Projected contact area method and its application to rolling tire simulation (May 2007)

J. C. Cho

R&D Center, Hankook Tire Co., Ltd.

23-1, Jang-dong, Yuseong-gu, Daejeon, 305-725, Republic of Korea

spingks@hankooktire.com

Abstract: It is well known that the friction coefficient of rubber-like materials is a function of normal contact pressure, sliding velocity and temperature. In this reason, the exact calculation of normal contact pressure is very important when the rubber frictional forces are computed under a pressure dependent frictional model. Nevertheless, in many finite element codes including ABAQUS have been observed not to exactly calculate the nodal contact area and pressure at contact surface edges and corners.

To overcome this problem, PCAM (Projected Contact Area Method) is proposed and implemented via ABAQUS user subroutine VFRIC. After discussing the differences between the results by current approach and by PCAM approach through rubber block simulations, PCAM is applied to the actual tire problems. Three tread patterns of tires are simulated under cornering and braking situations and compared with the test results. Though PCAM is very simple concept, it is proved to be very effective in predicting the frictional performances.

Keywords: Projected contact area, Contact Pressure, Frictional coefficient, VFRIC, Rolling tire, traction force, frictional energy, Explicit FEM.

1. Introduction

In the design stage of tread pattern of a tire, multiple candidates of tire patterns are designed and one pattern showing the best performances is selected among them. In this selection process, FEM has been becoming a very popular tool to predict the tire performances because it does not require manufactured real tires. This study is motivated to improve the accuracy of predicted performances of rolling tire such as contact pressure distribution, frictional wear energy distribution and traction forces under braking, driving and cornering. Since most of the tire performances are evaluated under the contact with the ground, cautious calculation of normal and frictional contact forces interacting with the ground is very important in FEM prediction. In this reason, this paper will be focused on the frictional contact force calculation by proposing Projected Contact Area Method (PCAM).

It is well known that the friction coefficient of rubber-like material is a function of normal contact pressure [1] as well as sliding velocity and temperature. In this reason, the exact calculation of normal contact pressure is very important since the rubber frictional forces are computed based on a normal contact pressure. Nevertheless, in many finite element codes including ABAQUS have been observed not to exactly calculate the nodal contact area and pressure at contact surface edges and corners.

To overcome this problem, PCAM is proposed and implemented via ABAQUS user subroutine VFRIC. After discussing the differences between the results by current approach and by PCAM approach through rubber block simulations, PCAM is applied to the actual tire problems. Three tread patterns of tires are simulated under the cornering, braking and driving situations and compared with the test results.

2. PCAM (Projected Contact Area Method)

2.1 Concept of PCAM

For rubber-like material, frictional coefficients are generally known as pressure-dependent and this is experimentally proved in [1]. One of the simplest forms of this pressure dependency is expressed like following.

$$\mu = \mu_0 \times \left(\frac{p}{p_{ref}} \right)^{-k} \times f(\dot{\gamma}, T) \qquad (1)$$

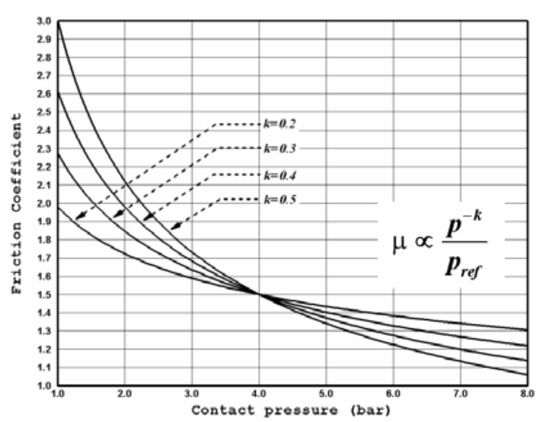


Figure 1. Pressure dependency of rubber friction.

where, μ is frictional coefficient, μ_0 is proportional coefficient, $\boldsymbol{p}$ is normal contact pressure, $\boldsymbol{p_{ref}}$ is reference pressure, $\boldsymbol{k}$ is a exponent representing pressure dependency and $\boldsymbol{f(\dot{\gamma},T)}$ is a function to stand for the effect of the slip velocity and temperature. Figure 1 shows the effects of the exponent $\boldsymbol{k}$ in equation (1).

To apply the friction model shown in equation (1) by ABAQUS/Explicit, user subroutine VFRIC should be used.

From the equation (1), it is easily seen that normal contact pressure plays an important role in determining the frictional coefficient. Normal contact pressure in FEM can be simply calculated like following.

$$\boldsymbol{p = N_{nodal} / A_{nodal}} \tag{2}$$

Where $\boldsymbol{p}$ is contact pressure, $\boldsymbol{N_{nodal}}$ is normal contact force and $\boldsymbol{A_{nodal}}$ is nodal area of a node in contact. If nodal area is not properly calculated, contact pressure also becomes incorrect and this leads to incorrect frictional coefficient. Therefore reasonable calculation of nodal area $\boldsymbol{A}$ is very important.

