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# Innovative Evaluation of Rebound Resilience for the Characterization of Sealing Materials

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The rebound resilience test according to Schob is an established method for determining hysteresis losses in rubber materials. Its significance stems not only from the simplicity of the procedure, but also from the characteristic contact times and modes of deformation, which closely resemble those encountered in sealing applications, such as radial shaft seals or flat gaskets. The highly dynamic rebound process yields valuable information that can be unlocked through analysis of the time derivatives of deformation. This presentation introduces a novel rebound tester enabling energy-constant, pulsed mechanical analysis of impacts at high deformation within just a few milliseconds. Data evaluation focuses on two key parameters: the elastic modulus E and the corresponding loss factor tan δ, both based on Hertzian contact mechanics as modified by Argatov. This approach offers a practical and efficient means to characterize the dynamic behavior of sealing materials under realistic loading conditions.

## 1 Introduction

Rebound testing has long been established in the rubber industry as a classical method for characterizing the dynamic properties of elastomers and their corresponding compounds. Despite its widespread use over several decades, the methodology has remained largely unchanged. The design of the apparatus and the essential parameters of the measurement are defined in various standards (see ISO 4662 [1] and ASTM D7121 [2]).

In a rebound experiment, a hammer is released from a defined height and impacts the specimen in a pendulum-like motion. The potential energy of the hammer is converted into kinetic energy during its descent. Upon contact, the hammer deforms the specimen, which absorbs the kinetic energy. A portion of this energy is stored elastically, while the remainder is dissipated. At the end of the contact phase, the stored energy is released, reconverted into kinetic and subsequently into potential energy. Due to energy dissipation within the specimen during impact, the rebound height is lower than the initial drop height.

As previously noted by Lacayo-Pineda and Rauschmann [3], the rebound test is inherently a dynamic experiment. The contact duration between the hammer and the specimen typically lies within the range of a few milliseconds. If the contact event is interpreted as a periodic process, a characteristic frequency can be assigned – typically in the range of several hundred hertz. During impact, the local deformation of the specimen can reach significant levels, often between 10 % and 50 %.

The rebound test therefore represents an ideal method for evaluating elastomeric components subjected to dynamic loading conditions similar to those encountered in sealing applications. This can be illustrated by two practical examples from sealing

technology: the sealing lip of a radial shaft seal, which is briefly and repeatedly deformed as it passes over the surface asperities of the rotating shaft, and a flat gasket, which experiences short, pulse-like compression during assembly and operation of a flanged joint.

Historically, the rebound test has not been utilized for the quantitative characterization of pulsed mechanical behavior, owing to the lack of a framework for extracting material parameters from the experiment.

Today, advancements in both electronic data acquisition and signal processing – on hardware and software fronts – offer significantly enhanced capabilities. High-resolution spatial and temporal measurements now allow for precise tracking of the impact event. Furthermore, the theoretical modeling of the impact process can now be performed in near real time, owing to the substantial increase in computational power.

This paper builds on the enhanced rebound testing setup and evaluation methodology introduced and validated by Wrana et al. [4] on model compounds based on natural rubber (NR). In the present contribution, this methodology is applied specifically to materials and loading conditions relevant to sealing applications. In particular, the response of this pulsed-loading approach – in the following referred to as Pulse Mechanical Analysis (PMA) – is compared in detail with conventional dynamic mechanical analysis (DMA) for the determination of the glass transition, before the method is applied to typical sealing materials.

This approach paves the way for transforming the rebound test into a dynamic-mechanical spectrometer for pulsed loading. Notably, the deformation amplitudes encountered in rebound testing differ significantly from those in conventional dynamic mechanical analysis (DMA): the method not only accommodates considerably higher deformation amplitudes, but also ensures constant energy input across all tests, in contrast to standard DMA procedures, which typically operate under constant strain or stress conditions.

