Inflation pressure effect on whole tyre hysteresis ratio and radial spring constant

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The basic equation for rolling loss \( R \) in terms of the whole tyre hysteresis ratio \( h \) is modified by incorporating tyre radial stiffness \( K \) and rewritten as \( R = L^2 (h/K) \), \((w/A)\), where \( w \) and \( A \) are footprint dimensions. Tyre inflation pressure \( p \) influences the magnitude of \( h \) and \( K \). The primary objective of the present study is to obtain quantitative expressions relating \( h \) versus \( p \) and \( K \) versus \( p \). Three P195/75R14 size radial tyres are selected for the present investigation. The \( h \) and \( K \) values of these tyres are measured as a function of \( p \) and analyzed by invoking two limiting structural terms, viz., structural hysteresis ratio \( h(0) \) and structural radial stiffness \( K(0) \). The empirical relation between \( h \) and \( p \) is found to be inversely related as \( h = k (1/p) \). The \( h(0) \) values are about 0.38, 0.27 and 0.28 for tyres 1, 2 and 3. The hysteresis ratio reduction factor \( h(f) \) is normalized with respect to \( h(0) \) and is found to be about 78\% of \( h(0) \) value of the respective tyre. The \( K \) term is partitioned into structural stiffness \( K(0) \) and inflation pressure stiffness \( K(a) \). The \( K(0) \) values are about 60, 25 and 67 N/mm respectively. The \( K \) versus \( p \) relation can be expressed as \( K = K(0) + m.p. = K(0) + K(a) \). The pressure stiffness \( K(a) \) is directly proportional to \( p \) as \( K(a) = 0.56p \). These empirical equations with experimentally determined fitting coefficients \( k \), \( x \) and \( m \) for the three P195/75R14 tyres are presented. This study indicates that the tyre size primarily controls the magnitude in reduction of \( h \), through \( h(f) \), and the increase in \( K \), through \( K(a) \), with \( p \). The total tyre load of 5337 N is separated into structural load and pressure load; the former load has a direct relationship with \( R \) while the latter has an inverse relation. This is a new analytical approach relating tyre load and rolling loss.

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Rolling loss or rolling resistance is one of the tyre performance properties of interest to tyre and automobile industries. Many researchers have performed extensive research to develop energy efficient tyre with lower rolling resistance to reduce gasoline consumption. This is all the more relevant now because of the steep increase in crude oil price. In the early 1980s, Clark\(^1\) presented a review on rolling resistance; later in the 1990s Schuring and Futamura\(^2\) published a comprehensive review with extensive bibliography\(^2\). These papers covered research work by various authors to understand and reduce rolling loss by compound modification, design changes, thermal modeling and finite element analysis method. Pillai and Fielding-Russell\(^3\) approached the problem from a different perspective, viz., the conservation of energy principle. They developed an equation for rolling loss \( R \) in terms of the whole tyre hysteresis ratio \( h \) as

\[
R = hLd(w/A)
\]

where \( L \), \( d \), \( w \) and \( A \) are tyre load, tyre deflection, footprint width and footprint area, respectively. The hysteresis ratio \( h \) of a loaded inflated rolling tyre is defined as the ratio of the energy lost to the total input energy as the footprint goes through a loading/unloading cycle. The radial stiffness \( K \) is defined as \( K = L/d \). Substituting for \( d \) Eq. (1) could be modified as

\[
R = L^2 (h/K)(w/A)
\]

The \( h \) and \( K \) terms were tyre composite properties and \( w \) and \( A \) were footprint dimensions. Eq. (2) indicated that \( h \), \( K \), \( w \) and \( A \) were the first order parameters that affect rolling resistance. The hysteresis ratio \( h \) was mainly due to the material property and the radial stiffness \( K \) due to tyre design. Values of \( h \) and \( K \) were measured at operating load/pressure conditions. Inflation pressure \( p \) was a tyre operating parameter. It could be inferred from first principles that the parameters \( h \) and \( K \) were related to the inflation pressure \( p \); but no quantitative expressions between these terms were known before. Earlier research had been confined to understand the direct relation between the pressure \( p \) and rolling loss \( R^{K3} \). The present study aims to quantify the relation between tyre operating pressure \( p \) on one side and tyre properties \( h \) and \( K \) on the other.
Special terms and explanation

The following terms, \( h(0) \) the tyre structural hysteresis ratio; \( h(f) \) the normalized hysteresis reduction factor; \( K(0) \) the tyre structural stiffness; and \( K(a) \) the stiffness of contained air in the tyre cavity were defined and introduced here.

