6th International Conference
ðComputational Mechanics and Virtual Engineering ð
COMEC 2015
15-16 October 2015, Braşov, Romania

A MODIFIED APPROACH OF SQUEEZE EFFECTSIN POROUS MEDIA IMBIBED WITH NEWTONIAN FLUIDS

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Abstract:*An innovative self-supporting lubrication mechanism based on porous media is studied in the laboratory of University Politehnica of Bucharest under the name of ex-poro-hydrodynamic lubrication. The squeeze of a highly deformable porous material imbibed with a Newtonian fluid under the action of a normal load, causes the fluid to be expelled through the pores. During compression, the porosity of the material decreases significantly, and so, the permeability. As a consequence, the resistance to flow increases and generates higher pressures. The model is based on Darcy equation of flow and takes into account the permeability dependence on porosity, defined using Kozeny-Carman law. The solution yields from two conservation laws, the conservation of the flow rate and conservation of the solid fraction which are independently used. By correlating the two laws and reformulating the work using the corrected form of the corresponding equations, a more accurate description of the process is obtained. By comparing the previous and the modified model, it is demonstrated that the previous model underestimated the force up to two times.*
Keywords:*lubrication, squeeze, porous, damping.*

1. INTRODUCTION

In the last 20 years, several studies concerning an original mechanism of self-supporting lubrication that occurs in a highly compressible porous material imbibed with a fluid were developed. The process was discovered and analyzed independently by prof. M. D. Pascovici from UPB and prof. S. Weinbaum from City University of New York. This mechanism was called by Pascovici ex-poro-hydrodynamic (XPHD) lubrication [1].The principle of XPHD lubrication can be explained by the thickness variation of the porous layer imbibed with fluid, in space and time, under a load, which is forcing the fluid to be expelled through the pores, dissipating energy through viscous friction. This produces a significant lift force, supporting the application of such phenomena in shock absorption [2].The porous material, also known as a Highly Compressible Porous Layer (HCPL), is a complex structure of capillaries or cavities, arbitrary distributed, characterized by *porosity* – represented by the pores of the structure, and *permeability* – represented by the capacity of the fluid to flow through it.
The lift effect of XPHD lubrication mechanism has been studied until now by Pascovici team, following various classic configurations, for translational motion and for normal motion. The moving part that is in translational motion is compressing the porous material and dislocating the fluid, generating a stationary pressure field. If the part is compressing the porous material, the normal movement is squeezing out the fluid inside. The squeeze process can be studied for three loading condition: *constant velocity*, *constant force* or *impact loading* (given impulse).

2. XPHD MODEL

Let a soft layer of a highly porous material fully imbibed with a fluid placed on a rigid and impermeable surface and compressed by a mating rigid body. The model of XPHD lubrication is based on a few hypotheses [3]:

- The surface of the compressing body is rigid and impermeable;
- The porous layer is relatively thin, homogeneous and isotropic, with an impermeable top surface;
- The pressure is constant across the thickness of the porous layer;
- The fluid is Newtonian, the flow is laminar, isothermal and isoviscous and modelled with Darcy equation;

- The elastic forces of the porous medium are negligible compared to the flow resistance forces.

The main characteristic of porous materials is the **porosity**, denoted by ε, defined as the ratio between the total pore volume V_p and the total volume occupied by the material V, that is:

$$\varepsilon = \frac{V_p}{V} \tag{1}$$

Nevertheless, at macro scale, the volume of the porous material imbibed with a fluid can be split into two components: one solid and one fluid. During compression, the pore geometry changes, expelling the fluid from the material. In this process, the solid volume of the structure is compressed until it reaches zero porosity. Considering that the cross-sectional area does not change until this limit, and that the fibbers of the material are re-arranged in the space left unoccupied, the solid fraction of the porous layer is conserved. The solid fraction conservation assumption yields to the following equation: the product of the thickness and the inverse of the porosity is constant throughout the compression:

$$h(1-\varepsilon) = h_0(1-\varepsilon_0) = \text{ct} \tag{2}$$

The thickness of the solid-state material, characterized by zero porosity, is therefore calculated as:

$$h_{\min} = h_0(1-\varepsilon_0) \tag{3}$$

The compression of the porous material is evaluated using the strain:

$$\sigma = \frac{h_0 - h}{h_0} = 1 - \frac{h}{h_0} \tag{4}$$

XPHD lubrication model is bounded by porosity limitations, so, the squeeze process can be studied in the compression interval (h_0, $h_{\min}$) or $(0, \sigma_{\min})$, where $\sigma_{\min} = h_0 - h_{\min}/h_0 = \varepsilon_0$.

