0.25 is given in Figure 11. Several observations can be made: 1) the higher the friction, the longer it takes a variable cone to reach expanded 8" OD; 2) when friction is too high, the variable cone OD change is much smaller; 3) A critical friction coefficient exists between 0.2 and 0.25. It is determined on the conservative side that critical friction for this case is 0.2.

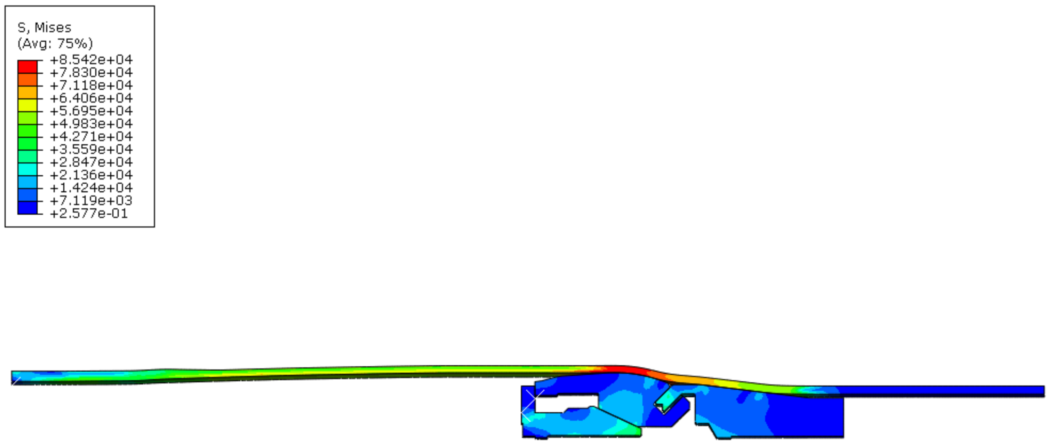

Figure 8. Wedge/cone friction coefficient = 0.2, variable cone reached 8" OD expanded state.

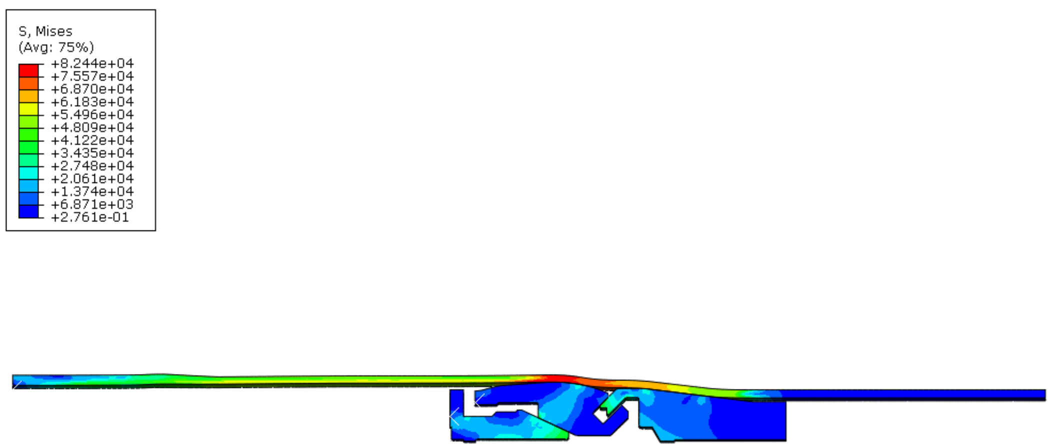

Figure 9. Wedge/cone friction coefficient = 0.25, variable cone did not reach fully expanded state.