Tyre structural hysteresis ratio \( h(0) \)

The \( h(0) \) term is defined as the hysteresis ratio of the tyre structure at zero inflation pressure supporting manufacturer’s recommended load for the selected tyre. Primarily, this is a material property. The \( h(0) \) is the maximum limiting hysteresis ratio value and is an inherent property.

Pneumatic hysteresis reduction factor \( h(f) \)

This is the percentage reduction in \( h(0) \) as pressure \( p \) increases. The reduction factor \( h(f) \) is equal to \([h(0) - h]/100\) \( h(0) \), i.e., \( h(f) \) value is normalized with respect to the tyre property \( h(0) \). All these hysteresis ratio values are obtained between zero and the recommended load and are dimensionless numbers.

Structural radial stiffness \( K(0) \)

\( K(0) \) term is defined as the stiffness of the physical structure of the tyre at zero inflation at the recommended load. This is the limiting minimum radial stiffness of the tyre and is another inherent property. The magnitude of \( K(0) \) might be mostly dependent on the various tyre design parameter values.

Radial stiffness of contained air \( K(a) \)

This radial stiffness \( K(a) \) is the stiffness due to the inflation pressure alone, i.e., the stiffness due to the contained air in the tyre cavity. \( K(a) \) is a direct function of pressure \( p \).

Inflation pressure effects

Inflation pressure effect on \( h \)

The \( h(0) \) may be considered as a basic tyre parameter combining the effect of material hysteresis ratio values of all tyre components, viz., tread, belt and carcass. As a tyre gets inflated to a pressure \( p \) its original \( h(0) \) value gets modified. The \( h \) value was measured at tyre operating load/pressure condition for passenger or truck tyre. The \( h \) value decreased as \( p \) increased. This experimental data implied an inverse relationship in the form \( h = k (1/p^x) \). The fitting coefficients \( k \) and \( x \) were determined and a quantitative expression connecting \( h \) and \( p \) was developed. The pneumatic hysteresis reduction factor \( h(f) \) was related to \( p \) through the parameter \( h \). Experimental details of measuring \( h \) and \( h(f) \) as a function of \( p \) were presented in the foregoing.

Inflation pressure effect on \( K \)

The total radial stiffness \( K \) term was partitioned into structural stiffness \( K(0) \) and inflation pressure stiffness \( K(a) \). The \( K \) values were measured as a function of inflation pressure \( p \). The empirical equation connecting \( K \) against \( p \), viz., \( K = K(0) + m.p \) expressed the inflation pressure effect. Here, the pressure stiffness \( K(a) \) was directly proportional to \( p \) as \( K(a) = m.p \). The \( K(0) \) stiffness value was an inherent property of tyre structure and could be considered as independent of \( p \). So, the pressure effect on \( K \) was acting through the \( K(a) \) term.

Experimental Procedure

Measuring \( h \) and \( K \) values

Three different P195/75R14 size tyres were selected for this study. The recommended load for this tyre was 5337 N and the working pressure range was 207-262 kPa. The experimental set-up and details to measure the whole tyre hysteresis ratio \( h \) and the radial stiffness \( K \) were published earlier. Each inflated tyre was mounted in an Instron, cycled between 0 and 5337 N load, hysteresis loop recorded, and the maximum deflection noted. The \( h \) values were determined over the range of \( p \) values from 103 to 262 kPa. These results ranged from 0.097 to 0.073 for tyre 1; ranged from 0.063 to 0.049 for tyre 2; and ranged from 0.078 to 0.060 for tyre 3. Tyre deflection \( d \) values were noted and the respective \( K \) values determined. These results are given in Table 1.

