Tyre design technology for reduction of rolling resistance

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Selected from International Polymer Science and Technology, 27, No. 2, 2000, reference NG 00/02/90; transl. serial no. 14467

1. INTRODUCTION

Given heightened concern for the global environment, vehicle manufacturers have been taking increased steps to reduce exhaust gas emission and improve fuel consumption. As automotive components, the tyres of the future will themselves need to provide better fuel economy (lower rolling resistance). The rolling resistance of tyres greatly affects vehicle fuel consumption, and reduction in this resistance is now an important priority in tyre development.

Reduction in the rolling resistance of tyres has hitherto been achieved mainly by reducing the loss factor of the materials (particularly in the cap tread), and by reducing the volume of material that produces hysteresis loss. While development work in this direction is still being keenly pursued, further reduction in rolling resistance calls for design innovations that would exclude materials of high loss from areas of large deformation or reduce deformation where materials of high loss are located.

Simulation based on finite element analysis has meanwhile proved to be indispensable in tyre structural design. Tyre manufacturers world-wide use the finite element method for tyre structural design in a myriad of forms. Rolling resistance in particular is measured as a physical quantity and directly constitutes a characteristic of tyres qualitatively distinct from other tyre characteristics (NHV, directional stability). Techniques for predicting rolling resistance with high precision are hence increasingly important in the development of technology for simulating other characteristics.

Numerous studies have addressed the prediction of tyre rolling resistance, or the energy dissipation distribution within the tyre (refs. 1–5). One technique used (ref. 1) is to find the energy dissipation as the product of the loss tangent ($\tan \delta$) of the material and the elastic strain energy generated by tyre deformation. A problem with this approach, however, is that it cannot readily handle the anisotropy of loss factor in FRR materials (the belt layer and carcass layer of a tyre, for example). One way of getting round the problem is to predict the energy dissipation from the rate of energy change per unit volume as a function of the rate of change of strain and the viscous damping matrix (ref. 2). Another technique proposed is to find the hysteresis loss from the variation in stress and strain and their phase difference (refs. 3–5).

The present article firstly describes a technique developed by the authors for simulating tyre rolling resistance, and after demonstrating the validity of the technique, examines the options for reducing rolling resistance based on the results of simulation.

2. OVERVIEW OF ROLLING RESISTANCE SIMULATION (REF. 6)

Fig. 1 shows the general approach to simulation of rolling resistance in tyres. Two things are needed to predict rolling resistance: static finite element analysis (FEA) to determine the strain distribution, and homogenisation of the energy dissipation model for the materials in the tyre. The anisotropic loss factor of FRR is determined by the phase difference between stress and strain.

Fig. 1  Procedure in simulation of rolling resistance
resistance with good precision: firstly an energy loss model that can readily handle the loss factor anisotropy in FRR materials, and secondly suitable values for the loss factors of FRR materials. The energy loss model used for this purpose estimates the energy loss from the variation in stress and strain approximated by a Fourier series and the displacement in phases. The loss factor of the FRR is found by dynamic viscoelastic analysis of the frequency domain on the basis of homogenisation (a technique whereby the mechanical behaviour of structures made up of materials possessing micro-periodicity can be rigorously analysed as coupled micro-macro behaviour; see reference 7 for details).

The specific procedure will now be described. Firstly, the stress and strain obtained by static FEM analysis are transformed to the stress and strain referred to a materials coordinate system appropriate to the calculation of the energy dissipation in FFRs like belt and carcass materials. The variation in stress and strain over a single cycle is then determined from neighbouring elements in the hoop direction with the same cross-sectional coordinates, as shown in Fig. 2, and a hysteresis loop is constructed by introducing the phase difference $\delta$ between the stress and strain due to viscoelasticity in the chosen element (see Fig. 3). However, tyre deformation is generally local as shown in Fig. 2, and this makes it impossible to obtain a suitable hysteresis loop directly from the stress and strain. The stress and strain variations obtained are therefore subjected to Fourier expansion as shown in Fig. 4. Hysteresis loops are then constructed by introducing a phase difference $\delta$ due to viscoelasticity between the stress and strain in successive harmonics and the loop areas are found (see Fig. 5). Similar calculations are performed for each element of the tyre cross-section, and the energies are then totalled to obtain the energy dissipation for the whole tyre (see Fig. 6).

