

Simulating the Static and Dynamic Response of an Automotive Weatherstrip Component

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ABSTRACT

Understanding the resonant behavior of vehicle closures such as doors, hoods, trunks, and rear lift gates can be critical to achieve structure-borne noise, vibration, and harshness (NVH) performance requirements, particularly below 100Hz. Nearly all closure systems have elastomer weatherstrip components that create a viscoelastic boundary condition along a continuous line around its perimeter and is capable of influencing the resonant behavior of the closure system. This paper outlines an approach to simulate the static and dynamic characteristics of a closed-cell Ethylene Propylene Diene Monomer (EPDM) foam rubber weatherstrip component that is first subjected to a large-strain quasi-static preload with a small-strain sinusoidal dynamic load superimposed. An outline of a theoretical approach using “phi-functions” as developed by K.N. Morman Jr., and J.C. Nagtegaal [1] is introduced followed by a discussion of the material characterization that was done to construct a suitable elastomer material model for finite element analysis (FEA). Next, to validate the approach, the FEA and correlation of a simple extension specimen is presented followed by the analysis and correlation of a weatherstrip component with a complex cross sectional shape. It is observed that the static and/or dynamic response of the weatherstrip material and component can be dependent on several factors such as excitation frequency, large-strain preload, vibration amplitude, component geometry, and friction. Correlation between simulation and experimental results for dynamic stiffness and loss factor are in general agreement below 100Hz.

INTRODUCTION

The capability to accurately predict noise, vibration, and harshness (NVH) inside the passenger cabin of a vehicle prior

to the existence of physical prototypes is critical to consistently meet or exceed customer expectations for quality and performance while concurrently meeting stringent development schedules and budgets. The fundamental resonant frequencies of automotive closures systems such as doors, hoods, trunks, and rear lift gates are often significant contributors to interior structure-borne NVH issues, particularly below 100Hz. Nearly all closures systems have weatherstrip composed of elastomeric materials that form a continuous viscoelastic line connection around the perimeter of the body opening. It has been observed on vehicle-level analysis models that closure resonance predictions can change significantly depending on the values assumed for the weatherstrip dynamic rate properties (Figure 1). However, accurate dynamic rate information is often not readily available to the NVH analysis engineer prior to the manufacturing and testing of a physical component, if ever. As a consequence, analysis engineers often must rely on substitute methods for selecting appropriate weatherstrip properties, such as referencing legacy component test data of similar seal designs or applying general “rules of thumb” particularly during early stages of vehicle development. Adhering to non-predictive methods such as these introduces additional uncertainty in the accuracy of simulations, especially when seal geometries and materials are all-new designs. If the stiffness and damping characteristics of weatherstrip components can be simulated on a component level with confidence and subsequently incorporated into higher vehicle-level analysis models, then it is anticipated that the accuracy of closure resonances and vehicle-level performances sensitive to closure vibration can ultimately be improved.

The objective of this paper is to present a simulation method to predict the hyperelastic and dynamic behavior of a weatherstrip component in order to address the issue of

unavailable static and dynamic properties of weatherstrip during early vehicle development. The method presented applies a theoretical approach first developed by Morman and Nagtegaal [1] for a particular type of problem where small-strain amplitude cyclic vibrations are superimposed on a preloaded, stress-relaxed elastomer component. This paper investigates the application of this approach to an Ethylene Propylene Diene Monomer (EPDM) closed-cell foam elastomer weatherstrip seal taken from a current production vehicle. The component-level simulation and experimental setup is intended to replicate an on-vehicle door seal that is preloaded to a large preset deformation by being compressed between a vehicle body and door in the fully closed and latched position for an extended period of time until the material reaches a stress-relaxed equilibrium state. Then the compressed, stress-relaxed seal is subjected to small amplitude dynamic oscillations originating from powertrain and tire-road input forces that propagate through the vehicle body and door metal structure.