The \( K(0) \) value of tyre 2, i.e., 25.0 N/mm is less than those of tyres 1 and 3 from Table 1. Tyre 2 has low \( R \) values (see Table 4). The low stiffness number apparently contradicts the lower \( R \) value for tyre 2; a possible explanation of this apparent inconsistency is presented here. Eq. (2) indicates that \( R \) is a function of \((h/K)\) ratio; hence \( R \) can be decreased by reducing \( h \) or by increasing \( K \). The compounding chemists generally approach the problem of reducing \( R \) by developing low hysteresis compound with low modulus. Based on this concept the compounding group developed low hysteresis compounds for tread, carcass and belt stocks and the tyre group built tyre 2 using these newly developed compounds. These low hysteresis compounds are of low modulus and hence soft. This explains the low stiffness value \( K(0) \). Though \( K(0) \) is
small for this tyre the corresponding \( h \) value is also low. This might explain the reduced \( R \) value for this tyre. The compounding recipe is proprietary and confidential.

**Determining \( h(0) \)**

As explained earlier the structural hysteresis ratio \( h(0) \) was defined as the hysteresis ratio of a tyre at zero inflation pressure and standard load. This meant that for these tyres the \( h(0) \) values were to be determined at the recommended load of 5337 N load at zero inflation. This load was too severe for the zero pressure condition. The tyre would become flat at this high load with no inflation and therefore the hysteresis loop could not be obtained. Hence, direct measurement was not possible. Therefore, one indirect experimental method and a second analytical method were used to estimate the \( h(0) \) values.

**Experimental method for \( h(0) \)**

Complete experimental details were given elsewhere. In brief two sets of hysteresis loops were collected: Set I – Inflation pressure range 35, 69, 103, 138, 241, 262 kPa and load range 0-5337 N; Set II – Inflation pressure range 0, 35, 69, 103 kPa and load range 0-890 N. The whole tyre hysteresis ratio relevant to the rolling resistance calculation is the \( h \) value at the operating load of 5337 N. Therefore, the \( h(0) \) value has also to be obtained at the same load. Because the \( h(0) \) value cannot be measured experimentally at the above load condition it was estimated using a correction factor. The hysteresis loop areas at the common inflation pressure conditions 35, 69 and 103 kPa were measured and the respective ratio obtained. The hysteresis correction factor for each tyre was estimated as the mean value of these three ratios. Each correction factor was applied to the respective hysteresis measurement at 0 kPa pressure condition and the corresponding \( h(0) \) value determined. The \( h(0) \) values were found to be about 0.38, 0.27 and 0.28 for tyres 1, 2 and 3 respectively.

**Components method for \( h(0) \)**

Here, \( h(0) \) was expressed as the sum of the product of the hysteresis ratio of the tread, carcass and belt package, respectively and the respective volume fractions. Then \( h(0) \) could be expressed as

\[
h(0) = h(t) \cdot v(t) + h(c) \cdot v(c) + h(b) \cdot v(b)
\]

... (3)

where \( h(t) \), \( h(c) \) and \( h(b) \) are the hysteresis ratio of the tread, carcass and belt package, respectively and \( v(t) \), \( v(c) \) and \( v(b) \) are the respective volume fractions. The experimental procedure was as follows: two test pieces, size about 25 × 100 mm of tread, carcass and belt package sections, were cut from each tyre. Each tread test piece was supported on a 3-point bending jig, the hysteresis loop obtained and the \( h(t) \) value estimated. Few repeat measurements were made and the mean \( h(t) \) value determined. Similarly, \( h(c) \) and \( h(b) \) hysteresis values were also obtained. Another research group supplied the component volume fractions. Then, \( h(0) \) values were calculated via Eq. (3) and were found to be about 0.35, 0.25 and 0.26 for the three tyres. The tyre bead region was too stiff to obtain the hysteresis loop. Also its component volume was too small and hence not included. The total tyre component volume fraction exclusive of the bead was about 93 to 98%. Table 2 lists the \( h(0) \) values by both methods.

