Influence of Interaction Between Oil and Rubber on Valve Stem Seal Oil Leakage

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Abstract: The valve stem seal is an important part of any internal combustion engine. The seal supplies a lubrication of valve stem and limits emission of oil. To design reliable and long-life stem seals a numerical simulation of the seal work is used. Numerical simulation helps to understand the main features of the stem seal working cycle and estimate the changing seal characteristics because of seal aging processes. The problem of oil flow via stem seal involves fluid-structure interaction between an oil flow induced by oscillating stem and deformable seal made from rubber. The Fluid-Structure Interaction Problem is solved numerically by using two codes: Abaqus/Explicit to get deformation of rubber seal and CFD code FlowVision to simulate oil flow. Both codes are two-way coupled by Multi Physics Manager. Simulation of the oil leakage through valve stem seal was studied for different engine rpm and for different rubber elasticity. Results from analysis show the strong dependence of the leakage on engine operating condition and elasticity of the rubber. Increasing engine speed and elasticity of the rubber result in increasing oil leakage through the seal. Moreover, increasing elasticity resulted in faster growth of the leakage with higher engine rpm. Also we found that during stem oscillation the rubber has complex motion. This motion results in wave-like changing of the clearance between the valve stem and the seal. Investigation of this effect allows predicting more accurately the properties of the valve stem seal.

Keywords: Fluid-Structure Simulation, Rubber seal, CFD coupling, Valve stem seal, Hyperelasticity, Lubrication.

1. Introduction

Simulation of Fluid-Structure interaction is one of the challenging branches of computational mechanics. Recent advances in finite-element analysis codes and final-volume methods allow solving this complex problem with reasonable accuracy for suitable time. As state-of-the-art of industrial codes, finite-element method with Lagrange description of moving media is base of codes for simulating flexible structures, finite-volume methods with Euler description of motion is base of codes for fluid simulations. Coupling these two methods for solving fluid-structure interaction problems is hard work of investigators for past several years. There are several methods and approaches for solving this problem, one of them is used in this paper to solve problem of oil leakage in stem seal.

Our approach of coupling finite-element analysis code like ABAQUS with CFD code FlowVision is based on Sub-Grid Resolution Method (Aksenov et al, 1996, Aksenov et al, 1998). This method is based on cutting cells of fluid computational domain by outer surface of finite-element grid. After cutting cells a link between finite elements and finite volumes is established and used for transferring boundary conditions from one grid to another (A. Aksenov et al, 2004) . Control of the both codes (ABAQUS/Explicit and FlowVision) and transferring data between them are supplied by Capvidia's Multi-Physics Manager.

This work is continuation of the paper published at previous ABAQUS Conference AUC2005 (A. Aksenov et al, 2005). Previous paper consisted in description of method for solving Fluid-Structure Interaction problem and state of the problem of oil leakage through stem seal. This paper has the goal to give results of the simulation.

Simulation of the oil leakage through valve stem seal was studied for different engine rpm and for different rubber elasticity. Results of analysis show the strong dependence of the leakage on engine operating condition and elasticity of the rubber. Increasing engine speed and elasticity of the rubber result in increasing oil leakage through the seal. Moreover, increasing elasticity resulted in faster growth of the leakage with higher engine rpm. Also we found that during stem oscillation, the rubber has complex motion. This motion results in wave-like changing of the clearance between the valve stem and the seal. Investigation of this effect allows predicting more accurately the properties of the valve stem seal.

2. Oil Stem Seal

Detail description of a typical valve seal is done in our previous paper [1] and is shown in Figure 1. The main parts of the valve seal are the rubber sealing lip, spring and the retainer. Sealing is pressed by spring to stem to limit oil leakage through stem seal.

