Dynamic Characterization of Rubber O-Rings: Squeeze and Size Effects

Original
Dynamic Characterization of Rubber O-Rings: Squeeze and Size Effects / Al-Bender, Farid; Colombo, Federico; Reynaerts, Dominiek; Villavicencio, Rodrigo; Waumans, Tobias. - In: ADVANCES IN TRIBOLOGY. - ISSN 1687-5915. - 2017(2017), pp. 1-12.

Availability:
This version is available at: 11583/2702000 since: 2018-02-27T18:25:56Z

Publisher:
Hindawi

Published
DOI:10.1155/2017/2509879

Terms of use:
openAccess
This article is made available under terms and conditions as specified in the corresponding bibliographic description in the repository

Publisher copyright

(Article begins on next page)
Dynamic Characterization of Rubber O-Rings: Squeeze and Size Effects

Farid Al-Bender,1 Federico Colombo,2 Dominiek Reynaerts,1 Rodrigo Villavicencio,2 and Tobias Waumans3

1Division of Production Engineering, Machine Design and Automation, KU Leuven, Leuven, Belgium
2Department of Mechanical and Aerospace Engineering, Politecnico di Torino, Torino, Italy
3Leuven Air Bearings, KU Leuven, Leuven, Belgium

Correspondence should be addressed to Federico Colombo; federico.colombo@polito.it

Received 2 May 2017; Accepted 13 June 2017; Published 12 July 2017

Copyright © 2017 Farid Al-Bender et al. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

This paper concerns the dynamic characterization of rubber O-rings used to introduce damping in high speed gas bearing systems. O-shaped rubber rings composed of high temperature rubber compounds are characterized in terms of stiffness and damping coefficients in the frequency range 100–800 Hz. Simple formulas with frequency independent coefficients were identified to express the viscoelastic properties of the O-rings. The formulas proposed approximate the stiffness and damping coefficients of O-rings of general size.

1. Introduction

Air bearings at very high speeds can suffer the unstable whirl. A method to overcome this problem is to modify the bearings geometry and increase the stability threshold. An alternative method is to introduce external damping in the system by using a bush supported on rubber O-rings or other elastomeric material. The first experimental work in which the half-speed whirl was avoided by mounting the bushes flexibly goes back 50 years [1]. O-rings were used in gas bearings to improve the static stiffness [2], but in most cases their main function is to overcome the whirl instability in journal bearings [3, 4] or the pneumatic hammer [5]. In [6, 7] an analytical model is developed to predict the restoring and hysteresis characteristics of elastomer O-rings mounted in squeeze film dampers. Stiffness and damping coefficients of the elastic supports which ensure the stability of the rotor are theoretically studied in [8], where it is shown that it is possible to avoid the half-speed whirl. In order to select the support parameters in an optimal way, a stability study is performed in paper [9], in which design guidelines are given.

Literature shows that real viscoelastic materials have to be characterized by more than one relaxation time [12]. Anyway, for the sake of simplicity, a simple Kelvin Voigt model can be sufficiently accurate to predict the dynamic characteristics of rubber O-rings [13]. Finite element method can be used to predict characteristics of rubber rings in static conditions [14–16]. However, the experimental characterization of these O-rings is essential for predicting the threshold speed and calculating the rotor runout in case they are used as damping supports.

The stiffness and damping coefficients of these rubber elements depend on several parameters: temperature, amplitude and frequency of the excitation, preload, material, and size of the O-ring [17]. In [18] axial forces transmitted by O-rings subjected to a reciprocating drag were measured for various amplitudes and frequencies. Papers [10, 19] describe some test benches used to measure the viscoelastic properties of O-rings. In paper [20] a simplified approach for the proper selection of elastomers is proposed.

In a previous work [11] dynamic stiffness and damping coefficients of O-rings composed of NBR and Viton® materials were measured. Analogous O-ring properties were found in [3]. In the present paper O-rings composed of high temperature resistant rubber are tested with a test rig for the purpose developed in University of Leuven. The aim is
to identify stiffness and damping properties of O-rings of
general size which could be used to study the stability of
gas bearings, which are prone to whirl instability [21] or to
pneumatic hammer instability. These coefficients could be
inserted in lumped parameters models of gas bearings [22–
24] to evaluate their increased stability thanks to the use of
the O-rings.