![Fig. 2 Stress and strain distributions in tyre ground contact](image)

![Fig. 3 Stress and strain relation for viscoelastic material under cyclic load](image)

![Fig. 4 Fourier series expansion](image)

![Fig. 5 Hysteresis loops calculated for successive harmonics](image)

![Fig. 6 Energy dissipated in whole tyre](image)
The loss tangent for the FRR, on the other hand, is calculated by the FEM-based homogenisation technique. To confirm the validity of the analytical technique, the loss tangent of a rubber composite comprising two phases amenable to experiment – a hard rubber and a soft rubber – was observed and compared with the results of the calculations. The experiments were carried out using a unidirectionally reinforced composite of hard rubber in the form of a 1.5 mm diameter cylinder, corresponding to the reinforcement, embedded in a soft rubber, corresponding to the matrix. The observed viscoelastic properties of the respective rubbers are shown in Table 1.

Fig. 7 shows a typical finite element model of the FRR used in the calculations.

Fig. 8 shows the calculated and experimental values of loss tangent with skew angle as parameter. The loss tangent obtained by homogenisation agrees closely with the experimental results, confirming the validity of the technique.

Fig. 9 plots the loss tangent of the FRR in the cord lengthwise direction \( (\tan \delta_L) \) and the loss tangent in the transverse direction \( (\tan \delta_T) \) against the cord volume fraction and shows how the values vary with change in the cord to matrix modulus ratio \( E_f / E_r \). It can be seen that, as the cord to matrix modulus ratio increases, the loss tangent in the cord lengthwise direction approaches the loss tangent of the cord while the loss tangent in the cord transverse direction approaches the loss tangent of the rubber.

### 3. Simulation Results

#### 3.1 Comparison of calculated and observed rolling resistance

Rolling resistance is calculated using the results of static deflection analysis with a non-commercial FEM program. In the light of the results obtained with the homogenisation technique, the observed values of loss tangent for the cord are input for values of the loss tangent of the FRR in the cord direction while the observed values of loss tangent for the matrix rubber are used in the transverse direction. This is possible because, as noted earlier, the ratio of the Young’s moduli of cord and rubber is very large, of the order of \( 10^3 \sim 10^5 \), for the FRR materials used in tyres.
The computing time for rolling resistance excluding the FEM deflection analysis is approximately 1–2 min per case on an EWS (Sun SPARC Station 20).

Rolling resistance was measured after a preliminary 25 minute run at a speed of 80 km/h on a 1707 mm indoor drum tester with room temperature controlled to 25 ± 2°C.

The calculations and measurements of rolling resistance were carried out for 9 tyre sizes under a total of 26 different inflation pressure and load conditions. Fig. 10 compares the calculated and observed values of rolling resistance. There is clearly good general agreement between the calculated and observed values. The coefficient of correlation between the two is \( r = 0.949 \).

### 3.2 Dissipated energy density distribution

Fig. 11 shows an example of the dissipated energy density distribution found under conditions of inflation pressure 200 kPa and load 2.94 kN using a finite element model of a passenger car radial tyre (175/70 R 13). Overall, energy dissipation is large at the tread, particularly so at the belt edge and shoulder. The large energy dissipation in the tread is due to the large loss factor of the cap tread rubber compared with other parts of the tyre. Thus, the cap tread rubber is the part making contact with the road surface and has been designed taking into account other factors besides rolling resistance (wettingskidding, directional stability, vibrational characteristics). The large energy dissipation at the belt edge is due to the large interlaminar shear stress and strain generated in this part of the tyre. Again, the tread shoulder experiences large compressive stress from the tyre circumferential direction, radial direction and thickness direction as road contact occurs. Energy dissipation is also produced in the upper part of the bead filler by the compressive stress in the radial direction and the shear strain in the tyre circumferential direction-radial direction.

### 4. Tyre Structural Factors Contributing to Rolling Resistance

We will investigate how rolling resistance varies for a passenger vehicle radial tyre (175/70 R 13) when the usage conditions (inflation pressure and load) and tyre geometry are varied, taking a pressure of 200 kPa and load of 2.94 kN as standard.

