by I. Basdogan and E. Dikmen

MODELING VISCOELASTIC RESPONSE OF VEHICLE DOOR SEAL

Automotive weatherstrip seals are used in between the doors and vehicle body along the perimeter of the doors. The seals can be held in place through various methods such as intermittent push pins, continuous carriers, and flange mounts. They are mainly used to prevent water and dust entrance to the passenger compartment in all weather conditions and accommodate for the manufacturing variations.

The weatherstrip seal affects the door vibrations considerably by changing its stiffness and viscoelastic properties. Hence, accurate representation of the door seals is crucial in the simulation models used for predicting the dynamics of the vehicle. For this purpose, the material properties of the seal must be characterized properly. The weatherstrip seal investigated in this study is made of ethylene propylene diene monomer (EPDM) sponge rubber. The weatherstrip seal is generally in the form of dual extrusion bulbs of sponge and dense rubber. The bulbs can have different shapes generally with a height of approximately 15–30 mm. The wall thickness of the bulb is typically a few millimeters to provide maximum sealing area at a low compression force.[1] The rubber used in the seal can withstand large deformations without permanent deformation and have high damping characteristics. The mechanical properties of the rubber may vary with the amount of deformation, geometrical shape factors, previous load history, temperature, frequency, and amplitude of the motion in the presence of mechanical vibrations. Because these properties are difficult to predict, experimental methods must be often adopted for the dynamic characterization or system identification.[2–4]

Several groups have conducted experiments with rubber used in automotive industry to characterize its mechanical properties. In an earlier study, we developed hyperelastic and viscoelastic models of the weatherstrip seal to predict dynamic performance of a vehicle door and its effect on the overall vehicle dynamics.[5] Lin et al.[6] presented a simple experimental method to evaluate frequency dependent stiffness and damping characteristics of a rubber mount. Kren and Vriend[7] used dynamic indentation tests in order to determine viscoelastic properties of rubber. Hummel and Nied developed a procedure for measuring biaxial viscoelastic behavior of thermoplastics.[8] They designed and constructed a heated tensile testing machine to perform large strain deformation testing on polymers at elevated temperatures. They measured the elastic response of the material at elevated temperatures and large deformations. They also developed a numerical procedure to determine the elastic response from the raw viscoelastic data using the Mooney–Rivlin form of the elastic strain energy function. Kulik et al. developed an experimental technique to measure the dynamic properties of the viscoelastic materials.[9] The method is based on the analysis of forced oscillation of a cylindrical sample loaded with an inertial mass. For the calculation of the properties, a two-dimensional numerical model of cylindrical sample deformation was used. They studied the effect of altering the ratio of load mass to sample mass on the modulus of elasticity and loss tangent curves.

Jeong and Singh[10] proposed new analytical methods for modeling vibration isolators and mounts of a vehicle or machinery systems. They used the linear and nonlinear eigenvalue formulations to model the frequency dependency of elastic and dissipative parameters. They developed a nonlinear, frequency domain synthesis method to calculate the forced harmonic response of the overall system, and then validated the method by comparing it with the corresponding time domain method. Richards and Singh[11] proposed new methods to characterize nonlinear stiffness properties of rubber isolators. Their study included experiments investigating the response of single- and multi-degree-of-freedom models of rubber under different types of excitation loads. For analytical characterization of rubber isolators, they used a continuous quasi-linear representation and discrete nonlinear system models. In another study by Park,[12] different approaches to the mathematical modeling of viscoelastic dampers are addressed and their theoretical basis and performance are compared. Their study showed that despite the widespread notion of the inadequacy of spring-dashpot mechanical models for viscoelastic dampers, the generalized Maxwell or generalized Voigt model, with their expanded degrees of freedom, accurately describes the broad-band rheological behavior of common viscoelastic dampers. Gaillard and Singh[13] developed dynamic lumped parameter models of vehicle clutches using Voigt and Maxwell models, and a dry-friction element based on the Coulomb model. The theoretical predictions were then compared with the experimental data. They observed that the dynamic viscoelastic models with dry-friction component successfully simulate trends observed in the experiments and the dynamic properties depend on excitation frequency and amplitude. Zhang and Richards[14] used a parameter identification method based on constraint optimization for identifying the parameters of a Maxwell solid model having two or more Maxwell elements by fitting the model to measured frequency response spectra. The identification method was validated by several analytical examples. They conducted experiments with three different rubber isolators subjected to both static and dynamic loadings. For all three rubber isolators, they compared the performance of Voigt and Maxwell models and concluded that Maxwell solid having two Maxwell elements can accurately represent the measured static and dynamic characteristics of real elastomeric isolation systems. In a similar study, the same authors studied the dynamic characterization and parameter identification of a single mass elastomeric isolation system represented by a Maxwell–Voigt model.[15] They examined the influences that the stiffness and damping