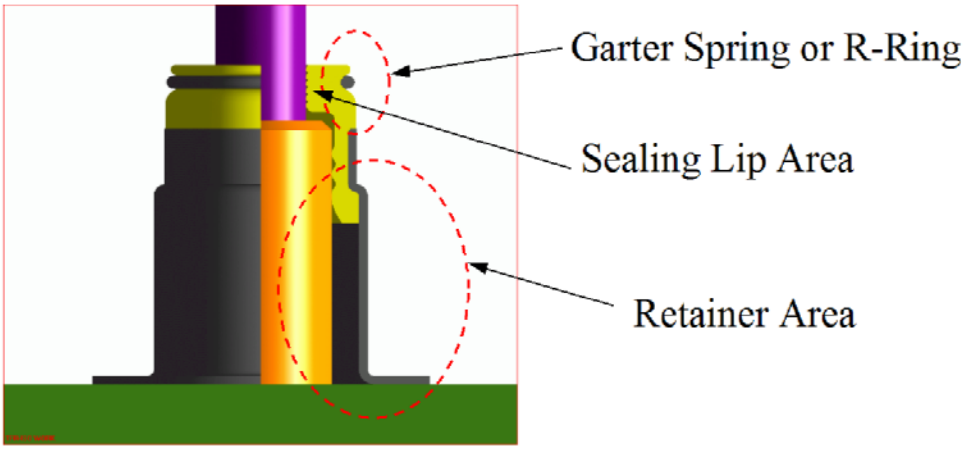

Figure 1 Oil Valve Stem Seal

3. Calculation Domain & Boundary Conditions

Fluid and rubber computational domains are shown in Figure 2. For CFD computations the Clearance Model [1] is used to model oil flow inside clearance between stem and rubber, amount of CFD cells is about 2000. Boundary conditions are shown in Figure 3. At bottom of computational domain is specified relative Pressure of 1 atm, at upper side - 0 atm.

Simulation was made with following main assumptions:

Stem moves with periodic low (Figure 4) $V = V_0 \cdot \sin\left(\frac{2 \cdot \pi \cdot t}{T}\right)$, where V_0 (amplitude of stem speed) and T (period of stem oscillation) depend on engine operation condition. Fatigue of rubber seal is not considered and behavior of material of rubber seal is simulated without residual deformation. Simulation was made for two rubber seals with different material properties for several regimes (Figure 5).