In using user subroutine VFRIC, the nodal area $\boldsymbol{A}$ is supplied by ABAQUS, but the supplied $\boldsymbol{A}$ is an estimated value by the method shown in Figure 2(b). $\boldsymbol{A}$ in Figure 2(b) includes the full portion of A_2 of which is actually not in contact at all. Thus, $\boldsymbol{A}$ is generally larger than that of actual contact area. This will underestimate the normal contact pressure and overestimate the frictional coefficient. To improve this undesired situation, $\boldsymbol{A_2}$ is projected onto the master surface with a weighting function as shown in figure 2(c). In this case, the area $\boldsymbol{A}$ in figure 2(c) is always less than that of figure 2(b).

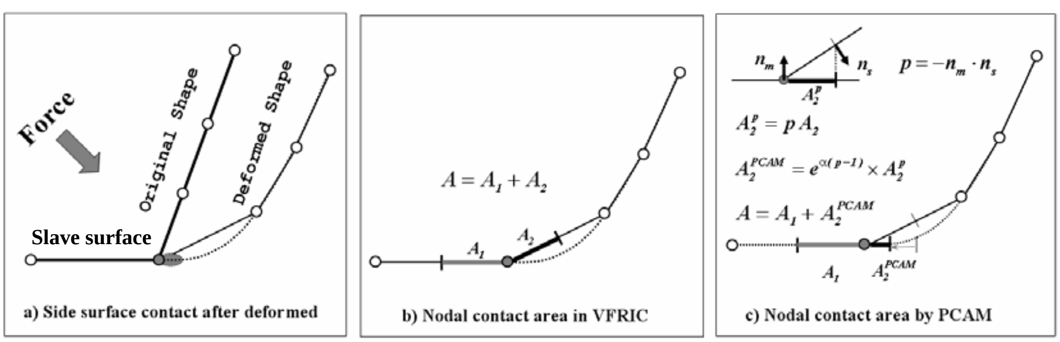


Figure 2. Concept of Projected Contact Area Method (PCAM).

If the slave surface are sufficiently fine so that the nodal area of contact edge is relatively small compared with the total surface area in contact, then overestimated contact pressure at edge may not be so important in computing the global frictional force. But because of computing cost, time and memory capacity, industrial FE model have limitations in using sufficiently fine mesh. Figure

3 shows the FE models of tires which are used in predicting pattern performances. The tread rubber blocks in these models use only 3~5 elements in the groove depth direction. This is the reason why we need to focus on the nodal contact area at contact edges.

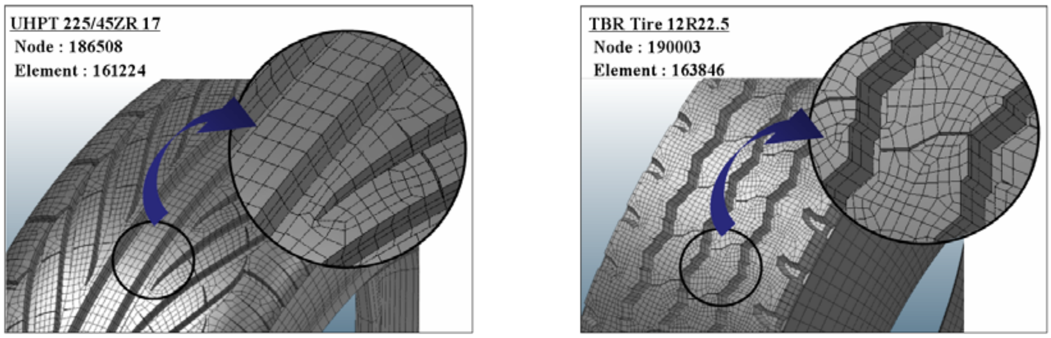


Figure 3. FE model of tires

The weight function shown in figure 2 is assumed like following.

$$w(p) = e^{\alpha(p-1)} \tag{3}$$

The weight function ***w(p)*** is plotted on figure 4. In this plot, ***w(p)*** becomes 1 at ***p***=1 where all the nodes in the slave face are in contact with the master surface.

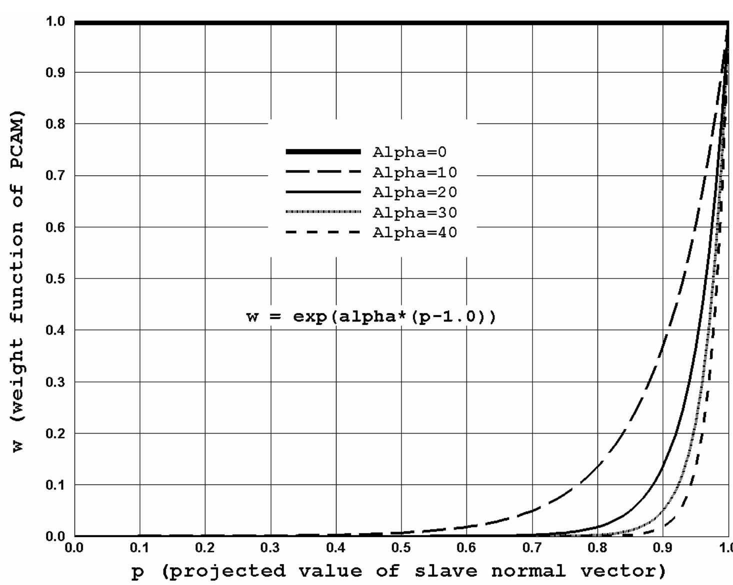


Figure 4. Plot of weight function *w(p)*.