## 2 Samples

Three sample systems were used to evaluate the pulsed mechanical response of typical sealing materials. The first is a vulcanized, unfilled natural rubber (NR) compound, cross-linked with sulfur; as the comparison in this section focuses on the general dynamic-mechanical response rather than on a specific formulation, the exact recipe is not given. In addition, two commercial sealing compounds of equal hardness (70 ShA) were investigated: a standard hydrogenated nitrile rubber (HNBR) compound and a standard fluoroelastomer (FKM) compound. Since the aim of this comparison is restricted to contrasting the characteristic PMA response of these widely used sealing materials, a detailed description of their composition is likewise omitted.

## 3 Experimental Setup

The device employed in this study is a newly developed prototype of an enhanced rebound elasticity testing system by Bareiss® Prüfgeräte GmbH, Germany, based on the classical Schob pendulum design. The pendulum system was modified in two ways. First, the pendulum structure and the attached hammer were optimized so that no natural vibrations or resonances occur in the frequency range up to 800 Hz. The second area of enhancement involves the sensor technology: the angular measurement system was upgraded to achieve a deformation resolution of 0.009° and a sampling interval of 10 µs at the hammer position, in compliance with the requirements of ISO 4662 [1]. Figure 1 shows the basic setup of the rebound experiment and illustrates the relationship between the deformation of the sample and the pendulum angle, $x(t) = l \cdot \sin \alpha(t)$; the resolution of the angle measurement therefore results in a local deformation resolution of approximately 30 µm for a pendulum length of 200 mm.

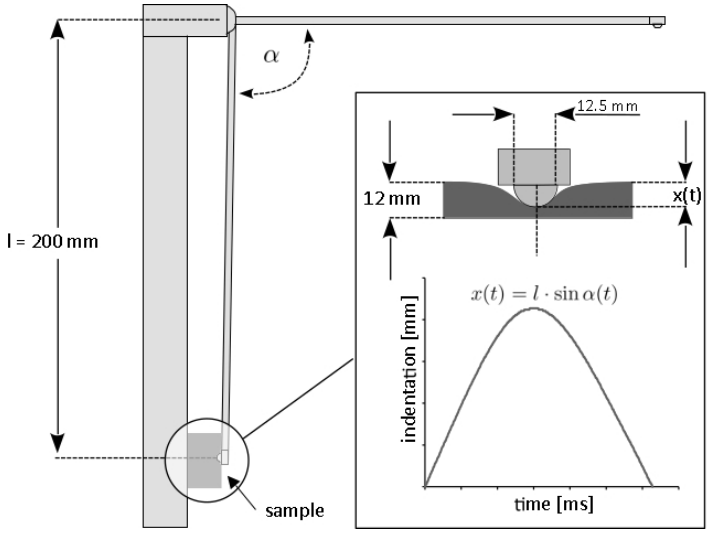


*Figure 1: Schematic diagram of the torsion pendulum, with the contact area between hammer and sample and the relationship x(t) = l · sin α(t)*

For the present study, the setup was further extended by a dedicated temperature sensor positioned directly at the contact area between the hammer and the sample, allowing the sample temperature to be measured precisely at the moment of impact. This addition enables temperature-dependent rebound measurements: the sample is conditioned to a defined temperature – by cooling or heating – prior to being mounted in the tester. Once installed, it gradually equilibrates towards room temperature through contact with the ambient environment, either warming up or cooling down accordingly. During this transient phase, rebound measurements are carried out at defined time intervals, so that the dynamic-mechanical response of the sample is recorded as a function of its actual, precisely measured temperature.

## 4 Analysis of Data

The evaluation of the measured, discrete deformation signal $x(t_i)$, sampled at the discrete times $t_i$, follows the procedure described in detail by Wrana et al. [4]. In brief, the deformation signal is fitted with a set of harmonic functions whose fundamental frequency is derived from the contact duration $t_C$; three harmonics were found to be sufficient to accurately capture the deformation of all samples considered here. This analytical description allows the velocity and, via Newton's second law, the force acting on the sample to be obtained directly by differentiation, avoiding the noise sensitivity inherent to numerical differentiation of the raw signal. For the full derivation, including the least-squares fitting procedure and the corresponding accuracy analysis, the reader is referred to [4].