#### 4.1 Rolling resistance in relation to inflation pressure and load

Fig. 12 shows the calculated and observed rolling resistance for different inflation pressures. Both the calculated and observed values are expressed as exponents referred to the standard pressure of 200 kPa. Rolling resistance clearly decreases as inflation pressure is raised. However, the resistance reduction effect diminishes the higher the pressure.
Fig. 13 shows the change in energy dissipated in different parts of the tyre (here divided into tread, belt, carcass, sidewall and lower sidewall) when the inflation pressure is varied. Clearly, much more energy is dissipated in the tread than elsewhere. Fig. 14 shows the percentage contributions of each part of the tyre to rolling resistance. It will be seen that, when inflation pressure increases, the belt makes an increasing contribution to rolling resistance while the sidewall and lower sidewall make less contribution.

Fig. 15 shows the relation between the calculated and observed rolling resistance when the load is varied. Both the calculated and observed values are shown as exponents referred to the values at a load of 3.0 kN. Rolling resistance clearly increases with increase in load. It will also be seen that, although the increase in rolling resistance is almost linear, the slope increases at loads above normal (3.0 kN in this case).

Fig. 16 shows the change in energy dissipation in different parts of the tyre when the load is varied. Although more energy is dissipated in all parts of the tyre with increase in load, there is a particularly large increase in energy dissipation in the tread. Fig. 17 shows the percentage contributions of different parts of the tyre. When load increases, the contribution made by the belt decreases while the contributions of the sidewall and lower sidewall (bead) increase. This is because, with increasing load, tyre deflection increases and the deformation corresponding to this deflection becomes relatively larger going from the tyre sidewall to the bead.
Fig. 14 and Fig. 17 show that decrease in inflation pressure is the same as increase in load if identified as a change in relative loading referred to the load capacity at that pressure (the load the tyre inflated at that pressure is capable of supporting). Thus, when the relative loading increases, the contribution of the belt decreases while the contributions of the sidewall and lower sidewall increase.

4.2 Rolling resistance in relation to tyre structure and geometry

Fig. 18 shows the relation between rolling resistance and the section width of the inflated tyre. It will be seen that as the tyre width increases, rolling resistance tends to decrease. This is because the stiffness of the sidewall diminishes with increasing tyre width: this increases the deformation of the sidewall, which makes a small contribution to rolling resistance, but reduces the deformation of the tread, which make a large contribution to rolling resistance. Fig. 17 shows the change in energy dissipation in different parts of the tyre as the section width is varied. Clearly, the main effect of increased section width is to reduce energy dissipation in the tread and belt, supporting the foregoing explanation.

Fig. 19 shows the relation between bead filler height and rolling resistance. Rolling resistance increases the greater the height of the bead apex. The explanation for this is that the volume of material responsible for hysteresis loss increases as bead height increases, with the result that more energy is dissipated in the lower sidewall. This is clearly reflected in the distribution of energy dissipation among different parts of the tyre.
tyre in Fig. 21. Moreover, owing to the increased stiffness of the sidewall, sidewall deformation decreases when bead filler height increases, with the result that rolling resistance also increases in response to the relative increase in deformation of the tread, which makes a large contribution to rolling resistance.

Fig. 22 shows the relation between rolling resistance and tread radius (the radius of curvature of the tread surface in the tyre cross-section). Rolling resistance decreases with increase in tread radius. This is because, as the tread radius increases, less strain energy is produced by the bending deformation generated when the tyre deforms into planar ground contact, especially the bending deformation in the tyre cross-sectional direction. Fig. 23 shows the energy dissipation in different parts of the tyre for different tread radii. It is clear that the decrease in rolling resistance as tread radius increases is due mainly to reduced energy dissipation in the tread and belt.

5. CONCLUSION

The above account has described the use of simulation as a means of reducing the rolling resistance of tyres and presented the options for reducing resistance in relation to tyre structure. Reduced rolling resistance has to be realised by a combination of the various means indicated without detracting from other mutually conflicting requirements (such as wetskid resistance, directional stability and vibrational characteristics). Along with tyre geometry and the disposition of the rubber, specific measures must in particular consider the effects on rolling resistance of the belt and carcass layers, which are composite materials (FRR). In this context, rather than existing know-how and experience, predictive technology using simulation as a means of investigation from the tyre structural standpoint is essential for speeding up development.

This article is an amplified and revised version of ref. 6.

REFERENCES

6. Z. Shida, M. Koishi, T. Kogure and K. Kabe, Tire Science and Technology, TSTCA, 27, 1999, p. 84

Fig. 21 Energy dissipated in different parts of the tyre at different bead filler heights

Fig. 22 Relation between rolling resistance and tread radius

Fig. 23 Energy dissipated in different parts of the tyre for different tread radii

(No date given)