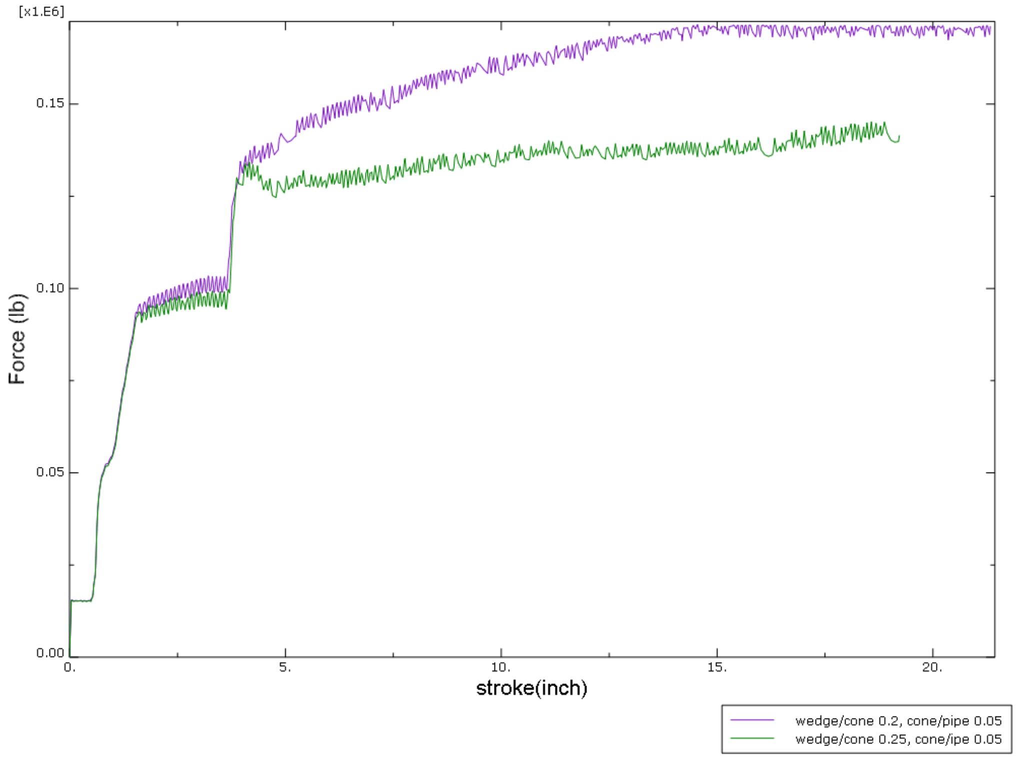

Figure 10. Expansion force vs. stroke.

It is interesting to note that when cone/pipe friction is reduced, (e.g. from 0.05 to 0.03), the critical friction coefficient decreases as well. In the case of cone/pipe friction = 0.03, the variable cone cannot reach fully expanded state, as shown in Figure 12. In fact for this cone/pipe μ=0.03, the critical friction coefficient is 0.15. So it is reasonable to say that critical friction coefficient between wedge and variable is dependent of geometry, load, and the friction between cone and pipe which change direction of load transferred from fix cone to variable cone.

To have a robust and reliable variable cone expansion process, it is desirable to make the critical friction for the expansion system as large as possible. There are several factors that can influence critical friction coefficient such as fixed cone angle or magnitude of force multiplier for the controlled load. The change in expansion process with the change in these two parameters is discussed next.