2. Materials and Methods

In literature two test methods can be found to measure the
elastomer O-rings properties: the indirect method, named
resonant mass method [17, 19], and the direct method.

In the first method (see [17]), the O-ring is compressed
between a shaft, connected to the shaker base, and a bush,
attached to a suspended mass. The displacements of the two
elements that compress the O-ring are measured and no force
transducers are needed.

The direct method, adopted in the present paper, consists
in measuring directly the force transmitted by the O-ring.
A test bench was set up as depicted in Figure 1. The O-ring
under test (1) is compressed between bushing (2), connected
to the stinger of shaker (7), and shaft (3), fixed to support (5).
The load cell (4) is placed between support (5) and the fixed
frame (6). By means of the shaker a sinusoidal displacement
is imposed to the bushing. This displacement is detected
by sensors (8), mounted on support (5). The signals from
the load cell and the displacement transducers are sent to a
DAQ system and then elaborated. Table 1 shows a list of the
instrumentation used and Figure 2 shows a photo of the test
bench.

The fixed frame was designed with FEM software to avoid
resonance in the frequency range of the tests. The first natural
frequency of the fixed frame is about 1.2 kHz, which is above
the frequency range of tests.
Table 1: List of instrumentation.

<table>
<thead>
<tr>
<th>Device</th>
<th>Model</th>
<th>Sensitivity, range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shaker</td>
<td>Type 4809, Bruel &amp; Kjær</td>
<td>45 N, 10 Hz to 2 KHz, 736 ms⁻¹</td>
</tr>
<tr>
<td>Load cell</td>
<td>Type 9256C1, KISTLER</td>
<td>13 pC/N, 250 N</td>
</tr>
<tr>
<td>Displacement transducer</td>
<td>capaNCDT 600, Micro-Epsilon</td>
<td>20 nm–20 μm</td>
</tr>
<tr>
<td>DAQ system</td>
<td>PXI 1100, National Instruments</td>
<td></td>
</tr>
</tbody>
</table>

The O-rings were compressed with a small excitation amplitude (2.5 μm), so their behavior can be assumed to be linear. They were preloaded with various squeeze levels (5%, 10%, 15%, and 20%). The squeeze is defined by

\[ S = \left( 1 - \frac{D_i - D_e}{2\Phi} \right) \cdot 100, \] (1)

where \( \Phi \) is the cross section diameter of the O-ring and \( D_i \) and \( D_e \) are the inside diameter of bushing (2) and the external diameter of shaft (3), respectively (see Figure 1).

2.1. O-Rings under Test. Rubber materials are used for different purposes, for example, vibration isolation, shock absorption, and sealing. Some compounds are designed for high temperatures, like Kalrez and Viton. O-rings composed with such materials can be useful to increase the stability of high speed rotors supported by gas bearings. In literature it is difficult to find experimental data about O-rings of such compounds. For this reason, O-rings made in Viton, Kalrez 4079, and Kalrez 6375 were selected to be tested.

Viton is a fluoropolymer elastomer categorized under the ISO 1629 designation of FKM. Its density (1800 kg/m³) is significantly higher than that of most types of rubber. It is used in a broad range of applications for its low cost. Compounds of Shore hardness of 75 and 90 were designated in this paper.

Kalrez is a perfluoroelastomer material (FFKM) with high chemical resistance; it has a temperature stability comparable with that of PTFE. It is mostly used in highly aggressive chemical processing, pharmaceutical, and aerospace applications. In particular, Kalrez 4079 is a carbon black filled compound with a maximum operating temperature of 315°C. Kalrez 6375 has maximum operating temperature of 275°C. Their Shore hardness is 75.

Table 2 shows details of the O-rings tested. The maximum temperature of the materials, the inner diameter \( d \), and the cross section diameter \( \Phi \) are indicated.

