Chapter 2
On the Study of Fatigue on Vulcanized Rubber Using Vibration Testing

Francesco Trainotti, T. Slimak, and D. J. Rixen

Abstract Thanks to the unique properties of high elongation, reversibility, incompressibility, and energy dissipation, rubber materials are employed in numerous engineering applications in industrial practice. The rheological behavior of rubbers depends on chemical composition, presence of additives, and curing process. As a consequence, a large variety of materials may be encountered with a rich phenomenological description of their static and dynamic characteristics. Rate, amplitude, and temperature, among others, are operational parameters that affect rubber's stiffness and damping properties. On top of that, to ensure the long-term performance and reliability of a rubber component, aging effects and fatigue life assessments are paramount. Existing laboratory vibrational techniques, based on uni-axial displacement-controlled cyclic tests, are capable of extracting storage and loss properties of the rubber under study as a function of frequency and amplitude of the oscillation. This paper investigates the robustness of a transmissibility-based shaker setup for the dynamic characterization of a rubber component extended to long-run operational loading. A preliminary analysis shows the influence of the adhesive substance used to hold the rubber in place in a variety of testing scenarios.

Keywords Rubber · Characterization · Testing · Shaker · Fatigue

2.1 Introduction

Rubber materials are widely adopted in engineering practice due to their high versatility and mechanical properties such as high strength, high elongation, and energy dissipation. Synthetic rubbers are commonly used in aerospace and automotive applications to produce mounts that act as vibration isolation interfaces. The rheological behavior of the polymeric compound will mostly depend on its chemical composition, the presence of additives, and the vulcanization process. As a result, a wide range of characteristics and sensitivity to mechanical loads and environmental conditions can be realized. On a macro-scale, for a mechanical engineer, the stiffness and damping properties along the principal deformation axes might show dependence on rate/frequency, temperature, state/amplitude, static pre-load, etc. [1, 2]. In addition, change in properties due to long operational loading cycles or exposure to extreme environmental conditions can lead to non-functioning and non-robust design solutions. An appropriate understanding of their characteristics via an experimental characterization process is therefore needed. Different strategies might be adopted depending on the level of detail desired/required, e.g., material or component level, phenomenological or constitutive approach, type of dependencies, inclusion of inertia contribution, single or multi-axial, etc. Material-level identification using standard(-ized) machines (e.g., dynamic mechanical analyzer) provides the most accurate, extensive, though expensive, characterization results [3]. A cheaper and faster option is commonly adopted in NVH analysis which consists in identifying the transfer of vibration of the rubber mount considered as a structural component. Standard single-DoF shaker- and impact-based laboratory testing may be adopted [4, 5]. Recently, multi-DoF substructuring identification based on frequency response measurements has gained popularity, thanks to the capability of handling complex rubber mounts and the versatility of the identified experimental model [6]. A comparison between the two mentioned component-based testing strategies has been offered by the authors in [7]. There, a transmissibility-based setup is presented to extract stiffness and damping characteristics as a function of frequency and amplitude in a uni-axial cyclic testing mode. Prior to extending the test capabilities to study long-term loading behavior (e.g., fatigue and/or aging), the

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reliability and robustness of the workflow must be assessed. This preliminary analysis focuses on the effect of the adhesive used to fix the rubber specimen in place and point out accuracy and repeatability of the experimental identification.

The characterization strategy along with the testing setup is outlined in Sect. 2.2. The processed results of the measurement campaigns are presented in Sect. 2.3. Conclusive remarks are collected in Sect. 2.4.

2.2 Transmissibility-Based Uni-axial Shaker Characterization

The transmissibility setup is briefly summarized in the following. A more comprehensive derivation can be found in [7].

The measurement configuration is shown in Fig. 2.1. The idea is to approximate a single-DoF oscillator with the rubber acting as a (complex) spring, a moving mass on the top of it, and a uni-axial base excitation via an electrodynamic shaker. By measuring the motion on either side of the rubber specimen while performing a dynamic excitation, the dynamic equilibrium of the system can be written as:

$$m\ddot{y} + k^*(y - x) = 0 \tag{2.1}$$

where k^* is the complex stiffness including both stiffness and damping contributions and y, x are the displacements above and below the rubber, respectively. Note that the single-DoF assumption in Eq. (2.1) holds for an ideal uni-axial motion and as long as the “excitation” mass underneath the rubber is significantly larger than the moving mass $m\ddot{y}$.

The rubber properties are identified by isolating the complex stiffness k^* and using the parametrization following the linear viscoelastic theory such that $k^* = k' + ik''$ where k', k'', $k^\star = |k^*|$, $\eta = \frac{k''}{k'}$ represent the storage stiffness, loss stiffness, dynamic stiffness, and loss factor, respectively.