## 5 Theoretical Considerations

The classical theory of Hertz [5] describes the time-dependent deformation of an elastic half-space in contact with a rigid, hemispherical body. Building on this framework, Huber [6] derived closed-form expressions for the resulting stress and deformation fields within the contacting bodies. In particular, Huber's solution provides closed-form expressions not only for the deformation directly beneath the point of contact, but also for the mean and maximum deformation across the sample, enabling a more rigorous assessment of the local strain experienced by the material during impact. However, both approaches are fundamentally unable to describe viscoelastic, energy-dissipating media. Argatov [7] extended this framework to viscoelastic Hertzian contact by modeling the sample as an ideal Maxwell solid, introducing a damping parameter λ in addition to the modulus E, which characterizes the elastic response:

$$\frac{d^2x(t)}{dt^2} + 2\lambda\left(\frac{dx(t)}{dt} - v_0\right) + k \cdot x(t)^{3/2} = 0, \quad \text{with} \quad k = \frac{8}{9}\sqrt{\frac{R}{m}} \cdot \frac{E}{1+\nu} \tag{1}$$

Here x(t) denotes the deformation of the sample as a function of time t, so that the first and second derivatives represent the deformation velocity and acceleration, respectively. $v_0$ is the velocity of the hammer at first contact, and λ is the damping parameter introduced above. The coefficient k combines the geometry of the contact with the elastic properties of the sample: R is the radius of the hemispherical hammer, m its mass, E the modulus of the sample and ν its Poisson's ratio, for which the value 0.5 was used throughout, as is customary for elastomers. The exponent 3/2 of the deformation term is characteristic of Hertzian contact between a sphere and a flat surface.

Argatov's formulation, however, is exact only up to the point of maximum deformation; beyond this point, during the unloading phase, it represents only an approximation of the true contact behavior, as noted by Argatov himself. In the present work, we extend Argatov's approach to provide an exact theoretical description of the complete contact event, from first contact through to the point of zero contact

force – i.e. full separation of hammer and sample – rather than only up to maximum deformation. For a viscoelastic, energy-dissipative medium, this point of zero force does not coincide with the geometric zero-deflection position of the pendulum: owing to the dissipation of energy during contact, it is reached earlier, at a smaller deflection angle. The complete derivation of this extended model will be presented in a separate publication, currently in preparation; in the present paper it is applied to determine the modulus E and the damping parameter λ over the full contact event, including the unloading phase.

While Argatov's damping parameter λ quantifies energy dissipation, it is not a familiar material property. In dynamic-mechanical characterization, the loss factor tan δ is conventionally used instead. Following the derivation given in [4], approximating the contact deformation by a damped sinusoidal function yields the following relationship between the damping parameter λ and the loss factor tan δ, where ω denotes the characteristic frequency of the contact, $\omega = \pi/t_C$, with $t_C$ the contact duration between hammer and sample:

$$\tan\delta = -\frac{2\lambda\,\omega}{\omega^2 - \lambda^2} \tag{2}$$

In this expression, tan δ is the loss factor, λ the damping parameter obtained from the fit of Equation (1), and ω the characteristic angular frequency of the contact as defined above. Since λ and ω both follow directly from the measured contact event, tan δ is available for every individual rebound stroke without any further assumptions.

Using the extended, energy-consistent description of the contact and separation process, the damping parameter λ is obtained over the complete contact event, including the unloading phase down to the point of zero force, and converted into the loss factor tan δ via Equation (2). This forms the basis for the material comparisons presented in the following sections.

## 6 NR: PMA vs. DMA

To validate the ability of the pulsed rebound experiment (Pulse Mechanical Analysis, PMA) to capture viscoelastic transitions, the temperature-dependent response of the unfilled NR reference compound was compared with a conventional dynamic mechanical analysis (DMA) reference measurement.