To select an adequate value of α for tire tread pattern problem. FE model of tapered rubber block is used as shown in Figure 5 and tested under severe normal load set by varying the α. Coarse mesh shown here has the normally used mesh density in tire performance prediction. If these models slide on the flat surface with high normal load, sidewall surface will begin to contact with the flat master surface as shown in figure 6.

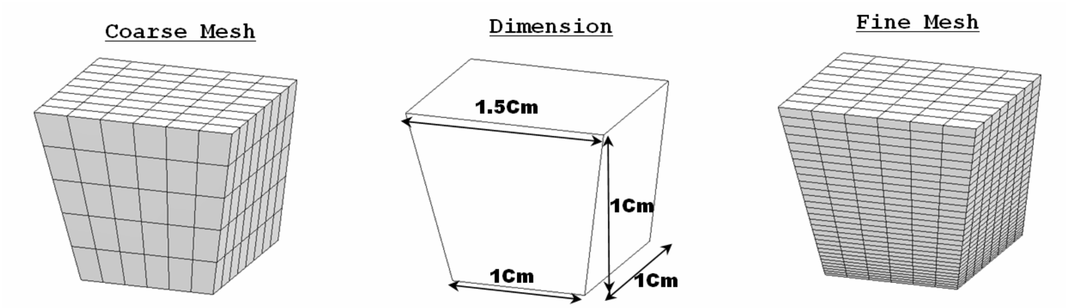


Figure 5. Definition of tapered FE block model.

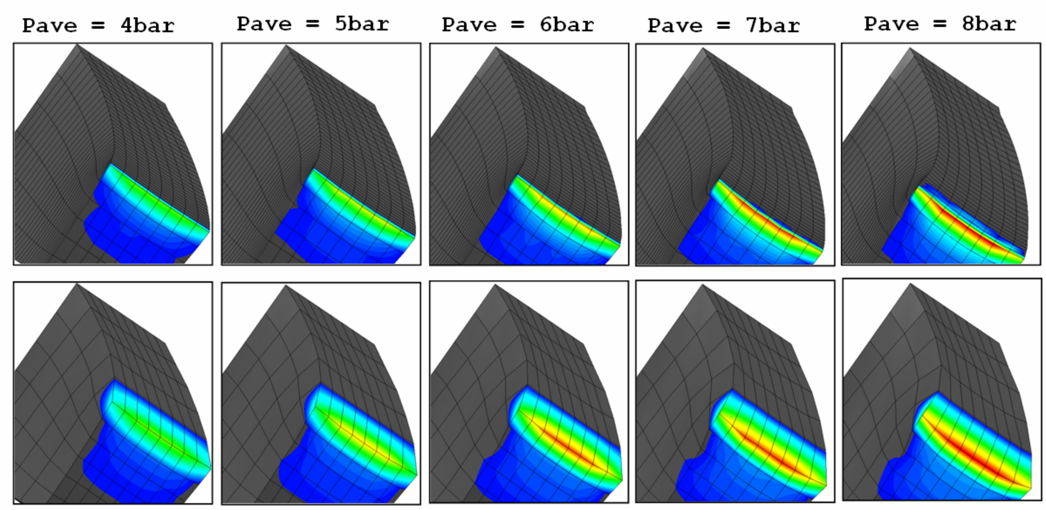


Figure 6. Contact pressure distribution of tapered FE block with $\alpha = 20$

In figure 6, side surface of fine mesh begins to contact with flat surface under average normal pressure 7bar while that of coarse mesh is not in contact with the flat surface even under 8bar condition. Figure 7 shows the comparison of normalized friction coefficient which is obtained by dividing frictional force by normal force using PCAM with varied α.