2.2. Test Procedure. In this section the procedure used to measure the dynamic stiffness of the O-rings is described. All tests were performed at constant ambient temperature of 20°C. Each O-ring was tested at different frequencies by imposing the sinusoidal displacement \( x \) (the input) and measuring the transmitted force \( F \) (the output). For each frequency, the shaker amplitude was adjusted in open loop until displacement sensors indicated the required value (small displacement). On the base of the time functions \( F(t) \) and \( x(t) \) acquired at several frequencies the experimental transfer functions \( F(s)/x(s) \) were obtained. The transfer function is defined as ratio:

\[ T_{xF}(\omega) = \frac{P_{FX}(\omega)}{P_{XX}(\omega)}, \] (2)

where \( P_{FX} \) is the cross power spectral density of \( x \) and \( F \) and \( P_{XX} \) is the power spectral density of \( x \). Using a Kelvin Voigt model the transfer function can be written as follows:

\[ \frac{F(s)}{x(s)} = k + cs. \] (3)

Stiffness and damping coefficients were calculated with the following formulas:

\[ k(\omega) = \text{Re} \left( \frac{F(j\omega)}{x(j\omega)} \right), \] (4a)

\[ c(\omega) = \frac{1}{\omega} \text{Im} \left( \frac{F(j\omega)}{x(j\omega)} \right). \] (4b)

Finally, a least square procedure (see Appendix A) was adopted to find a best fit for the experimental data. This brought expressions for stiffness and damping in the exponential form

\[ k = A\omega^{\alpha}, \] (5a)

\[ c = B\omega^{\beta}. \] (5b)

In these relations the pulsation is expressed in rad/s.

3. Results and Discussion

An example of Bode diagram is shown in Figure 3. It can be noticed that, approaching the resonance frequency of the test bench, the Bode diagram has a peak in the amplitude. Also the phase changes abruptly. For this reason, data at frequencies over 850 Hz are neglected.

3.1. Frequency Dependence. The results are summarized in Tables 3–5 for Viton 75, Viton 90, and Kalrez, respectively. They are presented in the form of coefficients \( A, B, \alpha, \) and \( \beta \).
### Table 3: Summary of the results for Viton 75 O-ring.

<table>
<thead>
<tr>
<th>d (mm)</th>
<th>Φ (mm)</th>
<th>S%</th>
<th>A · 10^6</th>
<th>α</th>
<th>k200 (MN/m)</th>
<th>B · 10^6</th>
<th>β</th>
<th>c200 (Ns/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>11</td>
<td>1.78</td>
<td>5</td>
<td>0.0347</td>
<td>0.331</td>
<td>0.368</td>
<td>0.0293</td>
<td>−0.666</td>
<td>253</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10</td>
<td>0.131</td>
<td>0.268</td>
<td>0.887</td>
<td>0.0298</td>
<td>−0.508</td>
<td>794</td>
</tr>
<tr>
<td></td>
<td></td>
<td>15</td>
<td>0.0666</td>
<td>0.384</td>
<td>1.032</td>
<td>0.0335</td>
<td>−0.544</td>
<td>690</td>
</tr>
<tr>
<td></td>
<td></td>
<td>20</td>
<td>0.155</td>
<td>0.295</td>
<td>1.272</td>
<td>0.094</td>
<td>−0.666</td>
<td>847</td>
</tr>
<tr>
<td>11</td>
<td>2.62</td>
<td>10</td>
<td>0.275</td>
<td>0.192</td>
<td>1.082</td>
<td>0.469</td>
<td>−0.923</td>
<td>647</td>
</tr>
<tr>
<td></td>
<td></td>
<td>15</td>
<td>0.111</td>
<td>0.384</td>
<td>1.720</td>
<td>0.177</td>
<td>−0.673</td>
<td>1453</td>
</tr>
<tr>
<td></td>
<td></td>
<td>20</td>
<td>0.08</td>
<td>0.492</td>
<td>2.679</td>
<td>0.369</td>
<td>−0.735</td>
<td>1946</td>
</tr>
<tr>
<td>41</td>
<td>1.78</td>
<td>5</td>
<td>0.1644</td>
<td>0.474</td>
<td>4.8402</td>
<td>0.0328</td>
<td>−0.297</td>
<td>3940</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10</td>
<td>0.1811</td>
<td>0.463</td>
<td>4.9298</td>
<td>0.0389</td>
<td>−0.311</td>
<td>4228</td>
</tr>
<tr>
<td></td>
<td></td>
<td>15</td>
<td>0.0550</td>
<td>0.631</td>
<td>4.9655</td>
<td>0.0320</td>
<td>−0.278</td>
<td>4405</td>
</tr>
<tr>
<td></td>
<td></td>
<td>20</td>
<td>0.1378</td>
<td>0.542</td>
<td>6.5927</td>
<td>0.0370</td>
<td>−0.273</td>
<td>5278</td>
</tr>
<tr>
<td>41</td>
<td>2.62</td>
<td>5</td>
<td>0.0791</td>
<td>0.51</td>
<td>3.0100</td>
<td>0.0115</td>
<td>−0.209</td>
<td>2584</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10</td>
<td>0.0903</td>
<td>0.555</td>
<td>4.7403</td>
<td>0.0223</td>
<td>−0.254</td>
<td>3647</td>
</tr>
<tr>
<td></td>
<td></td>
<td>15</td>
<td>0.0958</td>
<td>0.56</td>
<td>5.2100</td>
<td>0.0286</td>
<td>−0.27</td>
<td>4164</td>
</tr>
<tr>
<td></td>
<td></td>
<td>20</td>
<td>0.1427</td>
<td>0.541</td>
<td>6.7758</td>
<td>0.0408</td>
<td>−0.291</td>
<td>5112</td>
</tr>
</tbody>
</table>