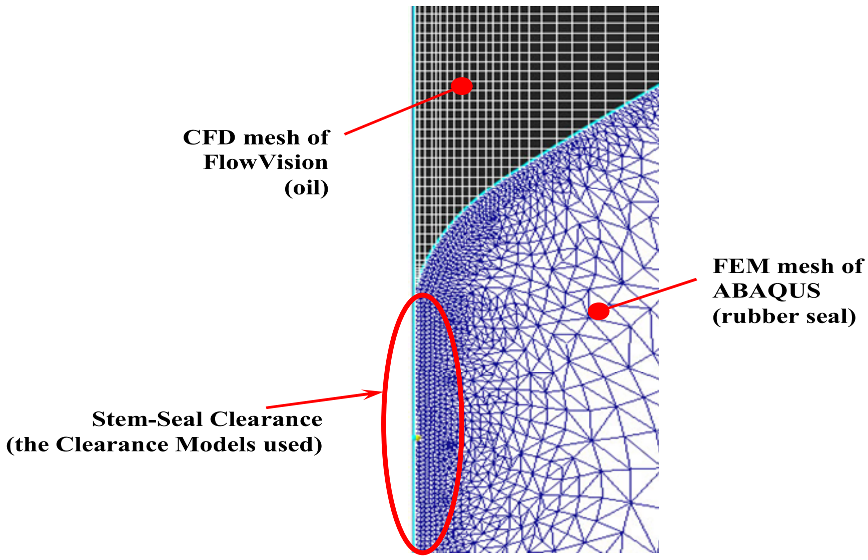

Figure 2 CFD and FEA meshes for FSI simulation

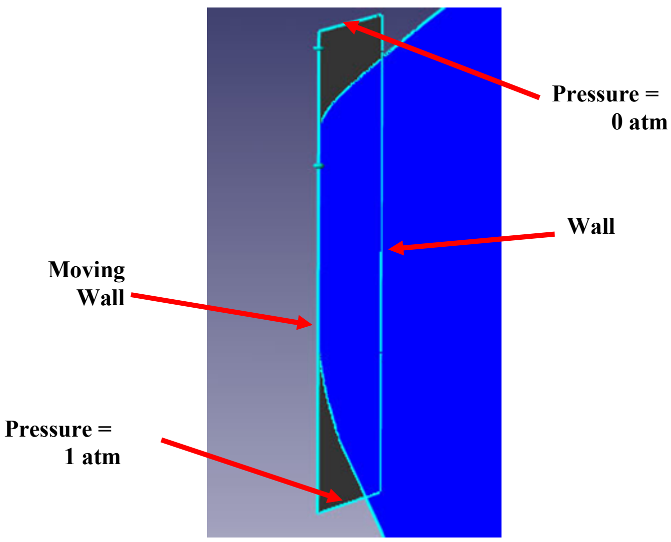

Figure 3 CFD Boundary Conditions

Table 1 Main parameters

Engine regime	V_0, m/sec	T, sec
R1	0.818	0.0311
R2	1.226	0.0467

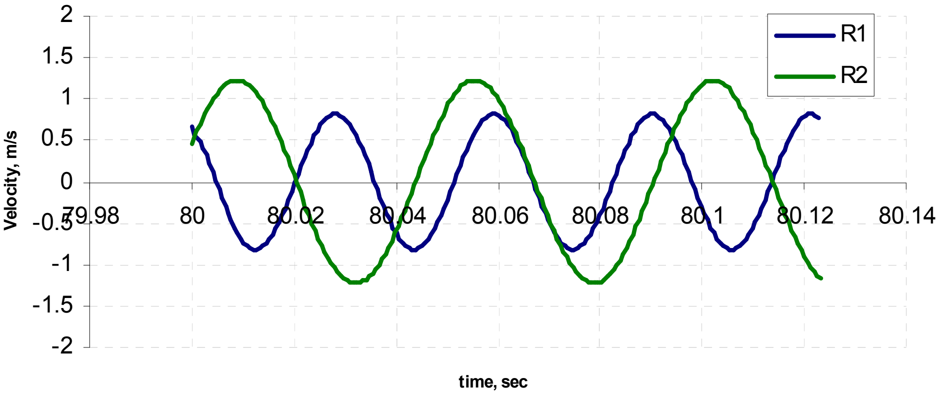

Figure 4 Stem cycles for different engine operation conditions

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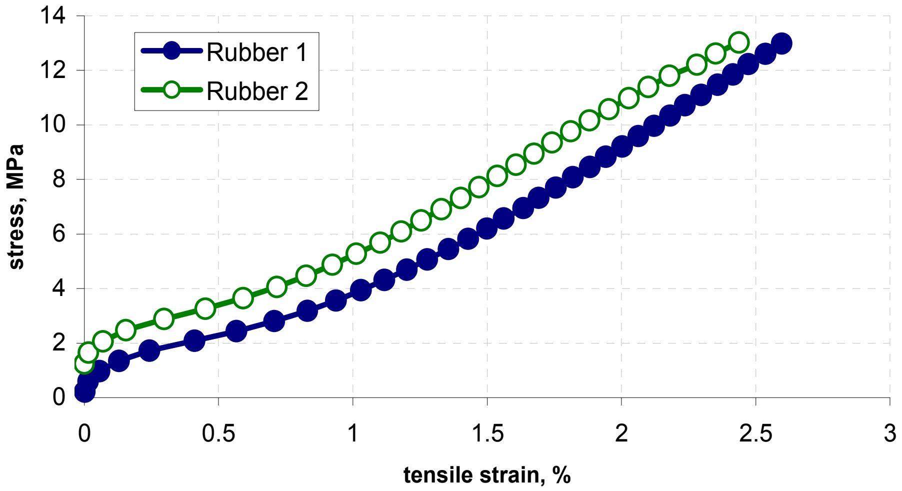


Figure 5 Material properties for different rubbers

4. Analytical estimations of oil pressure distribution in clearance

Let's estimate pressure distribution inside the clearance. Assume here that the stem motion has a constant speed, the rubber has no speed at all, the clearance is small and the Reynolds number is less than 1, and there is no effect of oil cavitation. In this case we can assume that along the clearance we have a superposition of Poisson flow (because of non-zero oil leakage via clearance) and linear shear flow (because of the stem motion and still rubber surface).

4.1 Nomenclature

L	length of the stem/seal clearance
x	distance along stem
W	speed of the stem
Q	volumetric leakage flow rate along clearance, m^2/s (for 1 meter of clearance width)
δ	clearance between stem and rubber, function of x
P_0	pressure P at x=0
P_1	pressure P at x=L

4.2 Pressure distribution

Let's write the truncated Navier-Stokes where we neglect convective terms and assume that the oil speed normal to stem direction is small. A pressure gradient along stem in clearance will be defined by the superposition of two forces. The first one is stress in shear flow

$$\mu \frac{W}{\delta^2} .$$

Another force is stress between two planes with non-zero fluid flow along parallel planes (so-called Poisson flow)

$$-\mu 12 V(x) \frac{1}{\delta(x)^2} .$$

As is incompressible fluid so oil flow rate along clearance is constant value. Oil leakage Q is sum of Poisson flow rate of the oil and flow rate because of shear flow:

$$Q = V\delta + \frac{1}{2} W\delta$$

Value of Q is normalized by length of the clearance over stem 2πr , where r is stem radius, that is why it has units m^2/s. Now we can express Poisson flow rate via Q

$$V = \frac{Q}{\delta} - \frac{1}{2} W$$

Write governing equation for estimation pressure distribution along clearance:

$$\frac{dP}{dx} = \mu\left(\frac{W}{\delta^2} - 12 \frac{\frac{Q}{\delta} - \frac{1}{2} W}{\delta^2}\right)$$