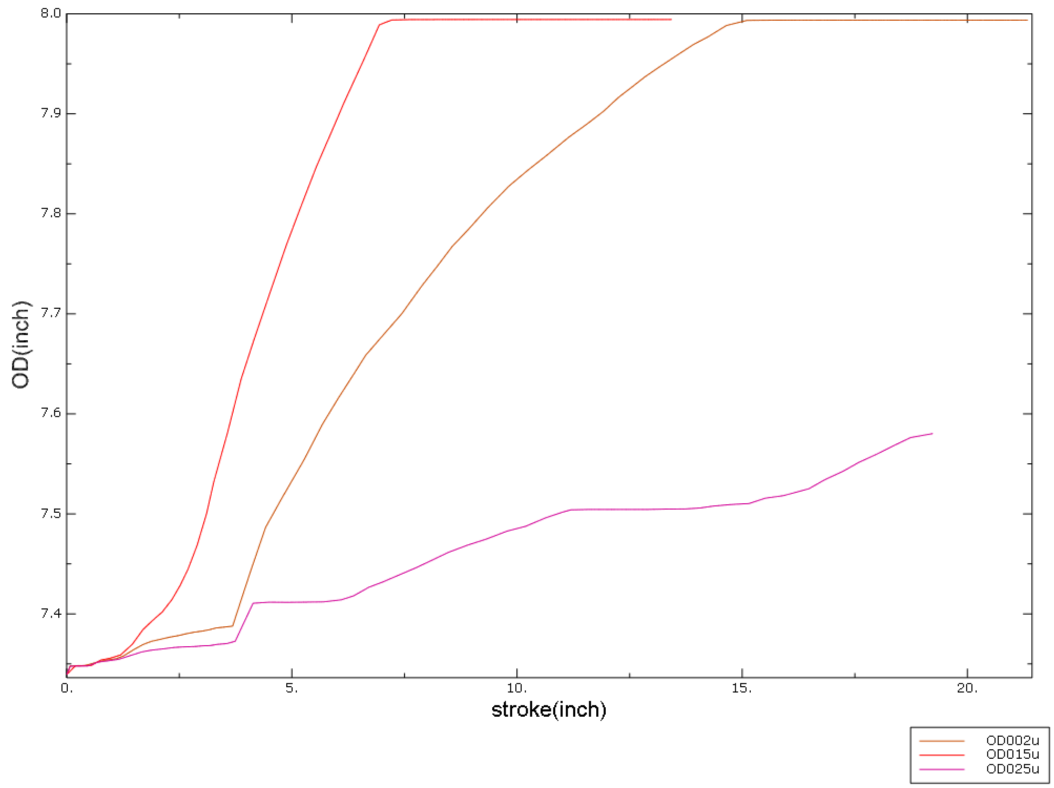

Figure 11. Variable cone OD change at different friction coefficients.

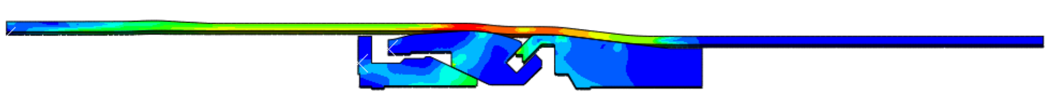

Figure 12. Variable cone cannot reach expanded state for cone/pipe μ = 0.03, wedge/cone μ = 0.2.

4.2 Design Considerations

Among many possible design parameters that can lead to change in critical friction coefficient, the cone angle and force multiplier can be considered in the FEA formulated here. Increase force multiplier. First the effect of cone angle is considered for the case of cone/pipe μ=0.03, the cone angle is increased from 7 degree to 10 degree, the variable cone OD change with stroke is given in

Figure 13. For this case, the critical friction coefficient is approximately 0.225, this compares to 0.15 critical friction coefficient for the 7 degree angle fix cone. So increased cone angle helps to increase the critical friction coefficient.