<table>
<thead>
<tr>
<th>Table 1 — The whole tyre hysteresis ratio ( h ) and radial stiffness ( K ) values as a function of inflation pressure ( p )</th>
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<tbody>
<tr>
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<tr>
<td><strong>Tyre 1</strong></td>
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<td>( h(0) )</td>
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<td>( K(0), \text{N/mm} )</td>
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<tr>
<td>Inflation pressure, kPa</td>
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<td>103</td>
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<td>138</td>
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Results and Discussion

Effect of pressure on hysteresis ratio $h$

As mentioned earlier the $h$ values were measured only for pressures higher than 103 kPa and the data presented in Table 1. Such $h$ measurements could not be performed for $p$ values less than 103 kPa because the 5337 N load was too heavy for this low pressure condition. The $h$ versus $p$ relation was estimated using the $h$ values corresponding to $p$ values higher than 103 kPa. It was obvious from these results that $h$ was inversely related to $p$. These $h$ versus $p$ data points were fitted to an inverse power equation

$$h = k \cdot \left(1/p^x\right) \quad \ldots \quad (4)$$

where $k$ and $x$ were fitting coefficients. The $h$ versus $p$ curves for the three tyres were shown in Fig. 1. The typical $h$ versus $p$ relation was found to be

- $h = 0.35 \cdot (1/p^{0.27})$ for tyre 1 \ldots (5a)
- $h = 0.22 \cdot (1/p^{0.27})$ for tyre 2 \ldots (5b)
- $h = 0.23 \cdot (1/p^{0.23})$ for tyre 3 \ldots (5c)

The magnitude of the exponent could be considered as the effect of pressure on $h$; the higher the values of $x$, the smaller the effect on $h$ assuming other parameters were constant. The pressure exponent might be a function of tyre design. The pressure dependence of $h$ for tyres 1 and 2 was almost the same while that of tyre 3 was different. So, it might be inferred that tyre 3 might be of different design. These empirical equations explain the inflation pressure effect on tyre hysteresis ratio.

Determining the hysteresis reduction factor $h(f)$

Using the $h$ and the $h(0)$ values the $h(f)$ percentages were obtained via the relation $h(f) = \left[h(0) - h\right]/h(0)$ for the three tyres and were given in Table 3. These results ranged between 74-80%. The $h(f)$ versus $p$ data of each tyre were fitted to a linear regression equation. The three $h(f)$ versus $p$ equations were not statistically different. Hence, all data points were combined and a composite plot made (Fig. 2). The composite linear equation could be expressed as

$$h(f) = 0.7149 + 0.0003 \cdot p \quad \ldots \quad (6)$$

Especially for the working pressure range $h(f)$ value was found to be the same with an average value of about 78% for all three tyres. This analysis implied that the $h$ value of each of these tyres at working pressure range was only about 22% (1-78%) of the

| Table 2— Structural hysteresis ratio $h(0)$ values by different methods |
|----------------|----------------|----------------|
| Method         | Tyre 1         | Tyre 2         | Tyre 3         |
| Experimental   | 0.38           | 0.27           | 0.28           |
| Analytical     | 0.35           | 0.25           | 0.25           |