Or after transforming:

(1) $$\frac{dP}{dx} = 12\mu\left(\frac{W}{2\delta^2} - \frac{Q}{\delta^3}\right)$$

Integrating (1) over x gives

(2) $$P(x) = P_0 + \mu(A(x)W + B(x)Q)$$

Where

(3) $$A(x) = 6\int_0^x \frac{dx}{\delta(x)^2}$$

(4) $$B(x) = -12\int_0^x \frac{dx}{\delta(x)^3}$$

As $P(L) = P_1$, we can find unknown leakage Q

$$P_1 = P_0 + \mu(A(L)W + B(L)Q)$$

(5) $$Q = \frac{\frac{P_1 - P_0}{\mu} - A(L)W}{B(L)}$$

And finally expression (2) is:

(6) $$P(x) = P_0 + \mu WA(L)\left(\frac{A(x)}{A(L)} - \frac{B(x)}{B(L)}\right) + \frac{B(x)}{B(L)}(P_1 - P_0)$$

From (5) and (6) we can do interesting consequents:

1) If the clearance is constant, that is A(x)/A(L) = x/L and B(x)/B(L)=x/L, we have linear distribution of pressure along clearance:

$$P(x) = P_0 + x(P_1 - P_0)/L$$

2) If inlet and outlet of the clearance are blocked, that is leakage Q=0, the pressure difference over clearance depends on linearly of stem speed

$$P_1 - P_0 = \mu A(L)W$$

For oil with viscosity 0.00952 kg/(m s), length of seal 1 mm and clearance 1micron the pressure difference is equal approximately 10 MPa.

4.3 Pressure distribution for model clearance

Let's solve (6) for configuration of the stem very close to real clearance between stem and seal. The form of the clearance (in logarithmic scale) is in Figure 6 . Minimum clearance is equal 1 micron, with small inclination along clearance from 1micron to 2 microns (see Figure 6). P_0 and P_1 equal 0 and 10^5 Pa respectively, speed is -0.8 m/s (stem is moving in negative direction to x axis). Maximum pressure is 2.5 MPa. If the stem is moving with positive speed (Figure 7) the pressure has negative values with a minimum value -2.5 MPa. Of course, in reality such big pressure cannot be realized because of non-rigid seal and beginning oil cavitation process in clearance.

Simulation of seal without any oil (zero clearance) in ABAQUS shows that maximum contact pressure is 6.82 MPa (Figure 8). This pressure can be achieved for small clearances. In Figure 6 one can see the channel with minimum clearance 0.6 micron. Maximum pressure is about 6 MPa. Thus, if our estimation is true we can say that lubrication exists at clearances in range of 0.5 - 1 micron.

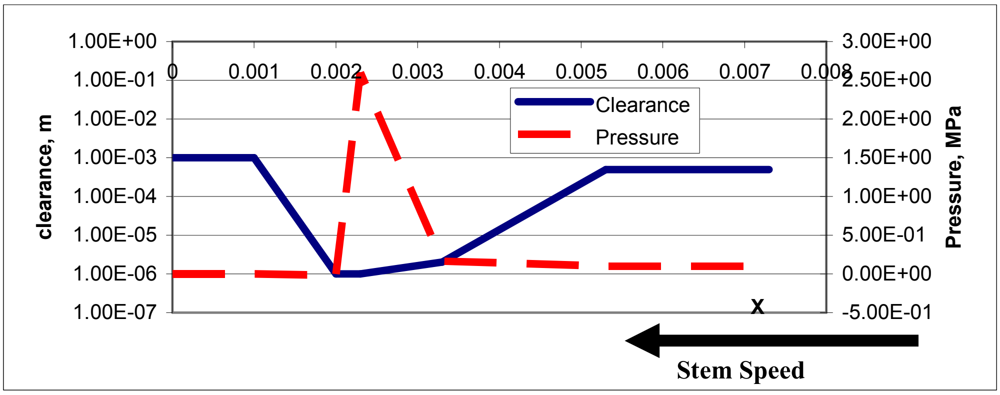


Figure 6. Clearance and Oil Pressure as function of the distance along stem.
Stem has speed – 0.8 m/s, minimum clearance is 1 micron