For the PMA measurements, cylindrical samples with the 6 mm thickness customary for rebound testing [1] were used. The samples were conditioned in a temperature chamber at -60 °C for several hours to ensure thermal equilibrium throughout the sample, then mounted in the rebound tester, and the measurement was started immediately.

Directly after removal from the temperature chamber, the temperature difference between the cold sample and its surroundings is greatest, so the initial heat flux – and with it the heating rate – is highest; both decrease continuously as the sample ap-

proaches ambient temperature, following a Newtonian-type asymptotic approach rather than a constant rate. This rapid initial warm-up (‘ballistic heating’) ensures that the sample passes quickly through the temperature range in which natural rubber is prone to crystallize [8], for the same reason as in the DMA protocol described below. Individual rebound strokes were triggered throughout the warm-up, so that, on average, one measurement point was obtained per degree Celsius of sample temperature.

The average local deformation of the sample during contact with the hammer, calculated from Huber’s solution [6], reached values of up to approximately 100 %, at average shear stresses of up to 4 MPa.

For orientation, these values are of a comparable order of magnitude to the loads occurring in the two sealing examples mentioned in the Introduction. In a radial shaft seal, the lip is squeezed against the shaft with a radial interference typically amounting to a few tenths of a millimeter relative to a lip cross-section of similar thickness, giving local strains of several tens of percent and mean contact pressures roughly in the range of 0.1 MPa to 1 MPa. In a flat gasket, a nominal compression of about 10 % to 25 % of the gasket thickness is common, with assembly pressures typically between about 1 MPa and a few MPa. The deformation and stress levels reached in the PMA measurement therefore bracket the range relevant to both applications, even though the exact figures naturally depend on the specific seal or gasket design.

The DMA reference measurements were performed on a Mettler-Toledo DMA/SDTA861e, an established shear-mode dynamic mechanical analyzer, at a constant frequency of 1 Hz. Samples were tested in shear using a double-sandwich sample holder, with two sample layers of 1 mm thickness each; the shear amplitude was held constant at 10 µm, corresponding to a strain of 1%. The sample was first cooled rapidly to -70 °C and then heated at a rate of 5 K/min while the response was recorded; both the initial cooling and the temperature sweep itself were carried out as quickly as practicable. Slower cooling or heating rates were deliberately avoided, since natural rubber is known to crystallize within the temperature range relevant to this measurement [8], and the resulting crystallinity would distort the measured glass transition. Figure 2 shows the loss factor tan δ as a function of temperature T, obtained from both methods.

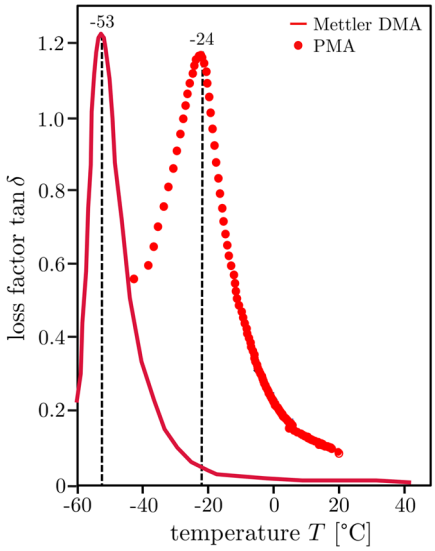


*Figure 2: Temperature-dependent measurement of an unfilled NR sample with PMA and DMA*

Both curves show a distinct tan δ maximum associated with the glass transition of the NR matrix, though at clearly different temperatures. The DMA measurement, run sinusoidally at 1 Hz with 1 % shear deformation, places the maximum at –53 °C. The PMA measurement, with its pulsed contact at a characteristic frequency of about 300 Hz and multiaxial local deformations of 20 % to 80 %, places the maximum at –24 °C, roughly 29 K higher.