I. Basdogan (ibasdogan@ku.edu.tr) is an assistant professor with the Department of Mechanical Engineering, Koc University, Rumeli Feneri Yolu, Sariyer, Istanbul, Turkey. E. Dikmen is a PhD student with the Department of Mechanical Engineering, University of Twente, Enschede, Netherlands.

doi: 10.1111/j.1747-1567.2009.00599.x

values of the Maxwell element have on natural frequency, damping ratio, and frequency response. It was shown that Voigt and Maxwell-Voigt models with equivalent natural frequencies and damping ratios can have considerably different frequency response spectra.

In this study, we developed a methodology to characterize the viscoelastic coefficients of the weatherstrip seal using experimental methods and curve fitting techniques. We conducted stress relaxation experiments using a robotic indenter equipped with force and displacement sensors to characterize the viscoelastic behavior of the seal. A curve-fitting algorithm is developed in MATLAB (The MathWorks, Natick, MA) that fits the experimental force relaxation response of the seal to a “ramp and hold” input using the generalized Maxwell solid. The fitting algorithm estimates the viscoelastic material coefficients of the system. These viscoelastic coefficients were substituted into the Maxwell solid model to estimate the frequency response function (FRF) of the seal. Independent of this approach, an impact test was also performed on the same seal to measure its FRF directly. The FRF obtained from the impact test was then compared with the one obtained through the stress relaxation experiments and the results are discussed.

STRESS RELAXATION EXPERIMENT

Rubber-like materials such as the weatherstrip seal show viscoelastic behavior. Viscoelasticity is a rate-dependent behavior where the material properties may be both time- and temperature-dependent. In order to characterize the viscoelastic behavior of the weatherstrip seal, stress relaxation experiments were conducted. Note that the experiments were conducted with the actual seal geometry because the geometric factors are known to play an important role in the analysis. We used a robotic indentor to perform the stress relaxation tests.

A robotic arm equipped with position sensors was used to compress the seal during the stress relaxation experiments (Fig. 1). A flat plate was attached to the tip of the arm as an indenter. A proportional–integral–derivative (PID) controller was implemented to move the indenter from an initial position to a desired position in 3-D space in discrete time steps. A force transducer (Nano 17 from ATI Industrial Automation, Apex, NC) was attached to the robotic arm for the purpose of measuring force response of the seal during compression. The force transducer has a range of ±70 N in the normal direction, ±50 N in other principal directions, and has a resolution of 1/1280 N along each of the three orthogonal axes when attached to a 16-bit A/D converter. The indentor position was measured using the motor encoders of the robotic arm. The force and position data were acquired using a 16-bit analog input card NI PCI-6034E (National Instruments, Austin, TX) with a maximum sampling rate of 200 kilosample/sec. The robotic indenter was programmed to compress the seal to a predefined indentation depth in 1 s and then it was held there for 40 s while the force relaxation response of the weatherstrip seal was recorded as a function of time. Stress relaxation experiment for the indentation depth of 8 mm (corresponding to the compression speed of 8 mm/s) is shown in Fig. 2. Figure 2a and b shows the displacement input and force response of the weatherstrip seal as a function of time, respectively.