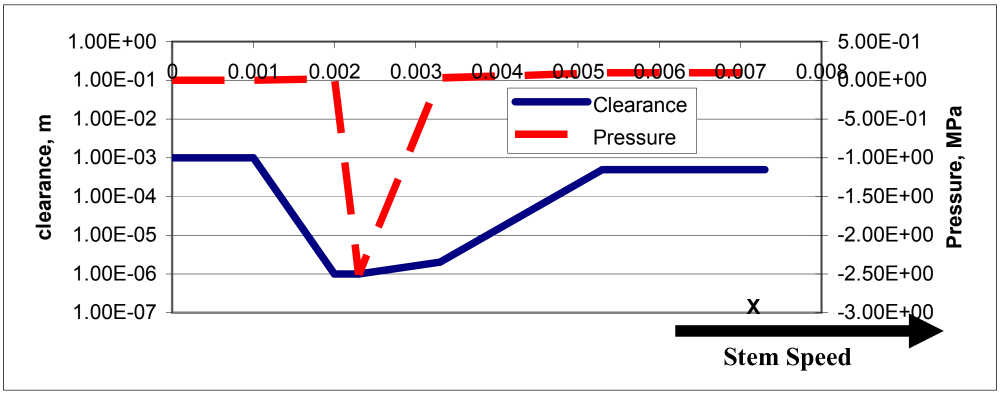


Figure 7. Clearance and Oil Pressure as function of the distance along stem. Stem has speed + 0.8 m/s

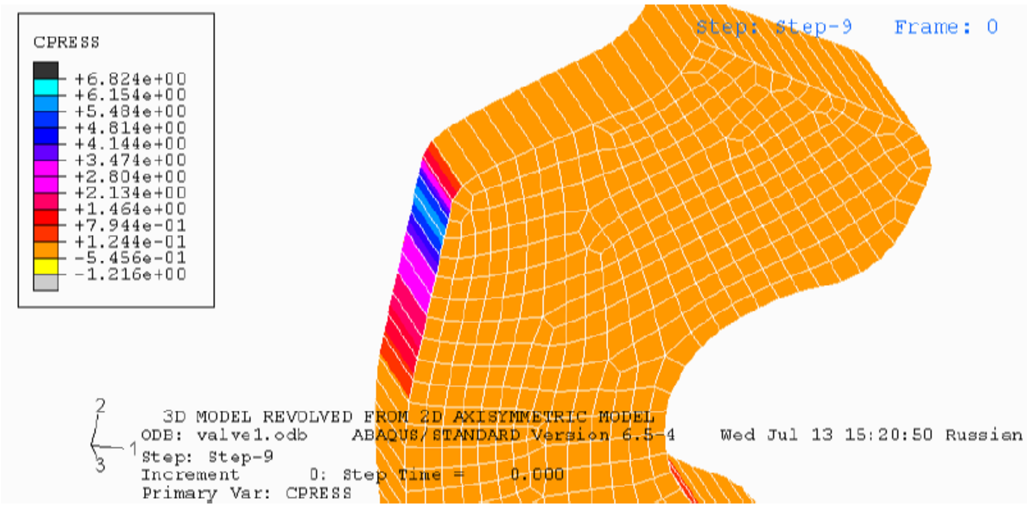


Figure 8. Clearance and Oil Pressure as function of the distance along stem.
Stem has speed + 0.8 m/s

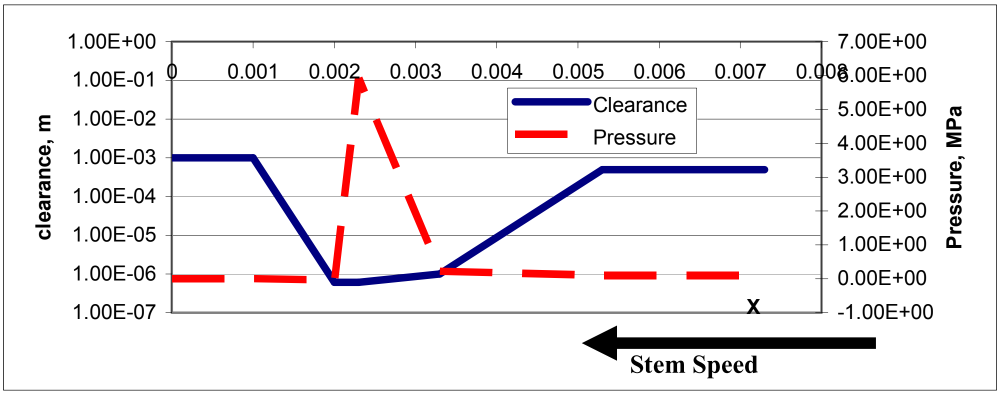


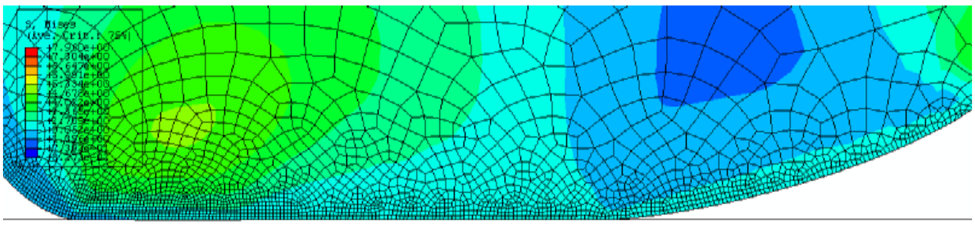
Figure 9. Clearance and Oil Pressure as function of the distance along stem. Stem has speed – 0.8 m/s, minimum clearance is 0.2 micron