Permeability, denoted by ϕ, is the property of the material to allow the fluid to flow through it. Kozeny[4], and then Carman [5], developed an expression for the permeability variation with porosity, used today under this form:

$$\phi = \frac{D\varepsilon^3}{(1-\varepsilon)^2} \tag{5}$$

where $D = \frac{{d_f}^2}{16k}$ is a complex parameter, k is the correction factor determined experimentally in the range 5÷10, and $d_f$isfibbers diameter.

The most simple equation that describes fluid flow through porous materials was developed by Darcy [6], which states that the pressure gradient on x direction is proportional to the mean velocity of the fluid in porous media u_m, which, in one-dimensional form, can be expressed as:

$$\frac{\mathrm{d}p}{\mathrm{d}x} = -\frac{\eta}{\phi} u_m \tag{6}$$

The model of XPHD lubrication, in the case of compression with *constant speed* (v = ct), is based on a flow rate conservation equation: the fluid that is dislocated by the compression of the material with speed v, will flow in axial direction according to Darcy law. The permeability variation with compression is expressed with Kozeny - Carman law- eq. 5. Therefore one can obtain the pressure derivative, and by integration the pressure distribution. Furthermore, by integrating the pressure on the contact surface, one can obtain the lift force.

However, all the models developed in previous studies ([7], [8], [9]0) do not correlate the equation of conservation of the solid fraction- eq. 2 in the equation of the conservation of the flow, considering that only the fluid that is inside the pores of the dislocated volume will be squeezed out. In reality, the solid agglomerates by compression, and the volume of fluid dislocated is determined by the entire volume dislocated by compression. This correction is applied in this paper, and the theoretical models for disc-on-plane and sphere-on-plane configurations, developed previously, are reconsidered.

2.1. The improved disc-on-plane configuration model

The geometry of disc-on-plane configuration is sketched in Fig. 1. A disc of radius ρ and a plane, both perfectly rigid and impermeable, with a homogeneous porous material of initial thickness h_0, and initial porosity ε_0, interposed between the two, is analyzed. The porous material is imbibed with a Newtonian fluid of viscosity η. The disc remains parallel (aligned) with the plane during compression, squeezing out the fluid imbibed in the porous material.

Taking into account the solid fraction conservation (eq. 2), the volume of the fluid expelled by compressing the material with Δh, is:

$$\Delta V = ® \cdot r^2 \cdot (£_1 \cdot h_1 - £_2 \cdot h_2) = ® \cdot r^2 \cdot \Delta h \qquad (7)$$

The volume calculated in eq. 7, dislocated by compression with velocity *v*, gives the flow rate:

$$q_{dis} = ® \cdot r^2 \cdot v \qquad (8)$$

much larger that the flow rate considered in previous models, as $q_{dis} = ® \cdot r^2 \cdot £ \cdot v$.

The flow of the fluid through the porous material can be defined using Darcy equation – eq.6:

$$q_{Darcy} = -2®r \cdot \frac{¤ \cdot h}{¦} \cdot \frac{dp}{dr} \qquad (9)$$

After integrating the flow conservation equation, the dimensionless pressure distribution $\bar{p} = pD/(¦ °v)$ yields:

$$\bar{p} = \frac{\bar{°}}{4} \frac{1}{\bar{¤}\bar{h}} \left(1 - \bar{r}^2\right) \qquad (10)$$

where $\bar{°} = °/h_0$ is the size factor, $\bar{¤} = ¤/D$ the dimensionless permeability, $\bar{h} = h/h_0$ the dimensionless thickness and $\bar{r} = r/°$ the dimensionless radial coordinate.