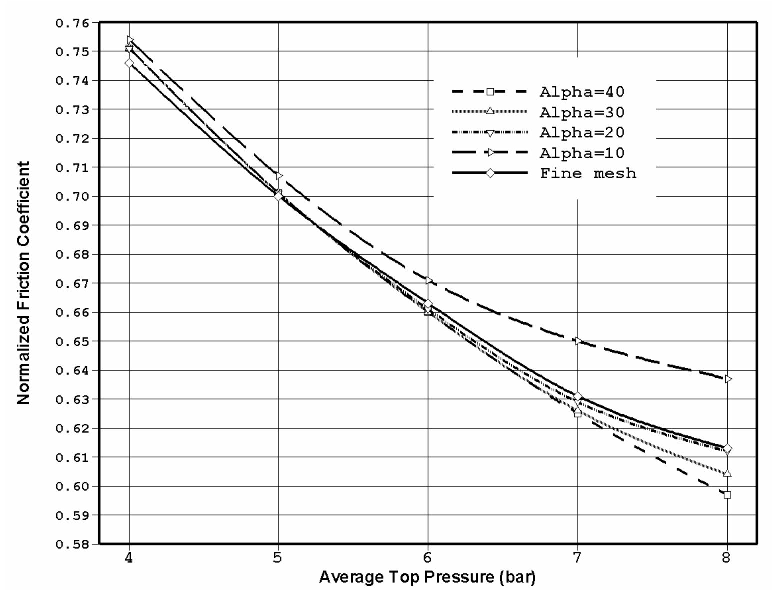
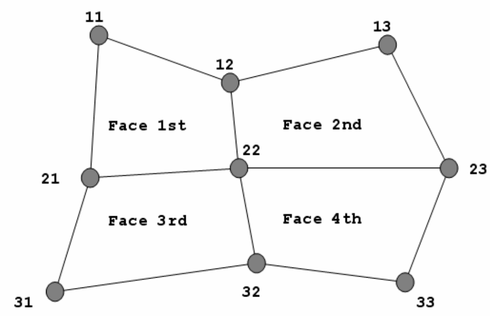


Figure 7. Comparison of normalized friction coefficient under varied α

In figure 7, we can see that the proper range of α exists. If α is less than 10, the results of coarse mesh become much different compared with the fine mesh particularly in high normal load condition. Setting α=20 yields good result in this problem. Therefore α=20 will be used in the tire performance simulations which will be shown later.

2.2 Implementation in ABAQUS

PCAM is implemented via ABAQUS user subroutine VFRIC[2]. The implementation is simple. The procedure is shown in figure 8. Figure 8(a) shows an example of connectivity of contact surface. This connectivity information should be prepared in a file before the ABAQUS run is started. The example format of this file is shown in figure 8(b). When VFRIC is called first time for the contact surface, this connectivity file is read and saved in FORTRAN common memory block. Then the projected nodal contact area can be calculated for each node in contact using this connectivity information by calling PCAM routine. Surface faces connected to a node are in common memory block, nodal connectivity information of each face is also in the common memory block and all the nodal coordinates connected to contact surface are supplied by ABAQUS. Therefore the calculation of projected nodal area becomes possible inside the PCAM routine.



(a) Surface connectivity

```
** no. of nodes, no. of faces
9, 4
** nid, global nid, ns, sid_1,..,sid_ns
1, 11, 1, 1
2, 12, 2, 1,2
3, 13, 1, 2
4, 21, 2, 1, 3
5, 22, 4, 1, 2, 3, 4
6, 23, 2, 2, 4
7, 31, 1, 3
8, 32, 2, 3, 4
9, 33, 1, 4
** sid, nid1, nid2, nid3, nid4
1, 5, 4, 2, 1
2, 6, 7, 3, 2
3, 7, 8, 6, 5
4, 8, 9, 6, 5
```

(b) Connectivity file

```
Subroutine VFRIC(…,nSlvNod,…,jSlvUid,…,jConSlvid,…,timGlb,…,fNormal,coordSlv,…, dircosN,…, areaSlv,…)
…
Common/Connectivity_Info/…
…
IF(timGlb.EQ.0.0) Call Read_connectivity(connectivity file name) !-- Call only once in the beginning.
…
Do I=1,nContact
  …
  idg = jSlvUid( jConSlvid(I) )
  If(using PCAM ? -> yes) then
   call PCAM(idg, nContact, jSlvUid, dircosN(1,I), coordSlv, Pcam_area) !—Calculate PCAM area.
   Cpress=fNormal(I)/Pcam_area !—Contact pressure by PCAM.
  else
   Cpress=fNormal(I)/areaSlv(jConSlvid(I)) !—Contact pressure without PCAM.
  endif
  …
Enddo
…
Return
```

(c) Implementation of PCAM in user subroutine VFRIC

Figure 8. Implementation of PCAM.

3. Example Problems

Three examples will be shown here to prove the effectiveness of PCAM. First example is for comparison of the contact pressure distribution of a rubber block between the fine side mesh and the coarse side mesh with PCAM. Second example is for comparison of the frictional force between the fine side mesh and the coarse side mesh with PCAM. The last example is to predict the cornering and braking force of three different patterns of tires with the same tire body.

3.1 Rubber Block Simulation

As mentioned earlier, very fine mesh for industrial use is not practical though it can yield the better result. Figure 8 shows the contact pressure distribution of a rubber block under a normal load. As the side mesh becomes finer, the contact pressure at edge becomes higher. This means that using coarse side mesh can yield incorrect contact pressure distribution. To overcome this problem, PCAM is applied for the coarse mesh and the contact pressure at coarse mesh. By using PCAM, edge contact pressure becomes almost the same level as the finest mesh. In real physics, the high pressure at contact edge is correct as experimented in [3].