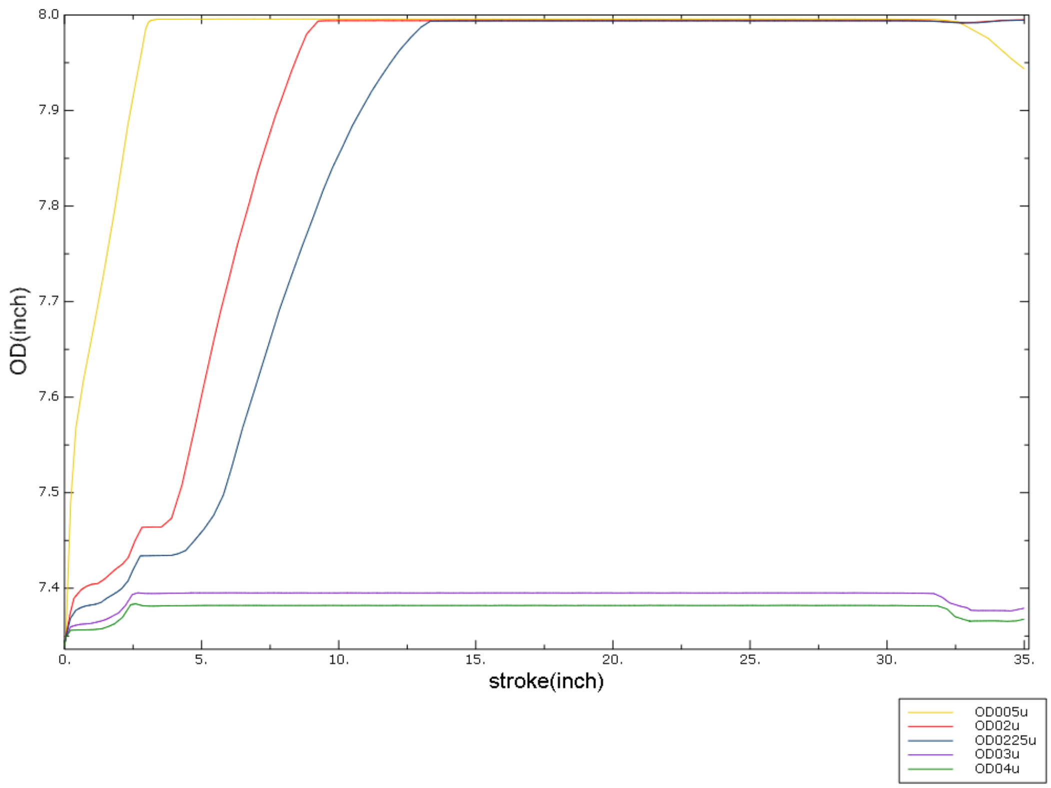

Figure 13. Variable cone OD change for cone/pipe μ=0.03, varying wedge/cone friction.

Another way to increase critical friction coefficient is to increase the wedge force multiplier – F2=**m**F1. The increase of the wedge force multiplier can be achieved in several ways such as adjustment of piston area(s) subject to system axial force limitation (to prevent pulling threads apart). Next, the effect of increasing of the multiplier from 1.32 to 1.82 is investigated.

For cone/pipe friction 0.03, 10 degree cone angle, the critical friction coefficient is 0.375, which is a significant increase from 0.225 as shown in figure 14. At this critical friction coefficient, it takes long strokes for the variable cone to reach expanded cone OD at 8” (see Figure 15).

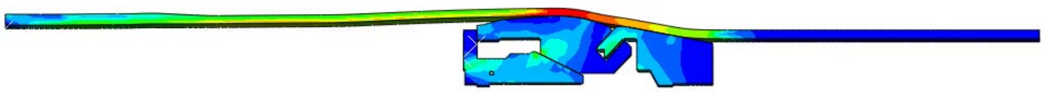

Figure 14. Force multiplier 1.82, cone angle 10 degree, cone pipe friction 0.03, cone wedge friction 0.375.