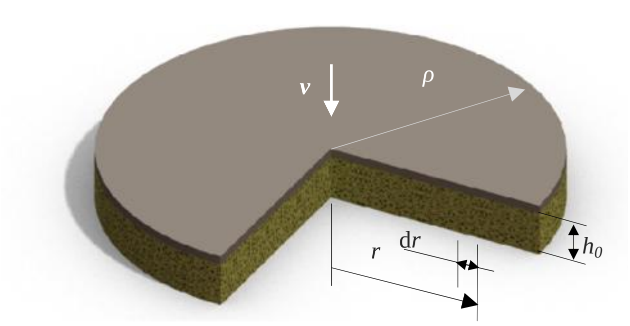

Figure 1: Disc-on-plane configuration

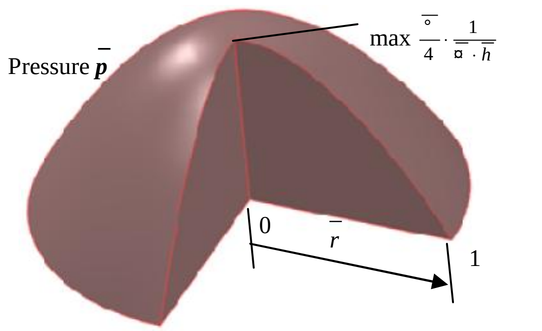

Figure 2: Pressure distribution for disc-on-plane configuration

As seen from eq. 10 and Fig. 2, the pressure increases with the compression of the material, due to the permeability that decreases to zero.

Integrating the pressure on the surface of contact, one can obtain the dimensionless lift force $\bar{F} = FD/(¦ °^2 h_0 v)$ at a given strain:

$$\bar{F} = \frac{® \bar{°}^2 (1 - £_0)^2}{8} \frac{1}{(£_0 - ¢)^3} \qquad (11)$$

From eq. 11 one can observe that the two important parameters for XPHD lubrication process are size factor, $\bar{°} = °/h_0$,and initial porosity ε_0. In Fig. 3 is presented the variation of the lift force with the strain. At the beginning of the compression, the lift force is low, and sharply increases after more than half of the compression strain. The lower is the size factor $\bar{°}$, the sharper the load increases (Fig. 4).

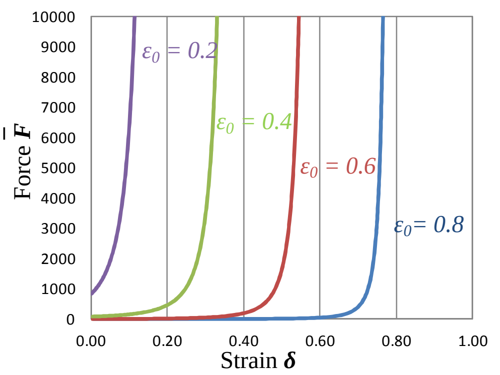

Figure 3: Dimensionless force $\bar{F}$ vs. strain δ for different initial porosities ε_0 ($v = ct$, $\bar{°} = 5$)

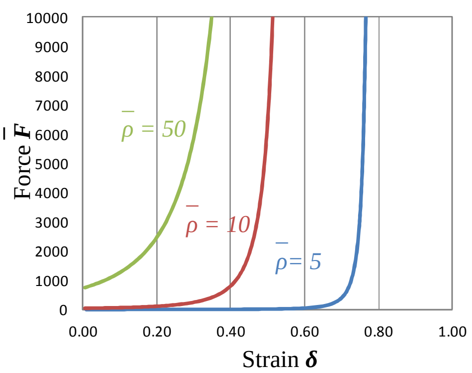

Figure 4: Dimensionless force $\bar{F}$ vs. strain δ for different values of size factor $\bar{°}$ ($v = ct$, $\varepsilon_0 = 0.8$)

2.2. The improved sphere-on-plane configuration model

The model for sphere-on-plane configuration is schematically presented in Fig. 5. A porous material of initial thickness h_0 and initial porosity ε_0, imbibed with a Newtonian fluid of viscosity η, is fixed on a plane and squeezed with a sphere of radius ρ. The footprint left by the sphere, is defined by radius R, that increases with the depth of penetration. The thickness of the material in the middle of the footprint is denoted by h_m. For the simplicity of the analytical model, and taking into account the large ratios $\bar{\rho}$ found in practice, the thickness of the porous material under compression can be expressed with classical parabolic approximation:

$$h = h_m + \frac{r^2}{2\rho} \tag{12}$$

The solution is found in a similar way as for disc-on-plane configuration. After integrating the flow conservation equation, the dimensionless pressure distribution $\bar{p} = pD/(\eta\rho v)$ yields:

$$\bar{p} = \frac{(1-\varepsilon_0)^2}{4} \cdot \left(\frac{1}{\left(\bar{r}^2 + \varepsilon_0 - \bar{R}^2\right)^2} - \frac{1}{\varepsilon_0^2} \right) \tag{13}$$

where $\bar{r} = r/\sqrt{2\rho h_0}$.