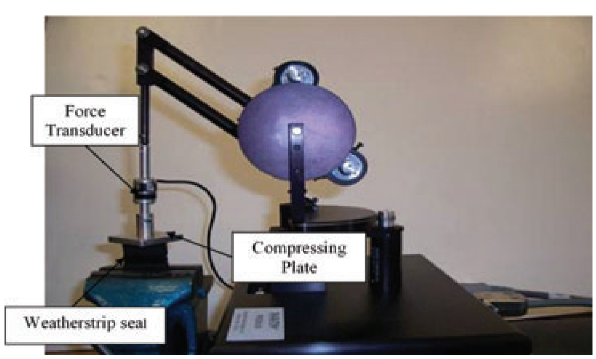

Fig. 1: Robotic indenter used for the stress relaxation experiments

Time dependency of stress relaxation function of viscoelastic materials can be represented by spring and dashpot models. In these models, the stress carried by the spring is proportional to the strain in the spring and is given by Hooke’s law. The stress carried in the dashpot is proportional to the strain rate and is given by Newton’s law of viscosity. Viscoelastic materials can be modeled as combination of springs and dashpots in series or parallel. In this study, we modeled the viscoelastic response of the weatherstrip seal using a generalized Maxwell solid. The model consists of a spring and “N” Maxwell units connected in parallel as illustrated in Fig. 3 (note that a series combination of a spring and a dashpot constitutes one Maxwell unit). The stress response, $\sigma(t)$, of a generalized Maxwell solid to a “ramp and hold” input can be described as in Lakes[16]

$$\sigma(t) = A[z(t) - z(t-c)u(t-c)] \tag{1}$$

where A is the slope of the ramp, c is the starting time for the hold, and $u(t-c)$ is the Heaviside unit step function shifted by c units to the right in the time domain and $z(t)$ is defined as:

$$z(t) = E_\infty t + \sum_{j=1}^{N} \eta_j \left(1 - \exp\left(\frac{-t}{\tau_j}\right)\right) \tag{2}$$

In this equation, E_j are the elastic moduli, n_j are the damping coefficient, and $\tau_j = (\eta_j/E_j)$ are the time constants. We are interested in the relaxation (hold) component of the Eq. 1 (when $t > c$), then the equation becomes,

$$\sigma(t) = A[z(t) - z(t-c)] \tag{3}$$

and the following relation is obtained for the stress function

$$\sigma(t) = A\left[E_\infty c - \sum_{j=1}^{N} \eta_j \exp\left(\frac{-t}{\tau_j}\right)\left(1 - \exp\left(\frac{c}{\tau_j}\right)\right)\right] \tag{4}$$