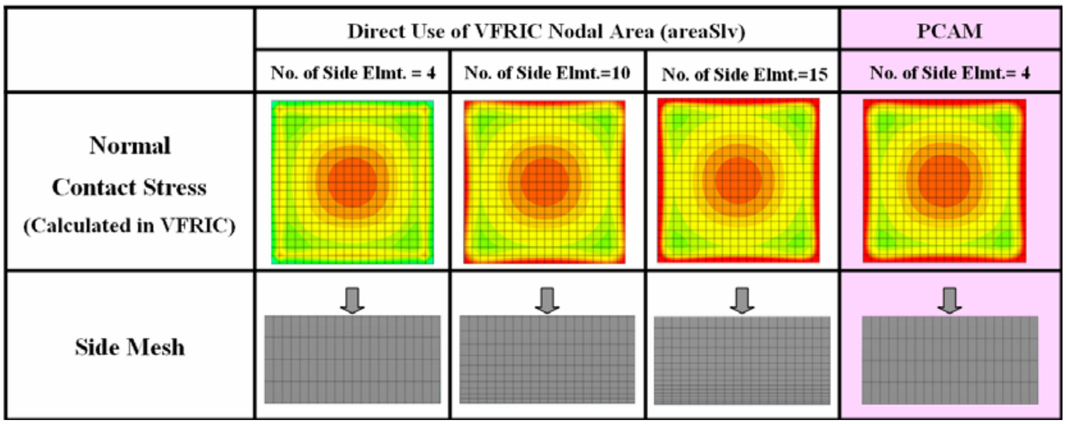


Figure 9. Correction of contact pressure distribution by using PCAM.

3.2 Rubber Block Simulation

Frictional force between tire and ground is the sum of the frictional forces generated in multiple rubber block surfaces building tire tread pattern. If a rubber block can generate larger frictional force, the total tire force will be larger in general. Therefore it is very important to predict the block-wise frictional force exactly as possible.

In this example, a rubber block is selected and simulated to compare the frictional force by fine side mesh and coarse side mesh with PCAM under constant sliding speed and varied normal loads.

Figure 10 shows the dimension of the rubber block and the several FE meshes used in this example.

Figure 11 shows the simulated result of each mesh without PCAM and result of coarse mesh with PCAM. The result by coarse mesh with PCAM shows approximately the same result as the finest mesh while the result of coarse mesh without PCAM shows about 5% larger than that of the finest one.