5. Results of Fluid-Structure Simulation

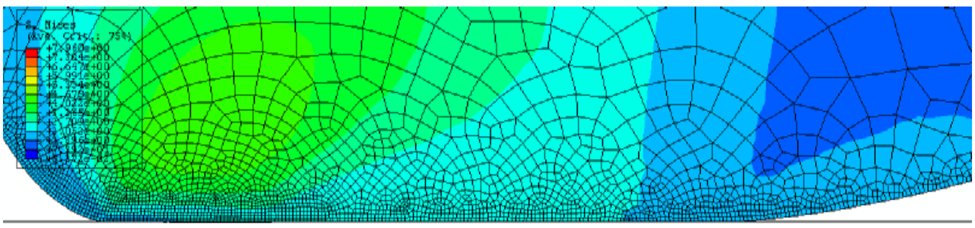
5.1 No stem motion

To estimate deformation of the rubber under static oil pressure the following task is solved. A small initial clearance 0.4 micron is specified between stem and rubber to form initial channel for oil. Pressure difference of1 bar is specified along clearance. Distribution of the stress in rubber seal for Rubber 1 and 2 is shown in Figure 10 (in this figure pressure is bigger on the right). One can see the maximum stress in region of seal lip area. The rubber is deformed during oil motion in clearance between stem and seal. It results in change of the clearance value. The maximum clearance change is in the contact area that is away from maximum stress region (in right in Figure 11)

Deformation of rubber is defined by only pressure at down side of the seal in case of unmoved stem. Pressure is changed almost linearly through the clearance (Figure 11b). This pressure distribution causes a small change of the clearance shape for different rubber materials. Softer material Rubber 1 has larger deformation (Figure 11a). Average clearance for different materials and the unmoved stem is shown in Table 3. For Rubber 2 (more rigid material) the average clearance is 6% less.

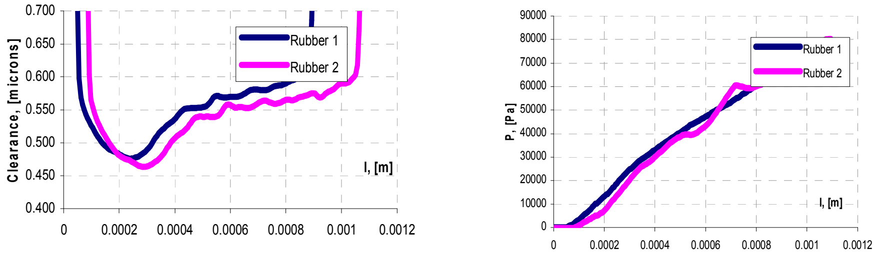


a)



b)

Figure 10 Stress distribution and deformation
a) Rubber 1; b) Rubber 2



a) b)

Figure 11 Distribution of main variables along clearance
a) clearance; b) relative pressure

Table 3 Average clearance along gap

Rubber 1	0.54 micron
Rubber 2	0.51 micron

5.2 Stem motion (regimes R1 and R2)

5.2.1 Varying Clearance in Time

Direction of the stem motion, as shown in [2], influences the pressure distribution of the clearance and the shape of the clearance. The average clearance is always smaller when the stem is moving down than when the stem is moving up (Table 4). One can see that the average clearance is bigger for rigid materials of rubber.

Table 4 Average clearance along gap, microns

	Regime 1		Regime 2	
	Stem moves Up	Stem moves Down	Stem moves Up	Stem moves Down
Rubber 1	2.594	1.44	3.03	2.67
Rubber 2	1.74	1.37	2.16	1.65

The rubber is deformed during stem motion by the influence of oil flow in clearance. It results in complex deformation of the clearance in time. The characteristic deformation of the clearance is shown in Figure 12. Two qualitative deformations exist: primary deformation and secondary. Primary deformation exists for all materials and regimes; secondary deformation occurs generally for more elastic materials. It is interesting that secondary deformation has wave-like form in the clearance. From our point of view the generation of waves must be investigated by both simulation and experimental methods from point of view to be useful for the next generation of stem seals.