| Table 3— The normalized hysteresis reduction factor $h(f)$ as a function of pressure $p$ |
|----------------|----------------|----------------|
| Tyre 1         | Tyre 2         | Tyre 3         |
| $h(0)$         | 0.38           | 0.27           | 0.28           |
| Inflation pressure, kPa | $h(f)$ % | $h(f)$ % | $h(f)$ % |
| 103            | 74             | 77             | 73             |
| 138            | 76             | 77             | 75             |
| 173            | 77             | 78             | 76             |
| 207            | 78             | 79             | 75             |
| 242            | 79             | 81             | 77             |
| 262            | 81             | 82             | 78             |
hysteresis helps, but it is not the complete answer. This approach, which might be a method of reducing rolling resistance. Tyre 2 data substantiates this approach, and the design parameter of a particular component affect the component hysteresis and through it the tyre h(0). It is obvious that reducing h(0) of a tyre reduces its final h value which in turn reduces tyre rolling loss. This is the compounding approach, which might be a method of reducing rolling resistance. Tyre 2 data substantiates this approach as explained earlier. Thus, lower material hysteresis helps but it is not the complete answer.

Effect of pressure on radial stiffness $K$

$K$ versus $p$ data from Table 3 for the three tyres were fitted to a linear equation of the form

$$K = C + m.p \quad \ldots \quad (7)$$

where $C$ was a constant and $m$ was the slope. These $K$ versus $p$ linear equations

- $K = 60 + 0.54. \, p$ for tyre 1  \quad \ldots \quad (8a)
- $K = 25 + 0.60. \, p$ for tyre 2  \quad \ldots \quad (8b)
- $K = 67 + 0.55. \, p$ for tyre 3  \quad \ldots \quad (8c)$

were shown in Fig. 3. The $Y$ intercept $C$ could be taken as $K(0)$, the structural radial stiffness. The slope $m$ was nearly the same for the three tyres indicating that the pressure dependence of $K$ was approximately the same. The tyre size was the common factor in this case also. A composite plot of $K$ versus $p$ showed that $K(a)$ could be expressed as

$$K(a) = 0.56. \, p \quad \ldots \quad (9)$$

Equation $K = K(0) + m.p = K(0) + K(a)$ elucidates the relation between radial stiffness versus inflation pressure. It is seen that $K(a)$ is directly proportional to $p$. Tyre stiffness $K$ can be increased by increasing $K(0)$ and/or by increasing $K(a)$. In service situation the inflation pressure $p$ cannot be increased much beyond the working pressure range because of safety consideration and burst pressure limit. $K(0)$ value can be increased by suitably changing the design of one or more tyre components.

Partitioning total load into structural load and air pressure load

It could be deduced from tyre as a spring model the total radial stiffness $K$ supports the vertical load $L$ on the tyre, i.e., $L = K. \, d = [K(0) + K(a)]. \, d$, where $d$ was tyre deflection. Therefore, it could be concluded that part of the load was supported by the structural stiffness $K(0)$ and the remaining load was supported by the spring constant $K(a)$ of the contained air. Let $L(s)$ be the load supported by the tyre structure and $L(a)$ be the load supported by the inflation pressure. $K(a)$ values were calculated as a function of $p$ from 103 to 267 kPa. Then, the total applied load of 5337 N for each tyre was separated into the respective $L(s)$ and $L(a)$ load values. Table 4 showed these load results and the corresponding rolling loss values.

The magnitudes of the experimental parameters $d$, $h$ and $K$ of the three tyres and the respective $R$ values, shown in Tables 1 and 4, are further compared and analyzed. The $R$ value of tyre 2 is less than that of tyres 1 and 2 though the $d$ value is higher. This apparent contradiction can be explained by invoking Eq. (1). The magnitude of $R$ depends on the product of $d$ and $h$. The higher $d$ value of tyre 2 is compensated by the smaller $h$ value; therefore its $R$ value is small relative to other two tyres.