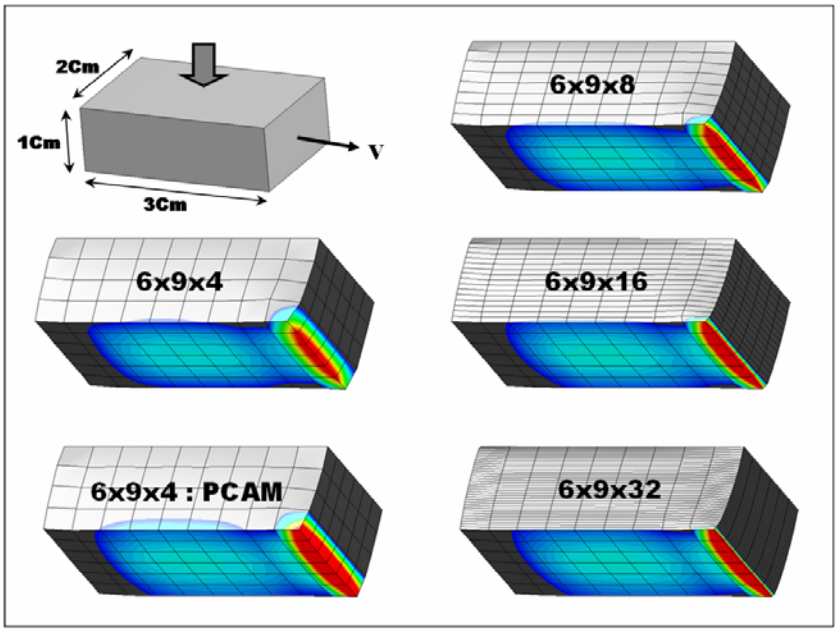


Figure 10. Rubber block models and contact pressure distributions

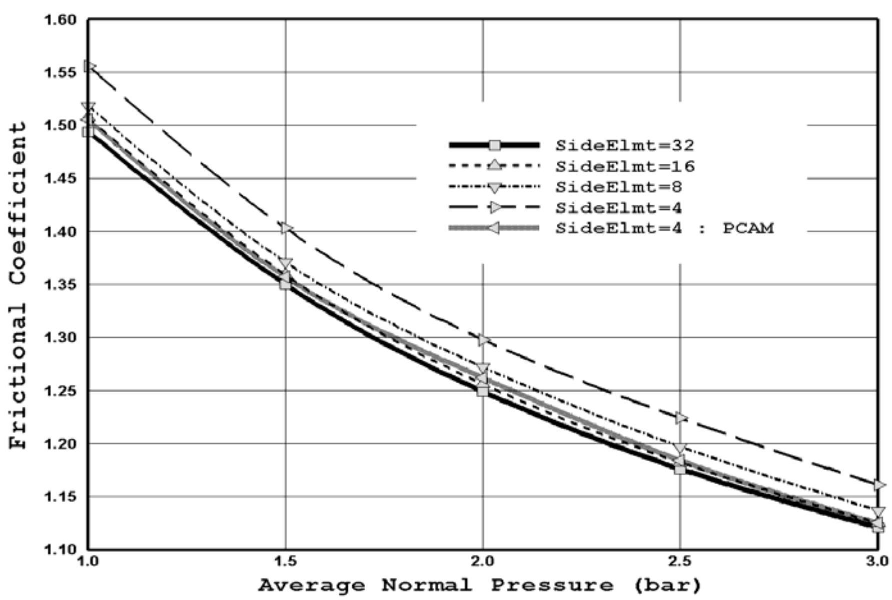


Figure 11. Comparison of frictional coefficients of rubber block simulations

3.3 Rolling Tire Simulation

In this example, three tire patterns of UHPT 225/45R17 size with the same tire body profile and construction are selected to examine the effectiveness of the proposed PCAM. Figure 12 shows the three patterns used in this example.

Lateral forces under 0^o to 15^o slip angle cornering and braking forces under 0% to 15% slip ratio are simulated under the conditions that the velocity is 60 km/h, inflation pressure is 2.5 bars, vertical load are 3871N. The indoor tests are also performed to compare with the simulation results under the same conditions.

(a) pattern A (b) pattern B (c) pattern C

Figure 22. Tire pattern models

Figure 13 shows the results of cornering tests. Each test results of the three patterns are plotted in two curves. One is 0^o to 15^o sweep results and the other is 15^o to 0^o sweep results. The curve fitting is performed using the two curves to remove the noisy oscillations and to get the averaged data. The braking test data will not be shown here but the curve fitting is also done by the same procedure.

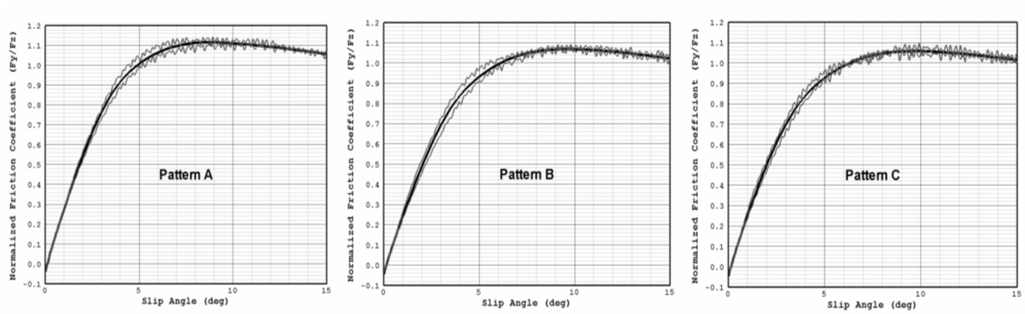


Figure 13. Curve fitting of cornering test data.

Figure 14 shows the simulated results of pattern A with PCAM for both cornering and braking condition and figure 15 compares the contact pressure distribution under 15^o slip angle of cornering and 15% slip ratio of braking.

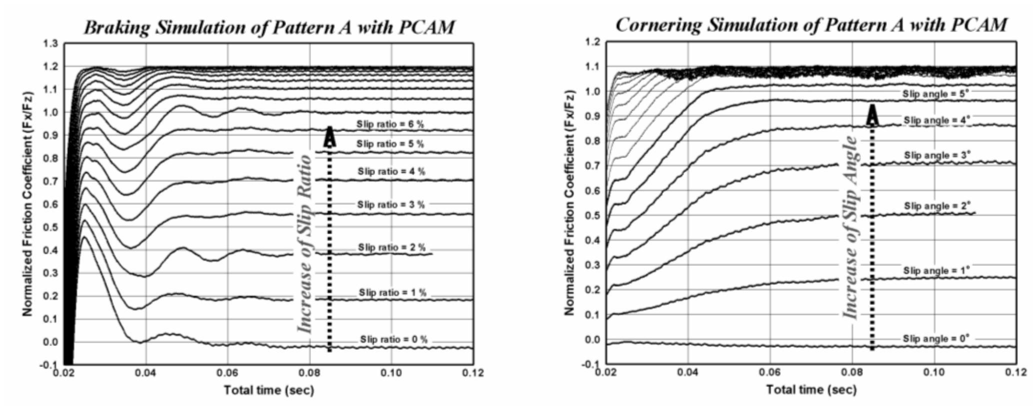


Figure 14. Simulated results of pattern A with PCAM.