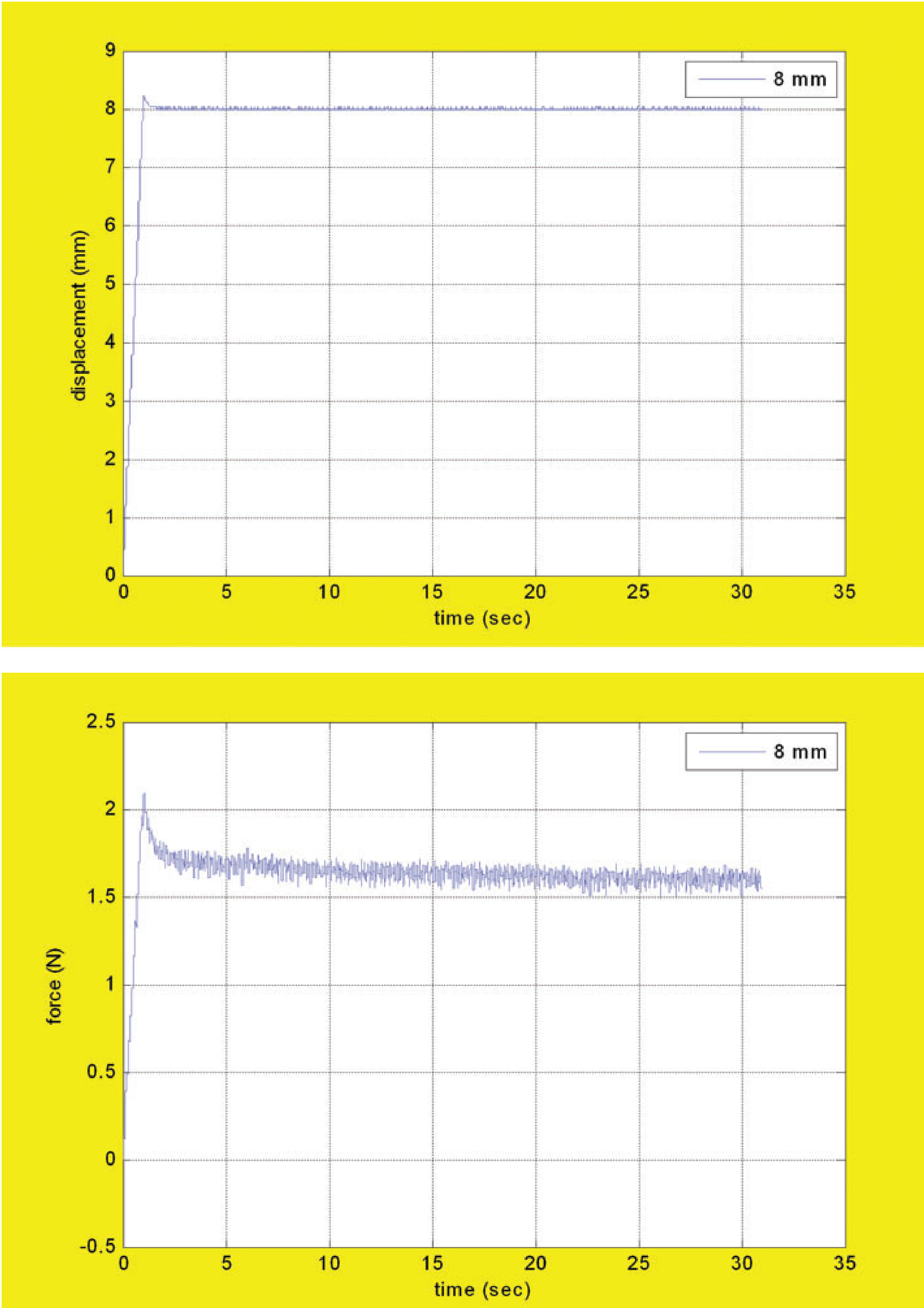

Fig. 2: Stress relaxation experiment with 8-mm indentation depth (a) displacement, (b) force

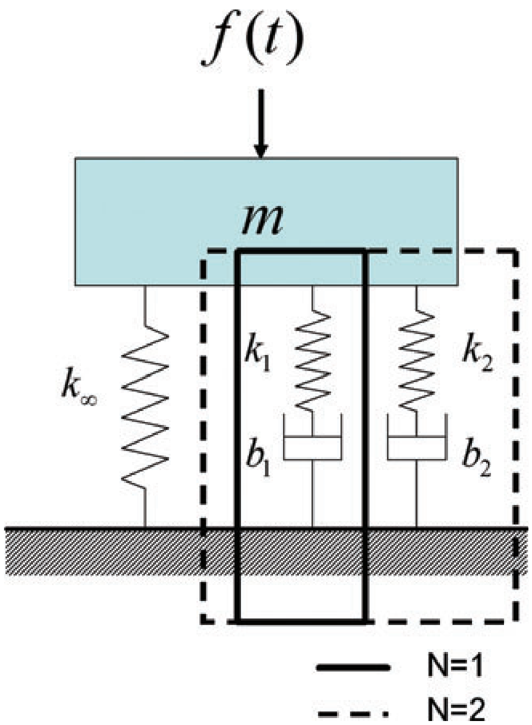

Fig. 3: Generalized Maxwell solid for *N* = 1 and *N* = 2

In this study, force rather than the stress will be used in the formulations because force-displacement (rather than stress-strain) data are obtained from the relaxation experiments. Assuming a constant cross sectional area, the elastic moduli E_∞ and E_j, and the damping coefficient η_j are replaced by k_∞, k_j and b_j, respectively, to obtain the force function of the Generalized Maxwell solid that can be written as:

$$F(t) = A\left[K_\infty c - \sum_{j=1}^{N} b_j \exp\left(\frac{-t}{\tau_j}\right)\left(1 - \exp\left(\frac{c}{\tau_j}\right)\right)\right] \quad (5)$$

$$\frac{X(s)}{F(s)} = \frac{(b_1 s + k_1)(b_2 s + k_2)}{m b_1 b_2 s^4 + [m b_1 k_2 + m b_2 k_1]s^3 + [m k_1 k_2 + k_\infty b_1 b_2 + b_1 b_2 k_1 + + b_1 b_2 k_2]s^2 + [k_\infty(b_1 k_2 + b_2 k_1) + b_1 k_1 k_2 + b_2 k_1 k_2]s + k_\infty k_1 k_2} \quad (6)$$

Now, τ_j is again the relaxation time constant and defined in terms of the linear damping and stiffness coefficients as $\tau_j = (b_j/k_j)$. The above formulation is used for curve fitting to the experimental force relaxation data. The generalized Maxwell solid with one ($N = 1$) and two ($N = 2$) Maxwell elements are tested for the best fit. For curve fitting, LSQNONLIN function of MATLAB is used. In addition to estimating the viscoelastic coefficients, the curve-fitting function also estimates the strain dependent stiffness coefficient k_∞. Before the curve-fitting algorithm is applied, the raw experimental data are filtered to obtain a smooth curve. Figure 4 compares the experimental force relaxation data with the fitted curves for $N = 1$ and $N = 2$. As it can be seen from the figure, the Maxwell solid with $N = 2$ fits to the relaxation component of the experimental data much better than $N = 1$ (note that the viscoelastic coefficients calculated by the curve-fitting method using two Maxwell elements is given in Table 1). For this reason, the viscoelastic coefficients of $N = 2$ are used to estimate the FRF of the seal, which is discussed in the following section.

FRF OF THE WEATHERSTRIP SEAL

The impact hammer is widely used in vibration tests to obtain the FRF.[17,18] It can be easily shown that the Fourier transform of the impulse response of a system gives the FRF of that system.[17] An experimental set-up consisting of a mass block and two weatherstrip seals placed in parallel are used to obtain the FRF (Fig. 5). Impact force was applied to the center of the block using the hammer and the response of the system was measured using two accelerometers attached to each side of the mass block. This arrangement cancels or minimizes the effect of rocking motion modes on the measured FRF of that system.[17] A soft rubber tip was attached to the impact hammer in order to generate low frequency force components and the data were averaged in each test to minimize the effect of random noise. The FRF obtained from the impact test is shown in Fig. 6. The natural frequency of the system is also determined from the same plot that is equal to 12.71 Hz.

In order to check the validity of the viscoelastic coefficients calculated by the curve-fitting method in section on Stress Relaxation Experiment, we modeled the single-degree-of-freedom (SDOF) system analyzed in the impact test using a generalized Maxwell solid for $N = 2$ elements. We obtained the analytical FRF such that we can compare the FRF with the one obtained from the impact test. The dynamic equations of the Maxwell solid for $N = 2$ carrying a mass block (see Fig. 5 for the representation of the SDOF system) are derived and the transfer function between the displacement output and the force input in the Laplace domain is obtained as:

The mass block is represented by "m" in the SDOF system. The weatherstrip seals are glued to the mass block at one end and they are fixed to the ground by a rigid fixture at the other end (see Fig. 5 for details). Mass of the seals is not taken into consideration in the SDOF model because they are significantly lower than the mass block. Dividing the numerator and denominator by $k_1 k_2$ and using the definition of the relaxation time constants, the magnitude of the FRF between acceleration and force, $|T(j\omega)|$, can be written in terms of the viscoelastic coefficients as:

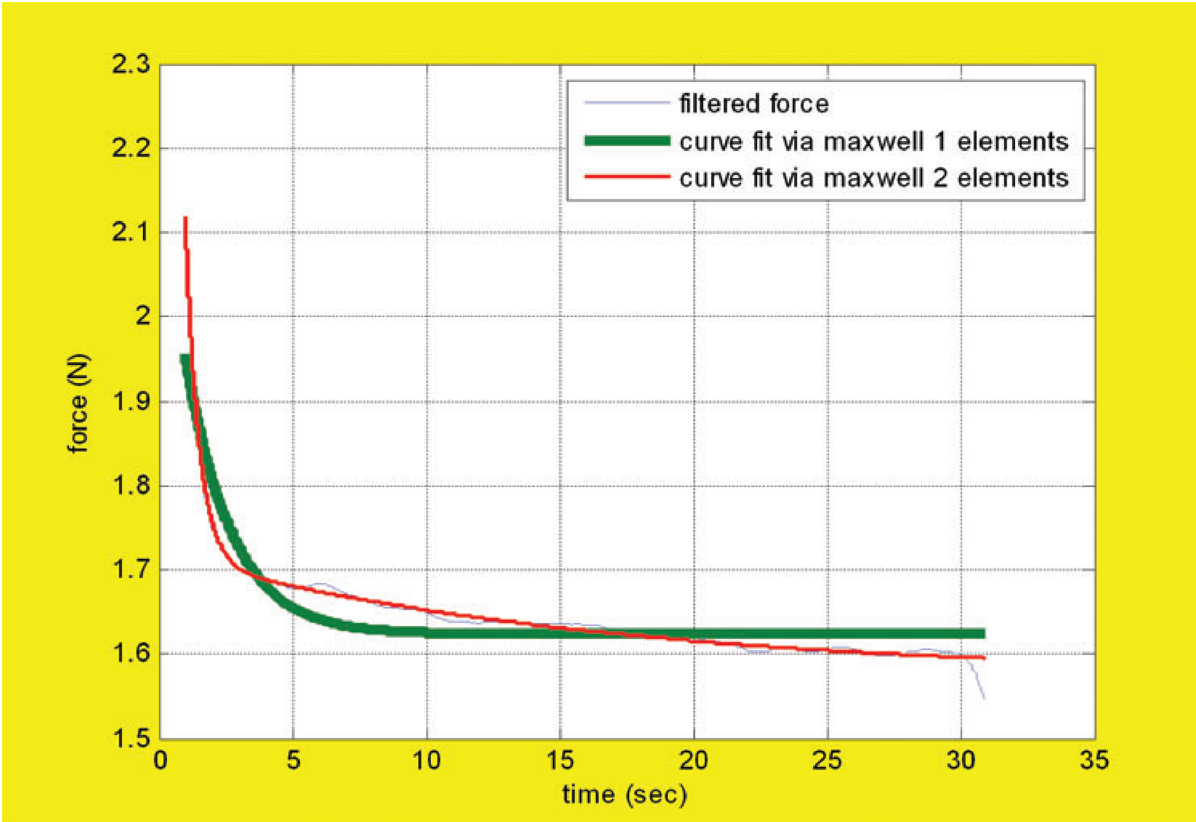

Fig. 4: Relaxation component of the fitted force function for *N* = 1 and *N* = 2

$$|T(j\omega)| = \frac{(-\omega^2)\sqrt{(1-\tau_1\tau_2\,\omega^2)^2 + (\tau_1+\tau_2)^2\,\omega^2}}{\sqrt{[m\tau_1\tau_2\,\omega^4 - (m + k_\infty\tau_1\tau_2 + \tau_1\tau_2 k_1 + \tau_1\tau_2 k_2)\omega^2 + k_\infty]^2 + [(k_\infty(\tau_1+\tau_2) + b_1 + b_2)\omega - m(\tau_1+\tau_2)\omega^3]^2}} \tag{7}$$