In Fig. 6 is presented the dimensionless pressure distribution for sphere-on-plane configuration.

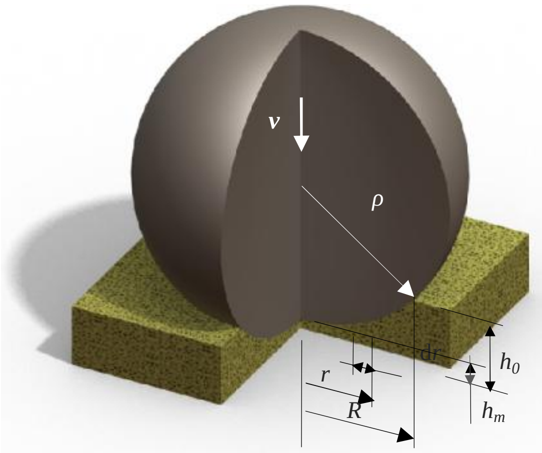

Figure 5: Sphere-on-plane configuration

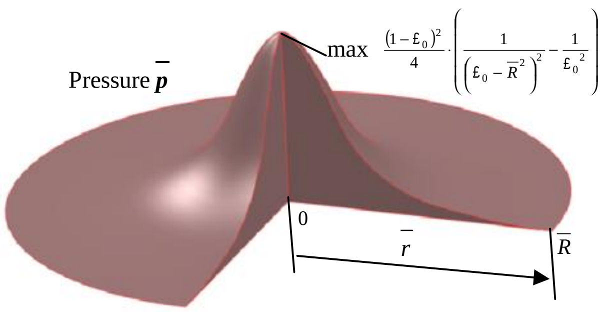

Figure 6: Pressure distribution for sphere-on-plane configuration

By integrating the pressure in eq. 13 on the contact surface, one can obtain the lift force in dimensionless form $\bar{F} = FD/\left(\eta\rho h_0\sqrt{2\rho h_0}\,v\right)$:

$$\bar{F} = \frac{\pi(1-\varepsilon_0)^2}{4}\sqrt{2\bar{\rho}}\left(\frac{1}{(\varepsilon_0 - \varepsilon_m)} - \frac{\varepsilon_m}{\varepsilon_0^2} - \frac{1}{\varepsilon_0} \right) \tag{14}$$

A parametric study shows that the force depends strongly on the initial porosity (Fig. 7), and that with the increase of the size factor $\bar{\rho}$, the lift force will increase, but not so insignificantly as for disc-on-plane configuration (Fig. 8).

2.3. Models comparison

The differences between previously published models and present ones are evaluated using the relative error:

$$Err = \frac{F - F^*}{F} \cdot 100\% \tag{15}$$

where F^* is the force calculated using the previous model, and F the force calculated including this new correction.

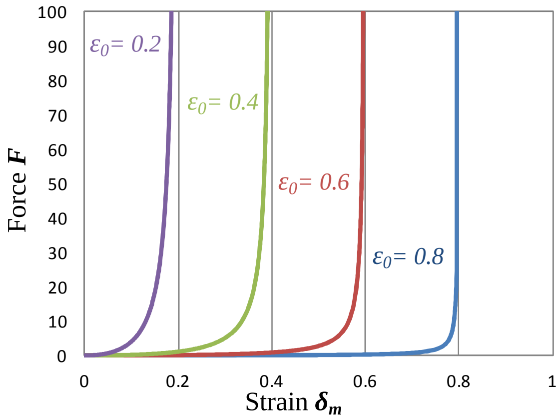

Figure 7: Dimensionless force $\overline{F}$ vs. strain δ_m for different values of initial porosity ε_0 ($v = ct$, $\overline{\rho} = 5$)

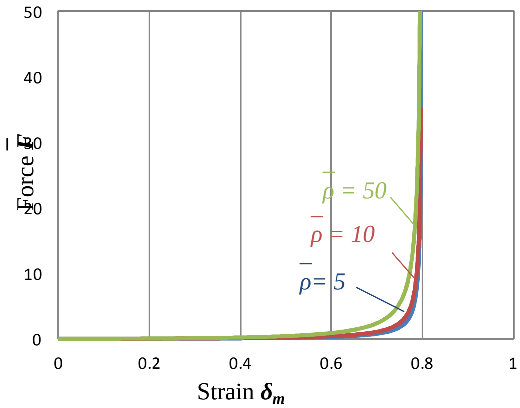

Figure 8: Dimensionless force $\overline{F}$ vs. strain δ_m for different values of size factor $\overline{\rho}$ ($v = ct$, $\varepsilon_0 = 0.8$)