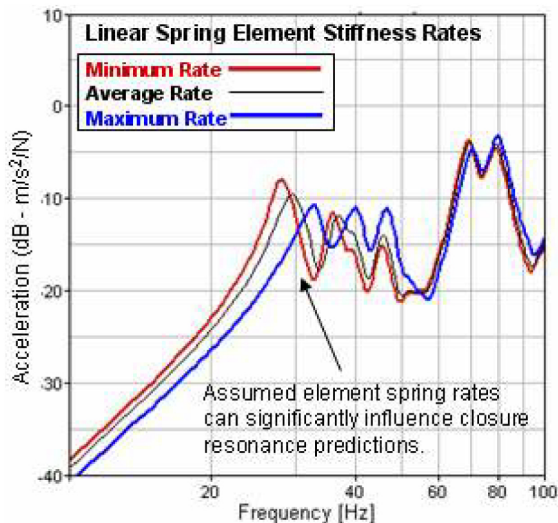


Figure 1. Effect of different dynamic rate assumptions on a door resonance prediction

Specifically, this study aims to predict the component-level dynamic stiffness (N/mm) and damping loss factor as a function of preload, forcing frequency (0-100Hz), and vibration amplitude. Also examined are the effects of friction between the seal and contacting fixture, as well as the effect of geometric differences between the nominal design and the actual manufactured part. Although temperature can significantly affect the properties of elastomers, it was held constant at 23 degrees Celsius to simplify the number of analysis and test conditions. [Figure 2](#) shows the weatherstrip cross section selected for this correlation study. This particular seal was chosen based on its typical complex shape for an automotive application and for its single material composition. A brief overview of the theoretical approach is introduced followed by an outline of the material

characterization procedure used to construct a suitable elastomer material model for simulation. As validation, the static and dynamic analysis of a simple extension specimen is compared to experimental data followed by the component-level analysis of the weatherstrip seal and its correlation to experimental bench test results.

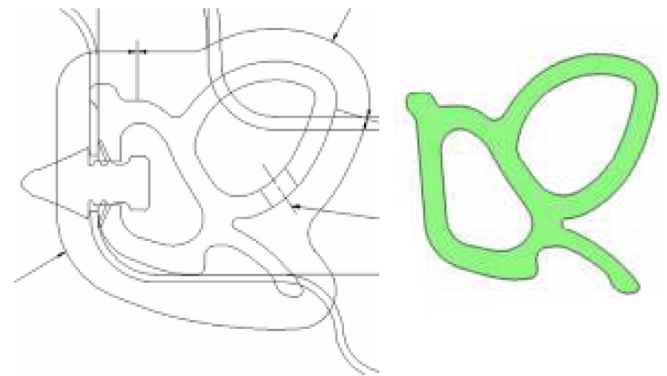


Figure 2. Cross-section of the EPDM door weatherstrip seal selected for this study

THEORETICAL REVIEW

The theoretical approach outlined by Morman et al [1, 2, 3] describes a condition where a large deformation is imposed on a solid viscoelastic component and held constant for a period time until the material reaches a stress-relaxed equilibrium state, at which point one is able to assume the large-strain effects are completely separable from time effects. In essence, the final stress state of the material is assumed to depend only on the current deformation condition and not on the history of deformations previously imposed. The theory applied is an extension of linear viscoelastic theory developed by Coleman and Noll [4] and later expanded by the theory of small amplitude vibrations superimposed on deformed viscoelastic solids developed by Lianis [5]. Morman and Nagtegaal [1] implemented an approach into commercially available finite element analysis (FEA) software that is capable of predicting dynamic stiffness and damping loss characteristics of viscoelastic materials as a function of preload, frequency, and vibration amplitude. They developed a simplified approach to construct a dynamic material model defined by a set of “phi-functions” which are based on measured values of the frequency dependent complex shear modulus $G^*(\omega)$ and equilibrium shear modulus $G(\infty)$ of a material. A review of the theory applied in this study is presented in two sections: The first section outlines the formulation of the hyperelastic quasi-static preload, and the second section outlines the formulation of the superimposed small-strain dynamic analysis and phi function formulation.

LARGE-STRAIN QUASI-STATIC ANALYSIS FORMULATION

A multi-term Mooney-Rivlin model, often also referred to as a James, Green, and Simpson model, was used to describe the large-strain hyperelastic response of the EPDM weatherstrip material. This model assumes the material is both isotropic and elastic, thus, it is expected to behave consistently in all directions and permanent plastic deformation of the material is not considered [2]. Below is the generalized form of a 3-term Mooney-Rivlin model where the strain energy density function W is expressed as a function of the first and second strain invariants I_1 and I_2

$$W(I_1, I_2) = C_{10}(I_1 - 3) + C_{01}(I_2 - 3) + C_{11}(I_1 - 3)(I_2 - 3) \quad (4)$$

$C_{\alpha\beta}$ are coefficients calibrated using material characterization experimental data while the strain invariants I_1 and I_2 are a function of strain in the three principle directions of translation and therefore are dependent on the instantaneous shape of the component and determined at each increment of deformation in the analysis.