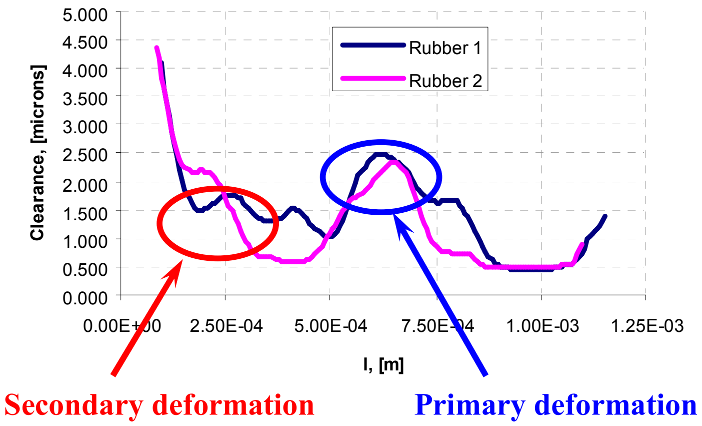


Figure 12 Effects of clearance deformation

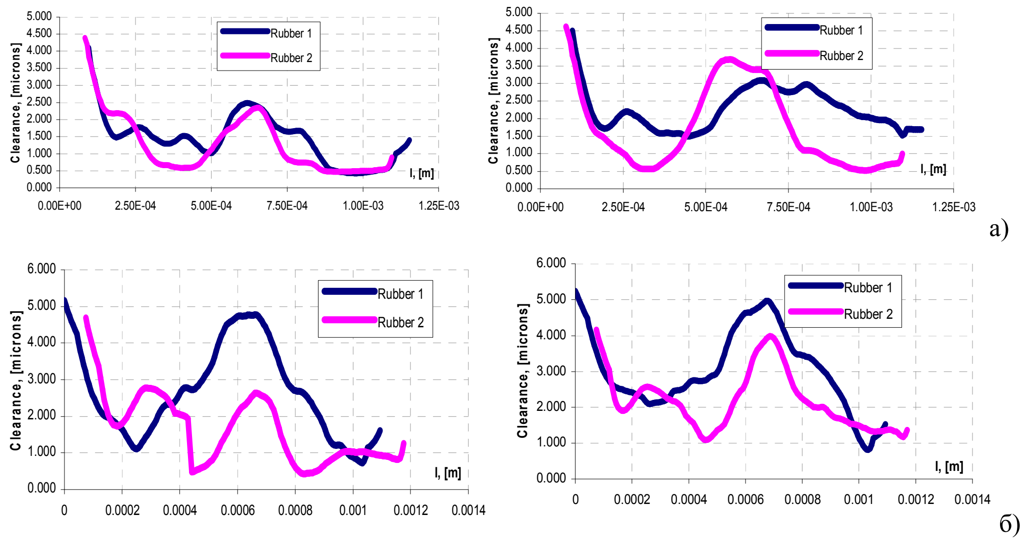


Figure 13 Clearance changing along stem
a) Regime 1 b) Regime2 (in left – stem moves down, in right – up)

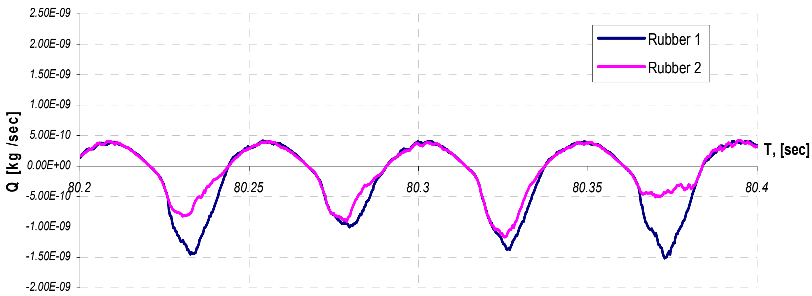
The change of the clearance along the stem is shown in Figure 13 for different frequencies of stem motion and for different materials of rubber. One can see that length and value (amplitude of clearance) of Primary deformation is increasing with growth of the frequency and material softness. Secondary deformation is significant for soft rubber. But it also appears for more rigid rubber at high stem frequency. The Maximum clearance that can be achieved is 4 or 5 microns during stem motion.