The squeeze model developed recently for disc-on-plane configuration [10], that doesn't include the correction of solid fraction conservation, gives a similar variation of the lift force F^*, smaller than the one presented in eq. 11, with an error of:

$$Err = 1 - \varepsilon \tag{16}$$

The errors introduced by the previously published models when compared with the present model for disc-on-plane configuration, increases with strain (Fig. 9). The results show that with the improved model, the lift force is between 0-100% higher, due to the larger volume of fluid that is dislocated through the pores of the material.

The variation of the force F in eq.14 is compared with the previous model for sphere-on-plane configuration (presented in [10]) resulting in the error below:

$$Err = 1 - \frac{\left(\frac{\delta_m^2 (4(1-\delta_m) - 1 + \varepsilon_0)}{(1-\delta_m)^2 \varepsilon_0^2} - \frac{2(1-\varepsilon_0)\delta_m}{\varepsilon_0 (1-\delta_m)^2} - \frac{2(1-\varepsilon_0)}{(1-\delta_m)^2} \ln\left(\frac{\varepsilon_0 - \delta_m}{\varepsilon_0} \right) \right)}{4 \cdot \left(\frac{1}{(\varepsilon_0 - \delta_m)} - \frac{\delta_m}{\varepsilon_0^2} - \frac{1}{\varepsilon_0} \right)} \tag{17}$$

The results of the applied correction gives an error that depends on the level of strain and shows that the lift force can be up to two times greater(Fig. 10).

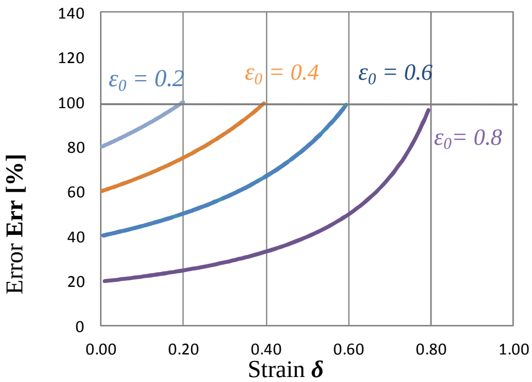

Figure 9: The variation of the error *Err* of the lift force with strain δ, for different initial porosities ε_0 (disc-on-plane configuration)

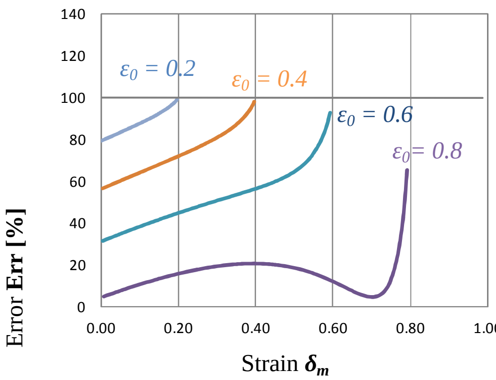

Figure 10: The variation of the error *Err* of the lift force with strain δ_m for different initial porosities ε_0 (sphere-on-plane configuration)

3. CONCLUSION

It was found that the assumption regarding flow rate conservation in previously published models for two tipicalcontact configurations (sphere-on-plane, disc-on-plane) neglected a term, underestimating the lift force generated. Therefore, the reformulation of the work dedicated to the corrected form of the corresponding equations was necessary to compare with the new developed experiments.

For both disc-on-plane and sphere-on-plane configurations, the mathematical model was reformulated in order to include the solid fraction conservation equation into the flow rate conservation equation. The effect of the improved model in comparison with the previously developed ones was estimated by taking the improved one as a reference. The results show that the lift effect was underestimated with a factor that is between 1-2, with a maximum when the compression is close to maximum (the porous material reaches the maximum compactness). The parametric study of the lift force was done in function of the initial porosity $£_0$, and dimensionless parameter $\overline{\circ}$, which permits an elegant and compact analysis.

ACKNOWLEDGEMENT

This work was partially supported by MEN-UEFISCDI Partnership Program PN-II Contract No 287/2014 (PROTHEIS).

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