SUPERIMPOSED SMALL-STRAIN DYNAMIC ANALYSIS & PHI-FUNCTION FORMULATION

The general expression for small sinusoidal deformations superimposed on an initial large deformation in viscoelastic solids as proposed by Lianis [5] is shown in [equation \(5\)](#).

$$\sigma_{ij} = \sigma_{ij}^0 + \Delta\sigma_{ij}^* \exp(i\omega t) \quad (5)$$

This approach assumes the viscoelastic solid is homogeneous, isotropic, and has been statically deformed for a sufficiently long time resulting in a state of stressed relaxed equilibrium σ_{ij}^0 . Next a dynamic steady-state sinusoidal vibration of sufficiently small stress amplitude represented by $\Delta\sigma_{ij}^*$ is superimposed at discrete, harmonic frequencies ω on a statically deformed, stress-relaxed material. σ_{ij} represents the overall stress response in the material at a specific preload, frequency, and vibration amplitude. The derivation and expansion of [equation 5](#) can be referenced further in [1, 5].

Morman et al. [1] developed a simplified approach to construct a dynamic material model that derives a set of nine complex-valued scalar relaxation functions, or phi-functions, using measured values of the frequency dependent complex shear modulus $G^*(\omega)$ and equilibrium shear modulus $G(\infty)$ to build a dynamic material model. Generally, the complex incremental stress $\Delta\sigma_{ij}^*$ shown in [equation \(5\)](#) is a function of the calculated phi-functions shown below:

$$\begin{aligned} \phi_0^*(\omega) &= 2g^*(\omega)I_2W_2 \\ \phi_1^*(\omega) &= 2g^*(\omega)(W_1 - I_1W_2) \\ \phi_2^*(\omega) &= 2g^*(\omega)W_2 \\ \phi_{10}^*(\omega) &= 4g^*(\omega)I_1W_2 \\ \phi_{11}^*(\omega) &= 4g^*(\omega)(W_{11} + 2I_1W_{12} + I_1^2W_{22}) \\ \phi_{12}^*(\omega) &= \phi_{21}^*(\omega) = -4g^*(\omega)(W_{12} - I_1W_{22}) \\ \phi_{20}^*(\omega) &= -4g^*(\omega)W_2 \\ \phi_{22}^*(\omega) &= 4g^*(\omega)W_{22} \end{aligned} \quad (6)$$

where

$$g^*(\omega) = \int_0^\infty g(t) \exp(-i\omega t) dt \quad (7)$$

and

$$g(t) = \frac{1}{2} \left[\frac{G^0(t)}{G_e^0} - 1 \right] = \frac{1}{2} \left[\frac{E^0(t)}{E_e^0} - 1 \right]. \quad (8)$$

In [equation \(8\)](#), $g(t)$ is termed the normalized time-dependent shear modulus, $G^0(t)$ is the shear stress-relaxation modulus of linear viscoelasticity, and $G_e^0 = G^0(\infty)$ is the long-time equilibrium modulus. The uniaxial stress-relaxation modulus $E^0(t)$ and equilibrium modulus E_e^0 can be directly substituted for $G^0(t)$ and G_e^0 [3] which is a useful relationship since the uniaxial specimen testing is typically more commonly available and economical. When [\(8\)](#) is solved for $G^0(t)$ the expression can be rewritten as:

$$G^0(t) = G_e^0(1 + 2g(t)). \quad (9)$$

Furthermore, if [\(9\)](#) is expressed with complex-valued terms substituted for the time-dependent shear modulus then $G^0(t)$ it can also be rewritten as:

$$G^*(\omega) = G_e^0(1 + 2g^*(\omega)). \quad (10)$$

Notice that the complex shear modulus $G^*(\omega)$ and the normalized complex shear modulus $g^*(\omega)$ can also be expressed as complex numbers of the form $a + ib$ as follows:

$$G^*(\omega) = G'(\omega) + iG''(\omega) \quad (11)$$

$$g^*(\omega) = g'(\omega) + ig''(\omega) \quad (12)$$

where G' and G'' are commonly referred to as the elastic storage modulus and the damping loss modulus, respectively. Together G' and G'' describe the complex viscoelastic response of the material as a function of frequency ω . If (10) is set equal to (11) and solved independently for the normalized storage and loss moduli $g'(\omega)$ and $g''(\omega)$ then the following equations are derived:

$$g'(\omega) = \frac{1}{2} \left(\frac{G'(\omega)}{G_e^0} - 1 \right) \quad (13)$$

$$g''(\omega) = \frac{1}{2} \left(\frac{G''(\omega)}{G_e^0} \right) \quad (14)$$

The critical inputs necessary to construct the hyperelastic and dynamic-harmonic material model presented in this paper are the $C_{\alpha\beta}$ coefficients in the multi-term Mooney-Rivlin strain energy density function W from equation (4) plus $G'(\omega)$, $G''(\omega)$, and G_e^0 . Each of the required inputs $C_{\alpha\beta}$, $G'(\omega)$, $G''(\omega)$, and G_e^0 can be derived from a set of experimental stress-strain data as discussed in the next section. Additionally, considering the irregular shape of the seal cross section and its orientation to the direction of fixture compression, friction between the rubber seal and the contacting metal fixture surface was anticipated to influence the experimental results; therefore, additional testing was conducted to approximate the Coulomb friction coefficient μ .

MATERIAL CHARACTERIZATION OF ELASTOMERS

OUTLINE

Although accurate mechanical properties of metals can often be obtained from handbooks, the mechanical properties of viscoelastic materials must be determined experimentally [6]. Unlike other materials which exhibit relatively consistent mechanical properties regardless of its environment and usage, the mechanical properties of viscoelastic materials can be highly sensitive to many factors such as preload, excitation frequency, vibration amplitude, geometry, contact friction,

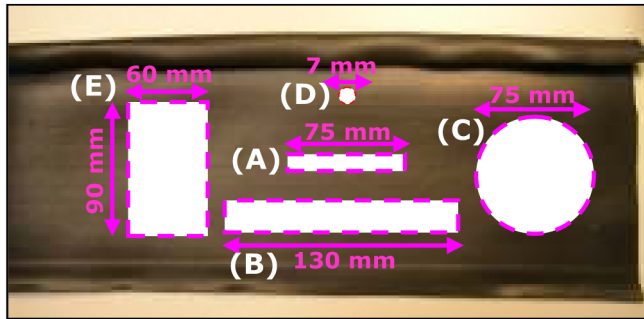
temperature, aging, permanent set, material compound formulation, curing conditions, among others. To predict the static and dynamic stiffness (N/mm) and loss factor coefficients of the weatherstrip seal at a constant temperature, the steps below were taken to characterize the EPDM weatherstrip material for calibrating and constructing the material model used in the simulations.

- Obtained a large ribbon sample using the same EPDM material and extrusion manufacturing and curing process as the actual component. Cut out material coupon samples from the large extruded ribbon for quasi-static and dynamic material characterization testing.
- Conducted quasi-static characterization tests to capture the non-linear hyperelastic stress-strain behavior of the material to be used to calibrate the Mooney-Rivlin $C_{\alpha\beta}$ coefficients.
- Conducted long-time stress-relaxation characterization tests to capture the effects of preset deformation on the equilibrium shear stress modulus G_e^0 .
- Conducted dynamic-harmonic non-resonance-based characterization tests to capture the effects of frequency, preload, and vibration amplitude on the material complex shear modulus G^* .

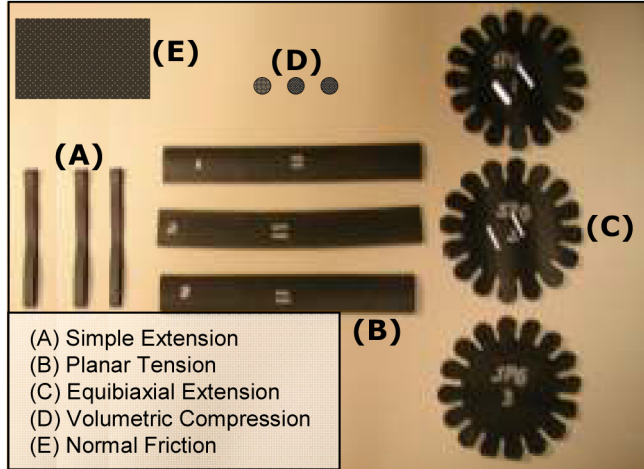
A brief overview of the experiments conducted to characterize the quasi-static and dynamic behavior of the EPDM material is briefly discussed in the following section but can be found outlined in detail in references [3, 7, 8, and 9].