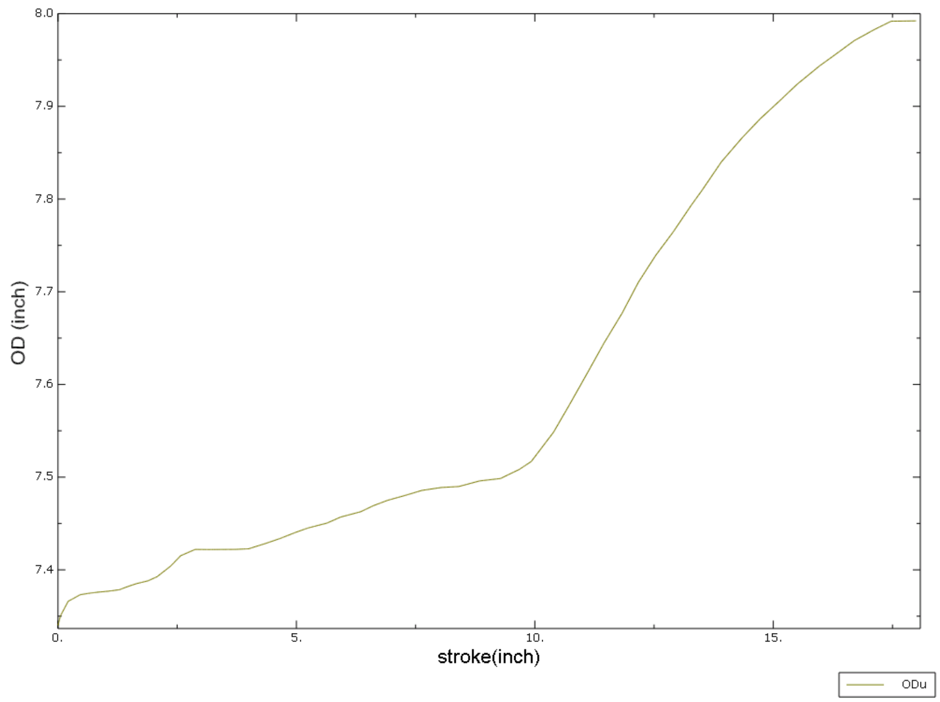

Figure 15. Force multiplier 1.82, cone angle 10 degree, cone pipe friction 0.03, cone wedge friction 0.375: variable cone OD change with stroke.

5. Summary and Discussions

The method developed for simulation of feedback controlled load is verified to function as designed. The method is successfully applied to determine critical friction coefficient for two fixed cone designs under different scenarios. The critical friction coefficient between production cone and wedge is between 0.2 and 0.25 for cone/pipe friction 0.05; it is between 0.15 and 0.2 for cone/pipe friction 0.03. The modified fixed cone, 7.25"/10 degree cone, under same conditions, would lead to higher critical friction as expected, ~ 0.225 for cone/pipe friction 0.03. An effective way to increase critical friction is to increase wedge force/expansion force ratio. Under cone/pipe friction 0.03, the critical friction increased from 0.225 to 0.375.

It is noted that the numerical models do have some limitations compared to physical tests or well operations. In the real world, friction has a wide range of values between static, dynamic, new, seated in, and low loading to high loading. In the models, constant friction is assumed. Pressure dependent friction coefficient can be included in the FEA model which will need to develop another user subroutine. Secondly, vibration of the expansion system during operation can influence the expansion process, which is not accounted for in the FEA model.

More generally, it is observed that critical cone/wedge friction is dependent of cone/pipe friction. The higher the cone/pipe friction, the higher the critical cone/wedge friction. When wedge/cone friction is near critical friction, it takes long strokes for the variable cone to move to its maximum OD, which seems to be the case in the well tests. This further enforces the viewpoint that wedge/cone friction is a main culprit for the under expansion observed in the physical tests.

FEA and approximate engineering calculation agree with each other quite well qualitatively. FEA does provide additional insight into the design and test evaluation, both in quantitative evaluation and load-path dependence of the expansion process.

The findings of this study helped to improve a variable cone expansion system for 7” pipe expansion. The system level physical test was successfully completed with full expansion of all components, with variable expansion through targets, connections, and etc. (Gano, 2008)

6. Reference

Gano, J.C. (2008), One Trip Variable Cone Expansion Tool System Validation System Integration Test, Halliburton Technology Test Report

7. Acknowledgements

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