### Table 4: Summary of the results for Viton 90 O-ring.

<table>
<thead>
<tr>
<th>d (mm)</th>
<th>Φ (mm)</th>
<th>S%</th>
<th>A · 10^6</th>
<th>α</th>
<th>k200 (MN/m)</th>
<th>B · 10^6</th>
<th>β</th>
<th>c200 (Ns/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>11</td>
<td>1.78</td>
<td>5</td>
<td>0.229</td>
<td>0.132</td>
<td>0.588</td>
<td>0.654</td>
<td>−1.006</td>
<td>499</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10</td>
<td>0.504</td>
<td>0.218</td>
<td>2.386</td>
<td>0.620</td>
<td>−0.917</td>
<td>892</td>
</tr>
<tr>
<td></td>
<td></td>
<td>15</td>
<td>0.125</td>
<td>0.379</td>
<td>1.861</td>
<td>0.058</td>
<td>−0.557</td>
<td>1082</td>
</tr>
<tr>
<td></td>
<td></td>
<td>20</td>
<td>1.380</td>
<td>0.160</td>
<td>4.323</td>
<td>0.069</td>
<td>−0.462</td>
<td>2568</td>
</tr>
<tr>
<td>11</td>
<td>2.62</td>
<td>10</td>
<td>1.428</td>
<td>0.114</td>
<td>3.221</td>
<td>0.460</td>
<td>−0.828</td>
<td>1249</td>
</tr>
<tr>
<td></td>
<td></td>
<td>15</td>
<td>5.602</td>
<td>0.072</td>
<td>9.385</td>
<td>22.750</td>
<td>−1.364</td>
<td>1348</td>
</tr>
<tr>
<td></td>
<td></td>
<td>20</td>
<td>0.472</td>
<td>0.416</td>
<td>9.188</td>
<td>11.280</td>
<td>−1.122</td>
<td>3758</td>
</tr>
<tr>
<td>41</td>
<td>1.78</td>
<td>5</td>
<td>0.0994</td>
<td>0.597</td>
<td>7.039</td>
<td>0.028</td>
<td>−0.245</td>
<td>4868</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10</td>
<td>0.116</td>
<td>0.617</td>
<td>9.485</td>
<td>0.050</td>
<td>−0.296</td>
<td>6048</td>
</tr>
<tr>
<td></td>
<td></td>
<td>15</td>
<td>0.284</td>
<td>0.521</td>
<td>11.691</td>
<td>0.090</td>
<td>−0.333</td>
<td>8404</td>
</tr>
<tr>
<td></td>
<td></td>
<td>20</td>
<td>0.164</td>
<td>0.625</td>
<td>14.204</td>
<td>0.195</td>
<td>−0.443</td>
<td>8249</td>
</tr>
<tr>
<td>41</td>
<td>2.62</td>
<td>5</td>
<td>0.329</td>
<td>0.487</td>
<td>10.637</td>
<td>0.093</td>
<td>−0.390</td>
<td>5750</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10</td>
<td>0.362</td>
<td>0.528</td>
<td>15.666</td>
<td>0.158</td>
<td>−0.421</td>
<td>7823</td>
</tr>
<tr>
<td></td>
<td></td>
<td>15</td>
<td>0.421</td>
<td>0.492</td>
<td>14.083</td>
<td>0.218</td>
<td>−0.463</td>
<td>8001</td>
</tr>
<tr>
<td></td>
<td></td>
<td>20</td>
<td>0.740</td>
<td>0.467</td>
<td>20.715</td>
<td>0.171</td>
<td>−0.387</td>
<td>10810</td>
</tr>
</tbody>
</table>