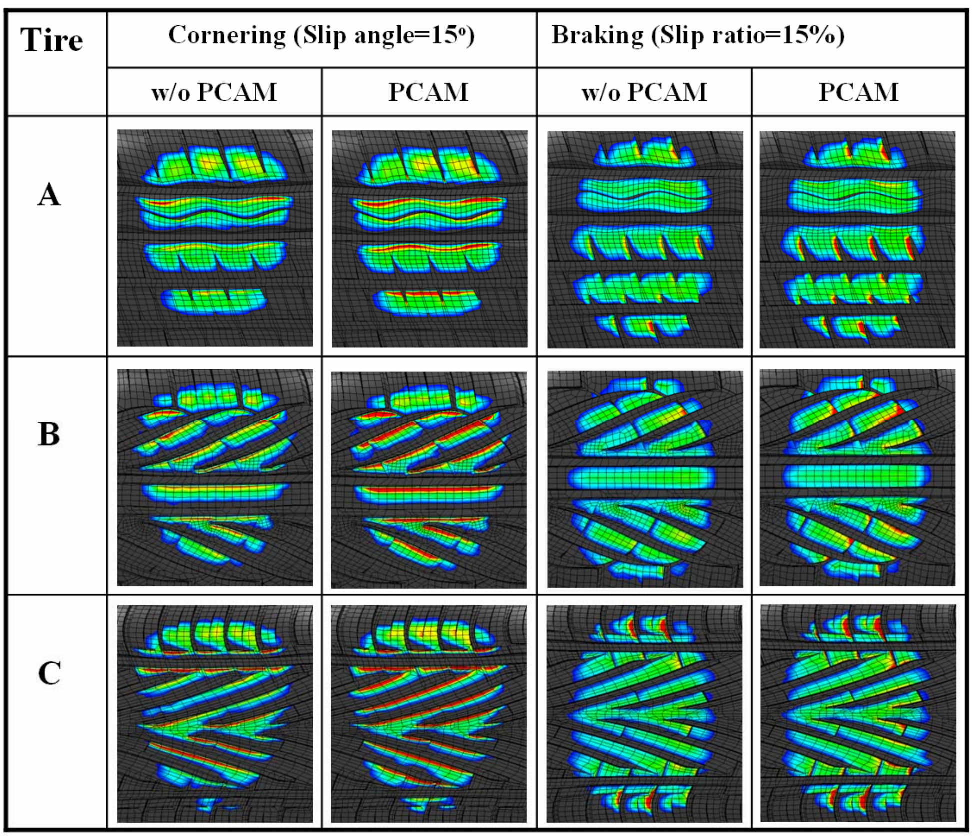


Figure 15. Contact pressure distribution of pattern A, B, C.

Figure 16 shows the comparison of cornering simulation results between the results without PCAM and results with PCAM. The results without PCAM is observed 4~6 % higher at peak values than the results with PCAM.

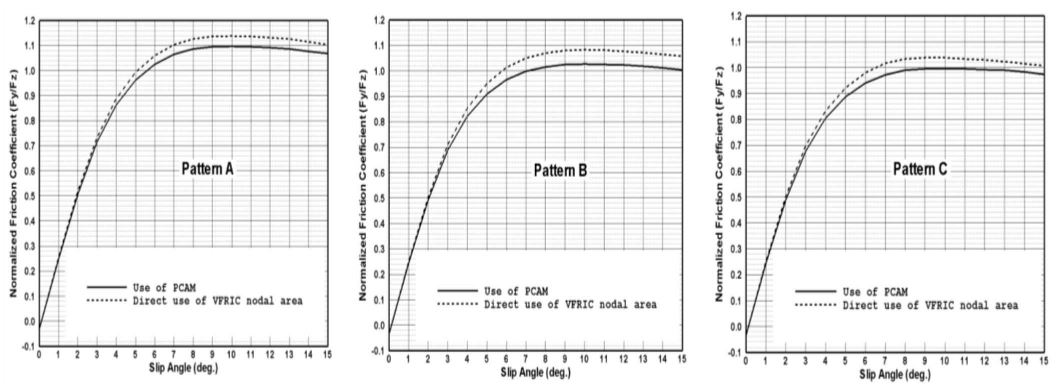


Figure 16. Comparison between the results without PCAM and the results with PCAM under cornering.

Figure 17 shows the comparison of braking simulation results between the results without PCAM and results with PCAM. The results without PCAM is observed 3~7 % higher at peak values than the results with PCAM.