![Fig. 3—Tyre stiffness $K$ versus inflation pressure $p$](image-url)
As $p$ increased the structural load $L(s)$ decreased and the pressure load $L(a)$ increased. The linear equations between $R$ and $L(s)$ were found to be

\[
R = 5.71 + 0.0174 \times L(s) \quad \text{for tyre 1} \quad \ldots \quad (10a) \\
R = 8.60 + 0.0207 \times L(s) \quad \text{for tyre 2} \quad \ldots \quad (10b) \\
R = 7.36 + 0.0123 \times L(s) \quad \text{for tyre 3} \quad \ldots \quad (10c)
\]

These equations showed one-to-one correspondence between $R$ and $L(s)$, i.e., $R$ increased linearly as $L(s)$ increased in agreement with Eq. (1). The direct linear relation between $R$ and $L(s)$ implied that $L(s)$ was the load that influenced the rolling loss. This analysis indicated that the effect of total load $L$ on $R$ was acting directly through the structural load $L(s)$. The $L(a)$ term influences the $R$ value only indirectly through its relation to $L(s)$. If the magnitude of $L(a)$ could be increased then the $L(s)$ value could be decreased; then the rolling loss could be reduced.

Two terms, total rolling resistance coefficient $R$(coeff.) and structural rolling resistance coefficient $R$(struc. coeff.), were introduced and defined as $R$(coeff.) = $[R, N/L, N] .100$ and $R$(struc. coeff.) = $[R, N/L(s), N] .100$. The $R$(coeff.) values were calculated for the three tyres using the total load $L = 5337$ N while the $R$(struc. coeff.) values were determined using the respective $L(s)$ values for each tyre. These coefficient values were given in Table 5. $R$(struc. coeff.) seemed to be independent of $p$ within experimental variation while the $R$(coeff.) was consistently decreased with increasing $p$ values. $R$(coeff.) was inversely related to $p$ as $[R$(coeff.), $\alpha 1/p^\gamma]$, where $\gamma$ is the pressure exponent. These exponent values were about 0.51, 0.56 and 0.45 for tyres 1, 2 and 3, which were in agreement with similar results obtained earlier. The mean $R$(struc. coeff.) values were about 2.0, 2.9 and 1.6 for tyres 1, 2 and 3 respectively.

As mentioned earlier, the magnitude of $L(a)$ was a function of $K(a)$ at a specific $p$ value. This analysis leads to an interesting suggestion: For a particular tyre size $L(a)$ can be increased by increasing $K(a)$. Probably, this can be accomplished by tyre design modification, viz., adjusting the belt parameters (cord size, epi, angle), tread parameters (rubber modulus, void volume, tread pattern) and carcass parameters (rubber modulus, cord tension, cord size and epi). It is suggested that the tyre design engineer has to focus the effort along this line to reduce the rolling loss.

In summary, this study partitioned $h$ into structural term $h(0)$ and a pneumatic reduction term $h(f)$. Then

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|c|c|c|c|c|}
\hline
 & Tyre 1 & & & Tyre 2 & & & Tyre 3 & \\
\hline
$d$, mm & $R$, N & $L(s)$, N & $L(a)$, N & $d$, mm & $R$, N & $L(s)$, N & $L(a)$, N & $d$, mm & $R$, N & $L(s)$, N & $L(a)$, N \\
\hline
47.33 & 55.6 & 2840 & 2497 & 60.96 & 40.5 & 1524 & 3779 & 40.80 & 44.3 & 2733 & 2603 \\
39.74 & 46.2 & 2384 & 2952 & 49.16 & 34.0 & 1229 & 4108 & 38.10 & 36.6 & 2553 & 2784 \\
34.40 & 41.8 & 2064 & 3273 & 41.75 & 29.8 & 1044 & 4293 & 33.24 & 33.3 & 2227 & 3116 \\
31.00 & 37.8 & 1860 & 3477 & 35.06 & 26.4 & 876 & 4341 & 28.86 & 31.4 & 1933 & 3406 \\
27.21 & 34.5 & 1633 & 3704 & 29.14 & 24.0 & 728 & 4626 & 24.60 & 29.1 & 1648 & 3689 \\
\hline
\end{tabular}
\caption{Structural load $L(s)$ and inflation pressure load $L(a)$ values}
\end{table}