If we substitute the viscoelastic coefficients calculated in the previous section into Eq. 7, we obtain the FRF shown in Fig. 6. As it can be seen from the figure, there is a good agreement between the experimental FRF obtained from the impact test and the Maxwell solid model approximation. The Maxwell solid model predicts the frequency of the SDOF system very accurately, which means that the curve fitting estimates the stiffness values of the Maxwell element coefficients k_∞, k_1, and k_2 very accurately. The value of the strain dependent k_∞ also agrees with the results of the compression experiment that was carried out in our previous study.[5] However, there is a slight mismatch between the amplitude of the SDOF system at the resonance value. The difference between the peak values shows that the damping of the model is slightly underestimated with the Maxwell model approximation. If we slightly change the damping values in the Maxwell model approximation, we can have a better match at the resonance value. The discrepancy between the experimental result and the model prediction could be also due to the sampling rate of the experimental data such that the resonance peak is not captured completely.

Table 1—Viscoelastic coefficients calculated by the curve-fitting method

STRESS RELAXATION WITH 8 mm INDENTATION DEPTH ($N = 2$)
$k_\infty = 0.1965$ N/mm
$k_1 = 0.1175$ N/mm
$k_2 = 0.0178$ N/mm
$b_1 = 0.0590$ N.s/mm
$b_2 = 0.2922$ N.s/mm

DISCUSSION AND CONCLUSION

In this study, a methodology is developed to calculate the viscoelastic properties of the weatherstrip seal using

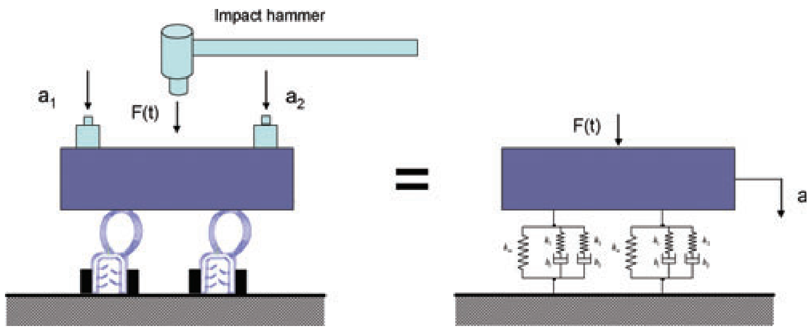

Fig. 5: Experimental set-up for the impact tests showing the analogy of Maxwell solid approximation