Depending on the excitation signal, different analyses can be conducted:

- Linearized sweeps: a linear sweep excites the system. The frequency-based counterparts of the top and bottom responses are estimated, and the transmissibility ratio is computed as $T(\omega) = \frac{Y(\omega)}{X(\omega)}$. The complex stiffness is then computed by solving Eq. (2.1), and the stiffness and damping terms identified. The change of properties due to deformation amplitude is neglected so that equivalent linearized frequency-dependent characteristics are retrieved. Temperature is assumed to be constant.
- Amplitude-frequency maps: a cyclic displacement-controlled dynamic excitation is performed. The controlled quantity is the relative displacement $y - x$. Per each controlled operating point defined by an oscillation frequency and peak amplitude, the stationary time responses are stored, and Eq. (2.1) is used to determine stiffness and damping via an averaged peak fitting and zero crossing strategy. The linearized values can be expressed as a function of the operating frequency and dynamic amplitude/strain, such that a 2D map is generated. Temperature is assumed to be constant.

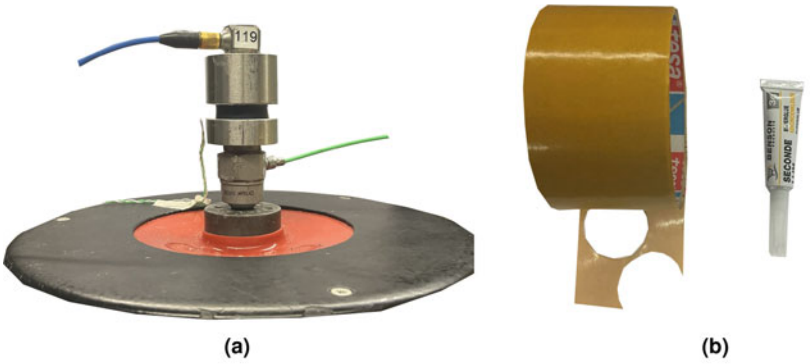

Fig. 2.1 Experimental setup used to characterize the rubber component. (**a**) Transmissibility shaker setup with an accelerometer attached to either side of the rubber sample and excitation from the bottom. (**b**) Adhesive substances used to fix the rubber sample. Left: double-sided adhesive tape. Right: cyanoacrylate glue

- Long-time runs: a cyclic displacement-controlled dynamic excitation is performed for a large number of measurement cycles. The processing is analogous to that of the amplitude-frequency map type of analysis, with the difference being the possible reversible or non-reversible fatigue effects affecting the behavior of the rubber.

The current setup uses an accelerometer on the moving mass and an impedance sensor (measuring force and acceleration) on the base. An additional sensor close to the rig is used to monitor the room temperature (assumed constant) during the testing. Two types of adhesive substances are investigated: a double-sided tape and a cyanoacrylate glue (see Fig. 2.1). A rubber disc with diameter 22 mm and thickness 6 mm is used as sample. To assess the robustness of the workflow, two different materials are tested, referred to as "MAT 1" and "MAT 2."

2.3 Testing Results

Tests are conducted as follows. First, a linearized sweep analysis is performed in the range 20–1000 Hz. This allows a quick evaluation of stiffness and damping trends as frequency-based curves and serves as a basis to choose reasonable operating points for the subsequent analysis. Then, a fully automated testing workflow is adopted as described below:

1. Amplitude-frequency map in the controllable/observable range 300–700 Hz and 0.03–0.25 % strain.
2. Pause 30 min.
3. Long-lasting run consisting of repeated cyclic loads at 500 Hz with 0.25 % peak strain. Time schedule: run 60 min—pause 30 min—run 60 min.
4. Pause 30 min.
5. Amplitude-frequency map in the controllable/observable range 300–700 Hz and 0.03–0.25 % strain.

The results of the sweep analysis are grouped in Fig. 2.2. Some considerations are as follows:

- The two materials present clearly distinguishable frequency trends. This indicates an appropriate/robust identification process.
- The repeatability of the attachment process for tape is significantly higher than that for glue.
- The frequency trends between tape and glue are similar, while there is a bias in the absolute value. Tape results present higher levels of damping and lower levels of stiffness. This might be due to the effect of tape acting as an additional viscoelastic layer.

The amplitude-frequency maps are shown in Fig. 2.3. All considerations regarding the comparison between the materials and between the adhesives made for the sweep are confirmed by the plots and readily extended to the amplitude/strain dependence. As additional information, no clear difference exists between maps before and after the long-lasting runs, thus suggesting a fully reversible behavior.