This shift is mainly a frequency effect. PMA and DMA differ in characteristic frequency by about 2.5 decades. Applying the time-temperature equivalence principle for NR, with a glass-transition shift of about 12 K per frequency decade, predicts a shift of roughly 30 K, in good agreement with the 29 K found here.

A second, smaller effect comes from the deformation mode. DMA imposes a small, linear, uniaxial shear strain of 1 %, while PMA generates a multiaxial, pulsed deformation reaching well into the range of rubber elasticity. In this range, modulus and loss factor depend not only on temperature and frequency but also on the type and amplitude of deformation, so an exact match between the two methods is not to be expected even at equal frequency. This mirrors the loading of real sealing components: the lip of a radial shaft seal, for example, is deformed briefly, multiaxially, and repeatedly each time a shaft asperity passes beneath it, much like the pulsed contact in PMA and unlike the small linear strain applied in DMA.

Beyond these physical differences, PMA is considerably simpler to carry out. The DMA measurement requires careful sample preparation – cutting the sandwich specimens to size, precise clamping in the shear holder, and calibration of the small-

amplitude drive – before the temperature sweep can even begin. For PMA, the sample only needs to be placed in the pendulum tester; once the measurement is started, a complete temperature-dependent tan δ curve such as the one in Figure 2 is obtained after about 10 minutes. This makes PMA attractive not only for fundamental characterization, but also for rapid, routine testing of sealing materials.

In the next section, typical sealing materials for demanding applications, HNBR and FKM, are compared using PMA.

## 7 HNBR vs. FKM

Figure 3 shows the PMA master curves of Young's modulus E and loss factor tan δ as a function of temperature T for two typical sealing materials, a hydrogenated nitrile rubber (HNBR) and a fluoroelastomer (FKM), both of 70 ShA hardness.

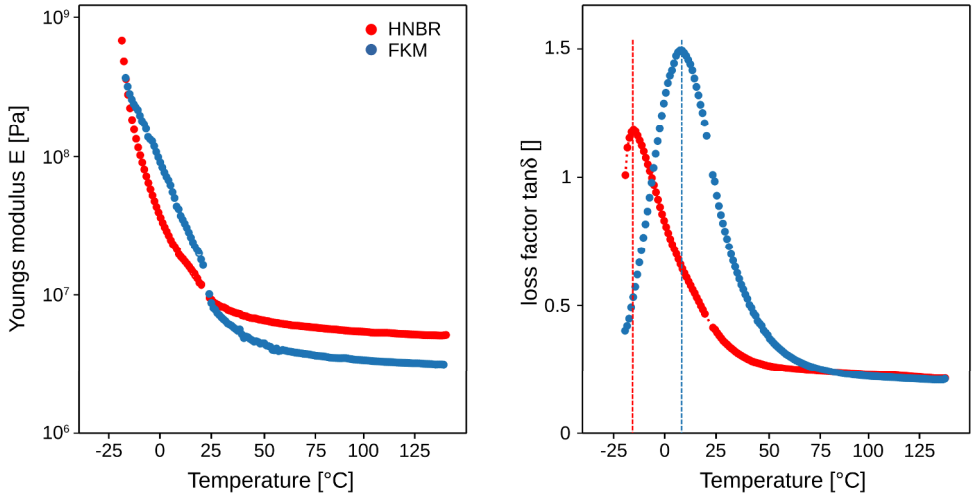


*Figure 3: PMA master curves of Young's modulus E and loss factor tan δ for HNBR and FKM as a function of temperature T*

The left-hand panel shows Young's modulus E on a logarithmic scale as a function of temperature T; the right-hand panel shows the loss factor tan δ over the same temperature range.

Both curves are dominated by the glass transition, seen in the right-hand panel as a pronounced tan δ maximum: at –15 °C for HNBR and at 8 °C for FKM. Strictly speaking, equating the glass transition temperature with the tan δ maximum is not entirely correct: depending on whether the onset of the storage modulus drop, the peak of the loss modulus, or the peak of tan δ is used, DMA-type measurements yield systematically different apparent Tg values, with the tan δ peak giving the highest of the three [9]. For practical engineering purposes, however, the tan δ maximum is a convenient and widely used indicator of the functional softening transition of a sealing material, and is used as such throughout this work.