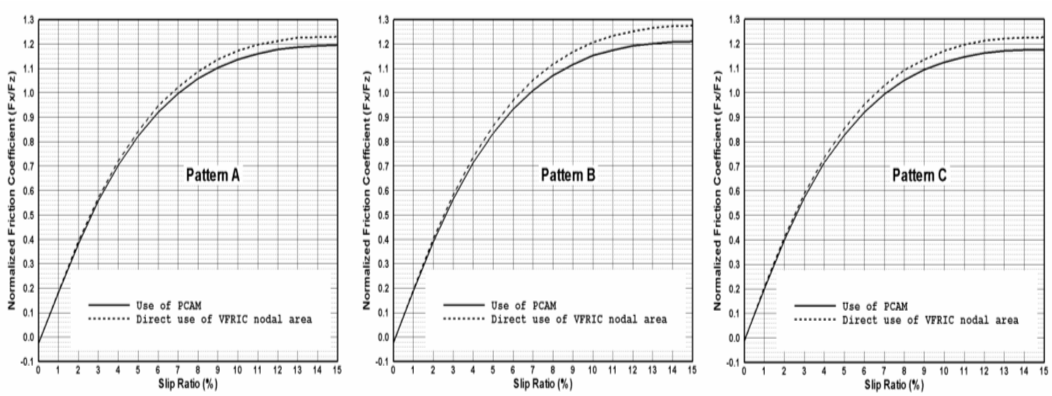


Figure 17. Comparison between the results without PCAM and the results with PCAM under braking.

Figure 18 shows the comparison between the simulation results and the test results of pattern A, B and C under cornering condition. Left figure is simulation results with PCAM, right figure is simulation result without PCAM and center figure is test results. Pattern A shows the highest frictional force and pattern B is slightly higher than pattern C. All the results shown here shows the same trend in performance rank. But the simulation results with PCAM are closer to the test data than the results without PCAM since the difference between pattern B and pattern C is smaller. Thus PCAM is proved to be efficient in cornering prediction.

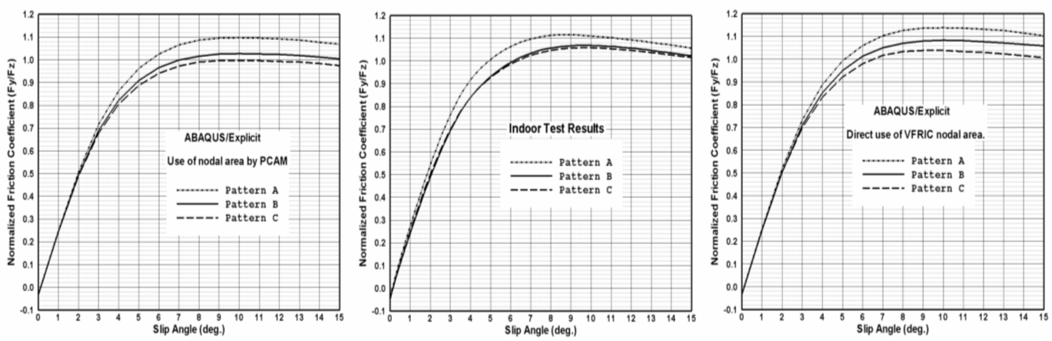


Figure 18. Comparison between simulated results and test results of pattern A, B, C under cornering

Figure 19 shows the comparison between the simulation results and the test results of pattern A, B and C under braking condition. The simulation results with PCAM is closer to the test data than the results without PCAM since the performance rank is the same as the test data while the performance rank of pattern B and C without PCAM is different compared with test. Thus PCAM is proved to be efficient in braking prediction.

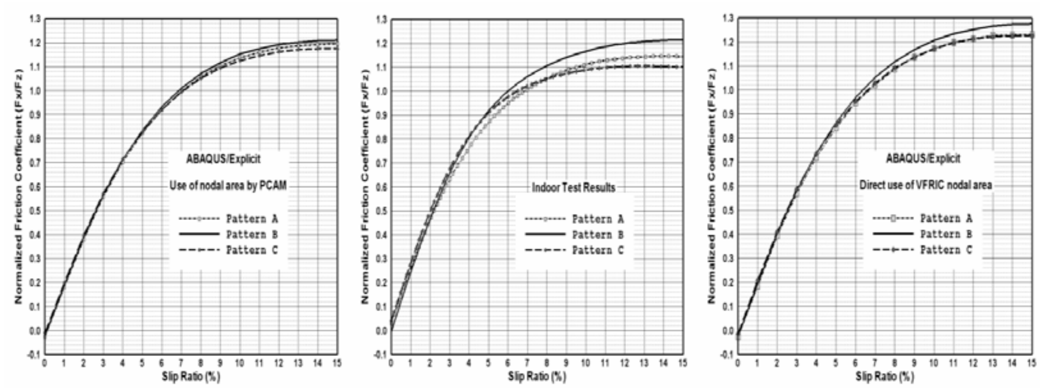


Figure 19. Comparison between simulated results and test results of pattern A, B, C under braking

4. Conclusions

Projected Contact Area Method (PCAM) is proposed and applied to predict the rubber block frictional force and tire cornering and braking performance. Through the examples shown here, PCAM is proved to be very efficient in predicting the frictional forces with coarse mesh FE model.

5. References

1. Samuel K. Clark, "Mechanics of Pneumatic Tires", pp. 367-370

2. ABAQUS 6.5 User's Manual

3. Y. Nakajima, F. Takahashi, and A. Abe, "Surface Shape Optimization of Tire Pattern by Optimality Criteria", *Tire Science and Technology*, Vol. 31, No. 1, 2003, pp. 2-18