Finally, the preliminary fatigue study is provided in Fig. 2.4. A very repeatable change in stiffness and damping properties is observed with increasing number of cycles (and time) for all combination of materials and adhesives. The change occurs

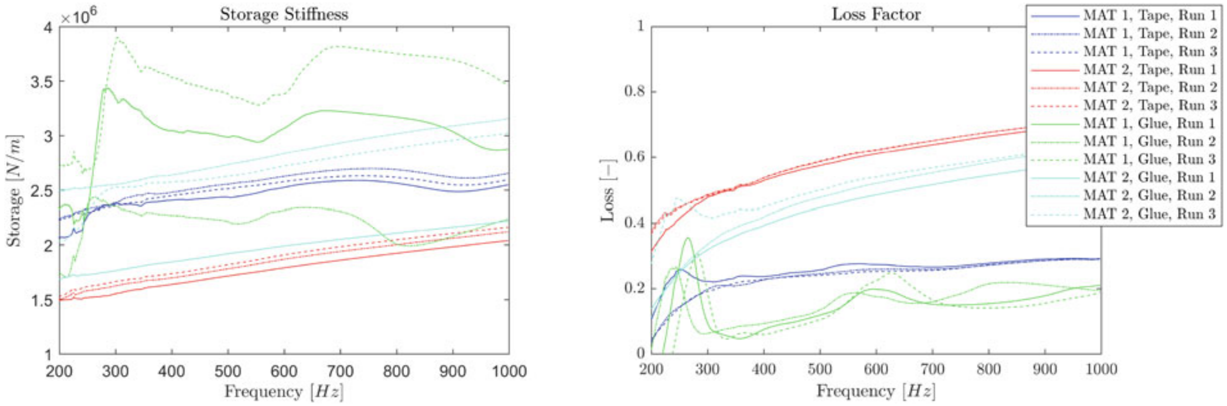

Fig. 2.2 Linearized sweep analysis on the rubber samples of MAT 1 and MAT 2 with both Tape and Glue. Three repetitions (Runs) are provided for each combination tested. Left: storage stiffness. Right: loss factor

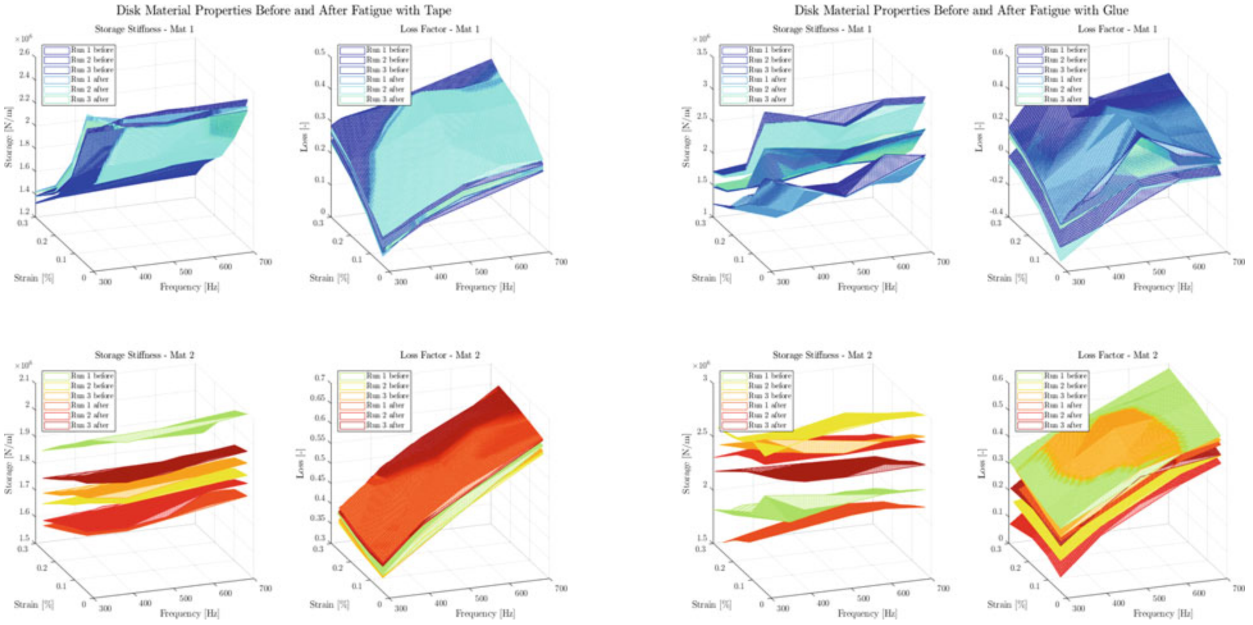

Fig. 2.3 Amplitude-frequency maps analysis on the rubber samples of MAT 1 and MAT 2 with both Tape and Glue. Three repetitions (Runs) are provided for each combination tested. Results before and after fatigue are shown. Left: storage stiffness and loss factor of MAT1 (top) and MAT2 (bottom) for Tape. Right: storage stiffness and loss factor of MAT1 (top) and MAT2 (bottom) for Glue