A further observation is that the tan δ maxima found here, –15 °C for HNBR and 8 °C for FKM, lie considerably higher than the transition temperatures typically quoted for these materials. As with the NR comparison discussed above, this reflects the characteristic frequency of the PMA test, on the order of 300 Hz, which is well above that of conventional low-frequency characterization methods; via the time-temperature equivalence principle, this higher frequency shifts the observed transition to distinctly higher temperatures.

This has a direct practical consequence. Under dynamic loading – that is, under short, high-frequency deformation such as a pulsed or rapidly cycling contact – a sealing material can already be glass-like, and therefore unable to seal, at temperatures where it would still appear rubbery in a quasi-static test. For HNBR, this dynamic vitrification sets in around –15 °C; for FKM, already around 8 °C. FKM is therefore suitable for highly dynamic sealing applications only at correspondingly higher temperatures. This makes PMA, which probes the material at frequencies representative of real dynamic loading, a very simple and direct way to characterize the behavior of dynamically loaded seals.

## 8 Summary and Conclusion

This paper presents an enhanced rebound resilience test as a Pulse Mechanical Analysis (PMA) for the dynamic-mechanical characterization of sealing materials. Building on the Hertzian contact framework extended by Huber and the viscoelastic extension by Argatov, the pulsed contact is evaluated over its complete duration, including the unloading phase down to zero force, yielding the modulus E and the loss factor tan δ from a single, millisecond-scale impact.

Applied to an unfilled NR reference compound, PMA correctly identifies the glass transition and places it at –24 °C, 29 K above the value obtained by conventional DMA at 1 Hz. This shift is explained almost entirely by the roughly 300-fold higher characteristic frequency of the pulsed contact, in good quantitative agreement with the time-temperature equivalence principle; a smaller, additional contribution comes from the different, multiaxial deformation mode of PMA. Compared with DMA, PMA also requires markedly less effort: a complete temperature-dependent curve is obtained from a single, unprepared specimen within about 10 minutes.

Applied to two typical sealing materials, HNBR and FKM, PMA locates the glass transition at –15 °C and 8 °C, respectively, again well above the values expected from quasi-static characterization. This has a direct practical consequence for sealing applications: under the short, high-frequency, multiaxial deformation typical of real dynamic loading, a sealing material can already be glass-like, and therefore unable to seal, at temperatures where it would still appear rubbery under quasi-static conditions. FKM, in particular, is suitable for highly dynamic sealing applications only at correspondingly higher temperatures than its low-temperature rating might suggest.

PMA therefore combines two advantages: it reproduces the pulsed, multiaxial loading typical of dynamically loaded seals – such as the sealing lip of a radial shaft seal

or a flat gasket – more closely than conventional DMA, and it does so with a fraction of the sample preparation and measurement time. This makes it a practical and efficient tool for screening and comparing sealing materials for demanding dynamic applications. The extended theoretical description of the complete contact event applied here will be presented in full in a forthcoming publication.

## 9 Acknowledgements

The authors thank Bareiss Prüfgerätebau GmbH, Oberdischingen, Germany, for providing the prototype rebound tester used in this study.

## 10 Nomenclature

| *Variable* | *Description* | *Unit* |
|---|---|---|
| | Modulus | [Pa] |
| | Pendulum length | [mm] |
| | Hammer mass | [kg] |
| | Hammer (contact) radius | [mm] |
| | Temperature | [°C] |
| | Time | [s] |
| | Contact duration | [ms] |
| | Impact velocity at first contact | [m/s] |
| | Deformation | [mm] |
| | Pendulum deflection angle | [°] |
| tan δ | Loss factor | [-] |
| | Damping parameter (Argatov) | [$s^{-1}$] |
| | Poisson’s ratio | [-] |
| | Characteristic frequency | [rad/s] |

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