5.2.2 Oil leakage

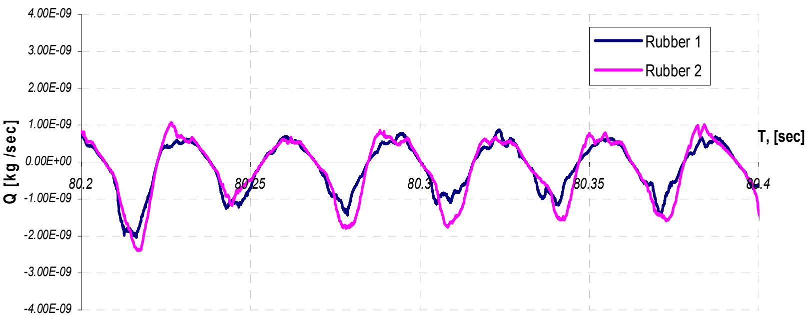
Harmonic oscillations of the stem results in oscillation of the clearance both in normal and along stem directions, as was shown in previous section. This complex change of the clearance results in non-harmonic change of the oil leakage Q(t) through the stem valve seal over time (Figure 14) with the main frequency corresponding to stem speed and additional frequencies corresponding to rubber oscillations. To find oil leakage Q_a through stem seal an averaging procedure is applied for Q(t).

Average oil leakage Q_a through valve stem is shown in Figure 15 for all simulated regimes and materials. One can see that the increasing speed of the stem oscillation results in increasing oil leakage. Change of oscillation from regime 1 to regime 2 results in 31% leakage growth for Rubber 1, for Rubber2 – 35% growth.

Increasing elasticity of the rubber results in increasing the oil leakage through the seal. For stem oscillation R1 Rubber1 has 26.6% leakage excess in comparison with Rubber2. For regime R2 excess is 22%. Thus, increasing elasticity results in not only growth of the oil leakage but also growth of the oil leakage rate with increasing speed of engine rotation.



a)



b)

Figure 14 Oil leakage a) Regime 1; b)Regime 2

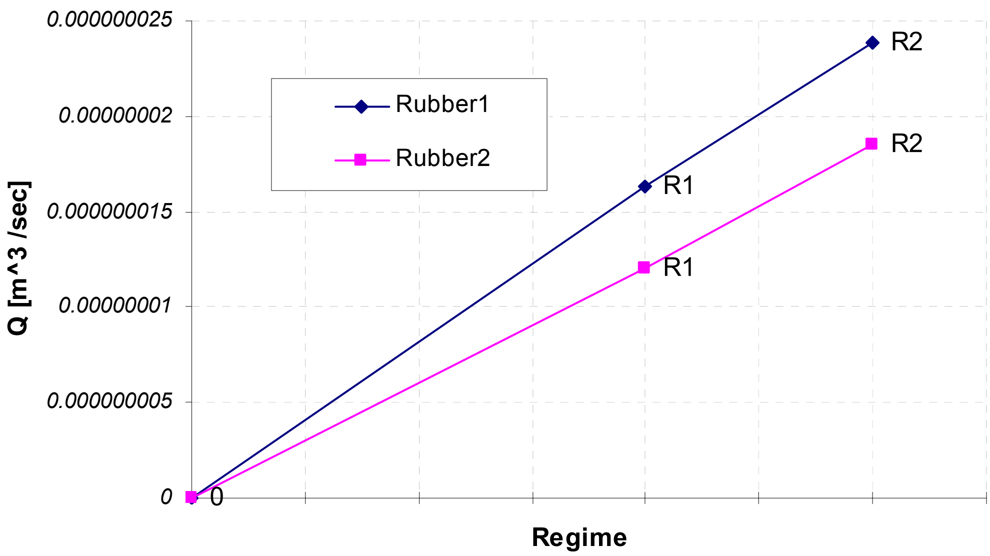


Figure 15 Average-weighted mass flow throw clearance

6. Conclusion

The problem of fluid-structure interaction between rubber seal and oil is solved by CFD code FlowVision and FEA code ABAQUS/explicit.

Analysis of the results shows the strong dependence of the oil leakage through valve stem seal on engine operation condition and elasticity of valve rubber and we can make the following conclusions:

1) Increasing speed of a stem oscillation results in increasing oil leakage through the valve stem seal. For rubber 1 change of rotation from R1 to R2 leads to 31% leakage increasing, for Rubber2 – 35% increasing.

2) Increasing elasticity of the rubber results in increasing the oil leakage through the seal. For stem oscillation R1, Rubber1 has 26.6% leakage excess in comparison with Rubber2. For R2 excess is 22%.

3) Increasing elasticity results not only in growth of the oil leakage but also growth of the oil leakage rate with increasing speed of engine rotation.

Also we found that during stem oscillation the rubber has complex motion. This motion results in complex changing of the clearance along the stem. Simulation shows that clearance along the stem has wave-like nature and for future work this effect must be investigated theoretically, numerically and experimentally.

7. References

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