### Table 5: Summary of the results for Kalrez O-ring (d = 11 mm, Φ = 1.78 mm).

<table>
<thead>
<tr>
<th>Material</th>
<th>S%</th>
<th>A · 10^6</th>
<th>α</th>
<th>k200 (MN/m)</th>
<th>B · 10^6</th>
<th>β</th>
<th>c200 (Ns/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kalrez 4079</td>
<td>5</td>
<td>n.a.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>0.080</td>
<td>0.409</td>
<td>1.481</td>
<td>0.0776</td>
<td>−0.580</td>
<td>1237</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>0.214</td>
<td>0.314</td>
<td>2.012</td>
<td>0.193</td>
<td>−0.675</td>
<td>1562</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>0.168</td>
<td>0.391</td>
<td>2.736</td>
<td>0.211</td>
<td>−0.654</td>
<td>1983</td>
</tr>
<tr>
<td>Kalrez 6375</td>
<td>5</td>
<td>0.0312</td>
<td>0.429</td>
<td>0.666</td>
<td>0.0370</td>
<td>−0.564</td>
<td>661</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>0.0266</td>
<td>0.514</td>
<td>1.042</td>
<td>0.0877</td>
<td>−0.637</td>
<td>931</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>0.0371</td>
<td>0.512</td>
<td>1.433</td>
<td>0.284</td>
<td>−0.778</td>
<td>1102</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>0.0983</td>
<td>0.377</td>
<td>1.449</td>
<td>0.0478</td>
<td>−0.501</td>
<td>1339</td>
</tr>
</tbody>
</table>
Figure 3: Body diagram of transfer function $F(s)/x(s)$ in case of Viton 75, $d = 11$ mm, $\Phi = 1.78$ mm.

Figure 4

Stiffness and damping coefficients at a frequency of 200 Hz are also given in the tables. These are more representative than the previous coefficients as they are less affected by measuring errors.

In Figures 4–7, the experimental points of stiffness and damping coefficients are plotted with the fitted power law lines.

Figures 4–7 show the squeeze effect on $k$ and $c$ coefficients for a selected size of the O-ring and the size influence on $k$ and $c$ at a medium squeeze level (15%).

Figure 4(a) shows the effect of squeeze on the stiffness coefficient of Viton 75 O-rings of size $d = 11$ mm, $\Phi = 1.78$ mm. It can be seen that stiffness increases with frequency and with the squeeze level.

Figure 4(b) shows the effect of squeeze on the damping coefficient of Viton 75 O-rings of size $d = 11$ mm, $\Phi = 1.78$ mm. Damping decreases with frequency and increases with the squeeze level.

Figures 5(a) and 5(b) show the influence of the size on the stiffness and damping coefficients at a 15% squeeze.
level. Stiffness and damping coefficients increase both with diameter \(d\) and cross diameter \(\Phi\), although the influence of \(\Phi\) is almost negligible when \(d\) is high. This is in accordance with data of paper [10], in which the influence of the cross section diameter is negligible with an O-ring of internal diameter \(d\) of about 73 mm.

Figures 6(a) and 6(b) show the effect of squeeze on stiffness and damping coefficients of Viton 90 O-rings of size \(d = 11\ mm, \Phi = 1.78\ mm\). It can be noticed that Viton 90 is more rigid and has also a greater damping capability.

Similar trends are shown in Figures 7(a) and 7(b) presenting the influence of the size on the stiffness and damping
coefficients at a 15% squeeze level for Viton 90 O-rings. Both stiffness and damping are greater in Viton 90 with respect to Viton 70.

Literature data on these coefficients are very difficult to be found. Table 6 shows details about O-rings from [10, 11] tested with the mass resonant method. Figure 8 compares these results with that of the present paper, with Viton material and a squeeze level of 15%. Considering that stiffness and damping should increase with the Shore hardness and with both $d$ and $\phi$, coefficients from [11] are compatible with that of $d = 41$ mm, as their Shore hardness and their cross section diameter are lower. Furthermore the coefficients from [10] are greater than that of $d = 41$ mm and squeeze 15% and also this comparison is good.
Considering that the sensitivity of rubber properties on temperature is very high, the discrepancies on the data from different test benches are acceptable. Also, as noticed in [19], the O-rings can easily be twisted during mounting and this fact could influence the test results. To avoid this problem the O-rings could be lubricated, but the presence of a lubricant could be another source of uncertainty.