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|c|c|c|c|}
\hline
Inflation & $R$(struc. coeff.)* & $R$(coeff.)* & & $R$(struc. coeff.)* & $R$(coeff.)* & & $R$(struc. coeff.)* & $R$(coeff.)* \\
p, kPa & Tyre 1 & Tyre 2 & Tyre 3 & Tyre 1 & Tyre 2 & Tyre 3 & Tyre 3 \\
\hline
103 & 1.95 & 2.65 & 1.62 & 1.04 & 0.76 & 0.83 & \\
138 & 1.92 & 2.76 & 1.43 & 0.86 & 0.63 & 0.68 & \\
173 & 2.00 & 2.85 & 1.49 & 0.78 & 0.55 & 0.62 & \\
207 & 2.00 & 3.00 & 1.62 & 0.71 & 0.50 & 0.59 & \\
262 & 2.10 & 3.31 & 1.76 & 0.64 & 0.45 & 0.54 & \\
Mean & 1.99 & 2.91 & 1.58 & & 0.19 & & \\
$\sigma$ & 0.045 & & & & 0.099 & & \\
\hline
\end{tabular}
\caption{$R$(struc. coeff.) and $R$(coeff.) values as functions of $p$}
\end{table}

* $R$(s. c)—$R$(struc. coeff.)
# $R$(co)—$R$(coeff.)
an empirical relationship between $h$ and $p$ was formulated as $h = k \cdot (1/p^x)$ for P195/75R14 size passenger tyre. Eqs (5a)-(5c) expressed similar quantitative relations between the hysteresis ratio $h$ on one side and inflation pressure $p$ on the other. Similarly, the $K$ term was bifurcated into structural component $K(0)$ and pressure stiffness term $K(a)$. Similarly, tyre stiffness $K$ was found to be related to the inflation pressure $p$ by a linear equation of the form $K = K(0) + 0.56 \cdot p$. Tyre load was separated into structural load and pressure spring load. The present analysis indicates that the operating parameter $p$ influences the $h$ and $K$ parameters through the $h(f)$ and $K(a)$ terms. Total tyre load has been partitioned into structural and pressure load.

Conclusions

Tyre size was the primary governing factor for hysteresis ratio reduction and the magnitude of stiffness increase with respect to working pressure range irrespective of tyre compound change and design difference. It was shown that the tyre parameters $h$ and $K$ could be separated into two components one pair $h(0)$ and $K(0)$ independent of inflation pressure $p$ and the second pair $h(f)$ and $K(a)$ as functions of $p$. The apparent contradiction between the low $K(0)$ value and low $R$ value of tyre 2 was explained by the low hysteresis compounds used for the tread, carcass and coat stock used in this tyre. Similarly, the apparent contradiction between the higher $d$ value and smaller $R$ value was also explained by the reduced $h$ value corresponding to low hysteresis compounds. In this case the rolling resistance is reduced via the compounding approach.

The structural hysteresis ratio $h(0)$ values were about 0.38, 0.27 and 0.28 for tyres 1, 2 and 3 respectively. The hysteresis ratio value decreased to about 22% (1-78%) of the original $h(0)$ value for the three tyres for the working pressure range of 207-262, kPa inflation. This reduction seemed to be independent of tyre construction. Simple empirical relations of the form $h = k \cdot (1/p^x)$ between $h$ and $p$ was established for the three tyres. The fitting coefficients $k$ and $x$ were obtained experimentally and $h$ versus $p$ equations were formulated for all these tyres. The radial stiffness $K$ was found to be linearly related to $p$ via the equation $K = K(0) + 0.56 \cdot p$, where the inflation pressure spring constant $K(a)$ was equal to $0.56 \cdot p$. The structural stiffness $K(0)$ values were about 60, 25 and 67 N/mm for the three tyres.

This analysis helped to bifurcate the total tyre load into structural load and pressure load. Higher the $K(a)$ value, the higher the pressure load and lower the structural load. This implies that tyre rolling loss could be reduced by increasing $K(a)$, i.e., by increasing inflation pressure. The $R$(struc.coeff.) was found to be independent of inflation pressure for each tyre. The mean values were about 2.0, 2.9 and 1.6 for tyres 1, 2 and 3.

References