EXTRUDED RIBBON SAMPLE

In order to create the test specimen coupons required to conduct material characterization testing, a sufficiently large extruded ribbon sample was obtained from the weatherstrip manufacturer. The ribbon sample was manufactured under near-identical conditions as the actual component to minimize the variation in material properties due to manufacturing and environmental conditions. The extruded ribbon sample used in this study is illustrated in Figure 3. The area of the ribbon sample is large enough to cut-out multiple sample sets of the test specimen coupons. Recommended dimensions for these coupon specimens are discussed in [3, 6, 7, 8, and 9] and the dimensions of those created for this study are shown in Figure 3. The material characterization plan was carried out on three complete sets of coupons and then averaged to account for natural variation from sample to sample.



Large extruded ribbon sample showing coupon cut-outs



3 coupon specimen sets for material characterization

Figure 3. Extruded EPDM ribbon and coupon samples extracted for material characterization

QUASI-STATIC HYPERELASTIC CHARACTERIZATION

In order to characterize the hyperelastic behavior of the EPDM weatherstrip material the stress-strain relationships for the following deformation modes were determined experimentally [3, 7]. The test setups are illustrated in [Figure 4](#):

- [Figure 4a](#). Simple Extension characterizes the tensile response of the material.
- [Figure 4b](#). Planar Tension characterizes the pure shear response of the material.
- [Figure 4c](#). Equi-Biaxial Extension characterizes the pure compression response of the material.
- [Figure 4d](#). Volumetric Compression characterizes the bulk modulus response of the material.

[Figure 5](#) shows the hyperelastic stress-strain response due to monotonic loading acquired experimentally for the EPDM material.

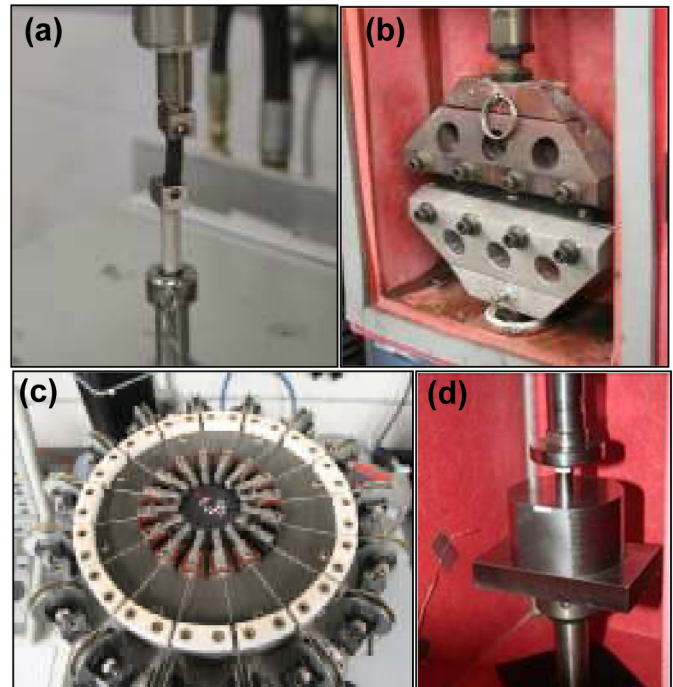


Figure 4. Material characterization test fixture setup

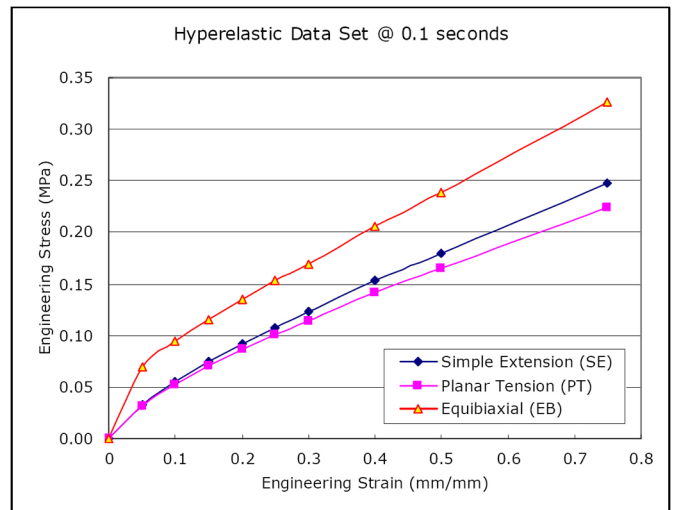


Figure 5. EPDM hyperelastic stress- strain curves data set