3.2. Dependence on the Squeeze. The relationship between the stiffness and damping coefficients and the squeeze $S$ is approximately linear. Figures 9 to 11 show the coefficients at frequency of 200 Hz.

3.3. Dependence on O-Ring Size. The effects of the inner diameter $d$ and of the cross section diameter $\Phi$ can be
evaluated plotting the coefficients obtained with the following ratios:

\[
\begin{align*}
\bar{k}_{200} &= \frac{k_{200}}{d \cdot \Phi}, \\
\bar{c}_{200} &= \frac{c_{200}}{d \cdot \Phi}.
\end{align*}
\] (6)

The results are depicted in Figures 12 and 13. In first approximation it is possible to collapse the four trends into one curve. In this way the properties of the O-rings can be identified independently of their size:

\[
\begin{align*}
\bar{k}_{200} &= C + \gamma S \\
\bar{c}_{200} &= D + \delta S.
\end{align*}
\] (7a, 7b)

The least squares procedure was adopted to fit the linear trends to experimental data (see Appendix B). In these equations the squeeze is expressed in percentage form (\(S = 5, 10, 15, 20\)). Table 7 summarizes the results.

4. Conclusions

In the present work the dynamic properties of rubber O-rings are provided. The following conclusions can be made:

(i) Stiffness increases with frequency, while damping decreases.

(ii) Stiffness and damping coefficients increase both with the size of the O-ring (internal diameter \(d\) and cross-sectional diameter \(\Phi\)) and with the squeeze level.

(iii) A material with higher Shore hardness has higher stiffness and damping.

Formulas are provided to identify as a first approximation the stiffness and damping coefficients of O-rings of general size. These formulas can be inserted in lumped parameters models of gas bearings to evaluate their increased stability with the use of the O-rings.

Future interesting investigations could concern the verification of these formulas with O-rings of different size. Also the effect of temperature could be taken into account setting up a temperature control.

Appendix

A. Interpolating Coefficients

Coefficients \(A\) and \(\alpha\) are calculated solving the following linear system by least squares procedure:

\[
\begin{bmatrix}
1 & \log \omega_1 \\
\vdots & \vdots \\
1 & \log \omega_n
\end{bmatrix}
\begin{bmatrix}
\log A \\
\alpha
\end{bmatrix} =
\begin{bmatrix}
\log k_1 \\
\vdots \\
\log k_n
\end{bmatrix},
\] (A.1)

The pulsation vector is expressed in rad/s.
Figure 12: $k_{200}$ and $c_{200}$ versus S for Viton 75.

Figure 13: $k_{200}$ and $c_{200}$ versus S for Viton 90.
Similar procedure was adopted for coefficients $B$ and $\beta$:

$$
\begin{bmatrix}
1 & \log \omega_1 \\
\vdots & \vdots \\
1 & \log \omega_n
\end{bmatrix}
\begin{bmatrix}
\log B \\
\beta \\
\log C_n
\end{bmatrix}
= 
\begin{bmatrix}
\log c_1 \\
\vdots \\
\log c_n
\end{bmatrix}.
$$

(A.2)

B. Extrapolating Coefficients

Coefficients $C$ and $\gamma$ are calculated solving the following linear system by least squares procedure:

$$
\begin{bmatrix}
1 & S_1 \\
\vdots & \vdots \\
1 & S_n
\end{bmatrix}
\begin{bmatrix}
C \\
\gamma
\end{bmatrix}
= 
\begin{bmatrix}
\bar{K}_{200,1} \\
\vdots \\
\bar{K}_{200,n}
\end{bmatrix}.
$$

(B.1)

The squeeze is expressed in percentage form.

Similar procedure was adopted for coefficients $D$ and $\delta$:

$$
\begin{bmatrix}
1 & S_1 \\
\vdots & \vdots \\
1 & S_n
\end{bmatrix}
\begin{bmatrix}
D \\
\delta
\end{bmatrix}
= 
\begin{bmatrix}
\bar{\tau}_{200,1} \\
\vdots \\
\bar{\tau}_{200,n}
\end{bmatrix}.
$$

(B.2)

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

The authors wish to acknowledge KU Leuven and Politecnico di Torino for the financial support to this work.

References