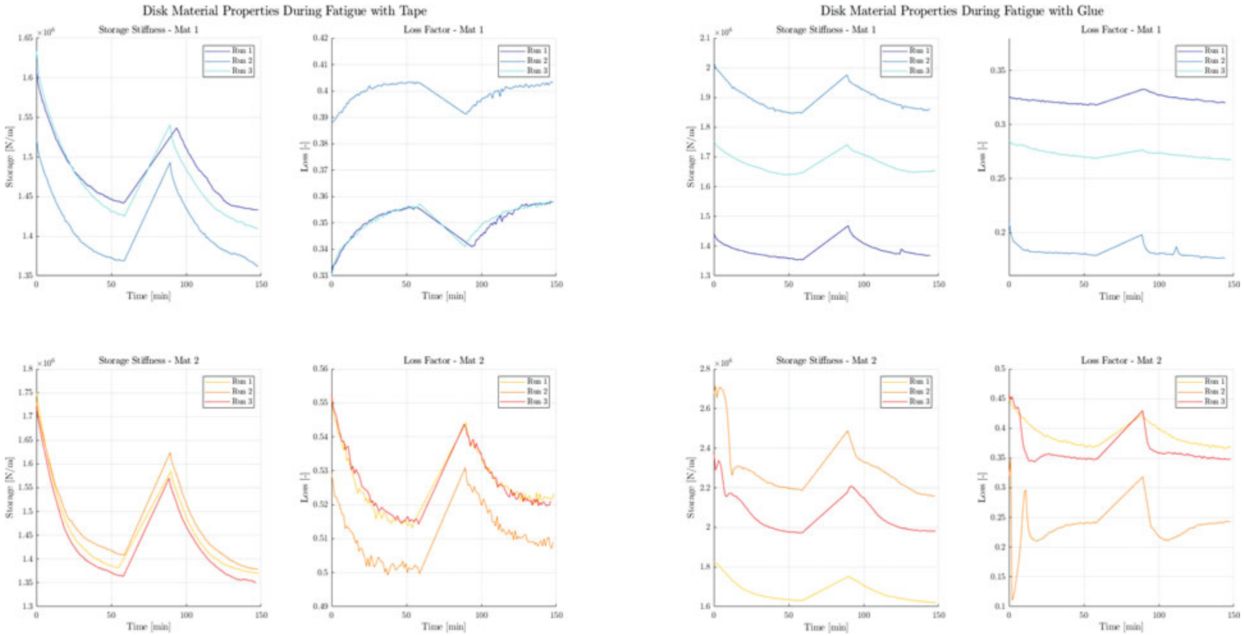

Fig. 2.4 Long-lasting runs (Fatigue) analysis on the rubber samples of MAT 1 and MAT 2 with both Tape and Glue. Three repetitions (Runs) are provided for each combination tested. Left: storage stiffness and loss factor of MAT1 (top) and MAT2 (bottom) for Tape. Right: storage stiffness and loss factor of MAT1 (Top) and MAT2 (bottom) for Glue

as a decrease in storage and loss properties for most cases analyzed, except for the loss factor of the combined tape and MAT 1, which shows the opposite trend. Further investigation is needed in this regard. Overall, the source of the long-lasting effect is unknown, but it seems to be fully reversible within the tests conducted (as also supported by Fig. 2.3).

2.4 Conclusion

Experimental testing is paramount for an adequate understanding of the mechanical properties of rubber components, which are widely spread in engineering applications.

A transmissibility-based uni-axial shaker configuration enables a cheap and automated testing chain to extract stiffness and damping properties of a rubber on a component level. This strategy is capable of identifying the frequency and (dynamic) amplitude dependence of the rubber characteristics by using a linearized equivalent viscoelastic (and steady-state) approach. In a first stage, the robustness of the methodology is investigated by comparing the results arising from repeated sweep and map data for different material compositions and adhesive types. The outcome revealed a significantly greater repeatability of the double-sided tape adhesive process in comparison with the glue. Nonetheless, although frequency and amplitude trends were successfully estimated in all scenarios, a non-negligible bias in absolute value seems to negatively affect the tape results. In a second stage, a preliminary study of fatigue is conducted. Overall, the results showed fully reversible time-dependent changes in both stiffness and damping.

A more extensive testing campaign is needed to assess the role of adhesive in long-lasting loading scenarios and comprehend the reasons behind the observed changes in rubber mechanical properties. Ultimately, a reliable and repeatable design solution is sought.

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