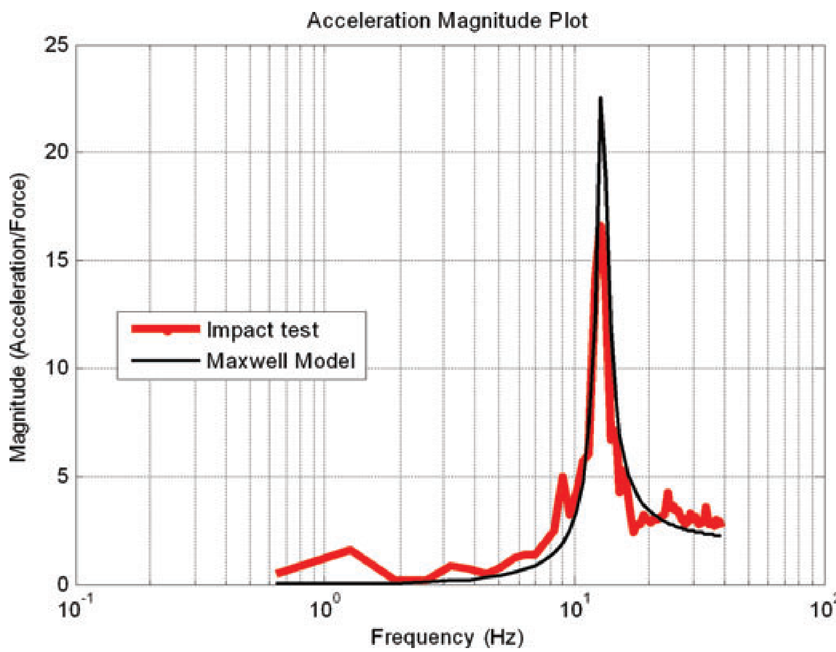

Fig. 6: Comparison of experimental and analytical frequency response functions

stress relaxation experiments and a generalized Maxwell solid approximation. A curve-fitting algorithm is developed in MATLAB that fits the force function of a generalized Maxwell solid to the experimental stress relaxation data obtained by applying "ramp and hold" displacement input to the seal. The results of the curve fitting shows that the viscoelastic response of the seal can be approximated well if two Maxwell arms ($N = 2$) are used in the model. Using the viscoelastic coefficients obtained from the stress relaxation experiments, the FRF of the seal was estimated for an SDOF system represented by a Maxwell solid. This function was then compared with the experimental one obtained from the impact test. The method presented in this paper proves itself to be an accurate technique to characterize the linear viscoelastic properties of rubber-like materials such as weatherstrip seal. Characterizing the viscoelastic material properties of the weatherstrip seal is very crucial especially when detailed modeling of the seal is required to investigate the effect of the seal on the vehicle dynamics.

ACKNOWLEDGEMENTS

The authors kindly acknowledge the support of Ford Otosan A.S. during the course of this study

References

1. Wagner, D.A., Kenneth, N.M., Gur, Y., and Koka, M.R., "Nonlinear Analysis of Automotive Door Weatherstrip Seals," *Finite Elements in Analysis and Design* **23:**33–50 (1997).

2. Gade, S., Zaveri, K., Konstantin-Hansen, H., and Herlufsen, H. "Stress/Strain Measurements of Viscoelastic Materials," *Sound and Vibration* 16–19 (1995).

3. Gobel, E.F., *Rubber Springs Design*, Halsted Press, New York (1974).

4. Gent, A.N., *Engineering with Rubber: how to Design Rubber Components*. Hanser Publishers, New York (1992).

5. Dikmen, E., and Basdogan, I., "Material Characteristics of Vehicle Door Seal and its Effect on Vehicle Vibrations," *Vehicle System Dynamics Journal*, in press.

6. Lin, T.R., Farag, N.H., Pan, J., "Evaluation of Frequency Dependent Rubber Mount Stiffness and Damping by Impact Test," *Applied Acoustics* **66:**829–844 (2005).

7. Vriend, N.M., Kren, A.P., "Determination of the Viscoelastic Properties of Elastomeric Materials by the Dynamic Indentation Method," *Polymer Testing* **23:**369–375 (2004).

8. Hummel, S.R., Nied, H.F., "A Procedure for Measuring Biaxial Viscoelastic Behavior of Thermoplastics," *Experimental Mechanics* **44:**381–386 (2004).

9. Kulik, V.M., Semenov, B.N., Boiko, A.V., Seoudi, B.M., Chun, H.H., Lee, I., "Measurement of Dynamic Properties of Viscoelastic Materials," *Experimental Mechanics* **23:**158–164 (1983).

10. Jeong, T., and Singh, R., "Inclusion of Measured Frequency and Amplitude-Dependent Mount Properties in Vehicle or Machinery Models," *Journal of Sound and Vibration* **245:**385–415 (2001).

11. Richards, C.M., and Singh, R., "Characterization of Rubber Isolator Nonlinearities in the Context of Single- and Multi-Degree-of-Freedom Experimental Systems," *Journal of Sound and Vibration* **247:**807–834 (2001).

12. Park, S.W., "Analytical Modeling of Viscoelastic Dampers for Structural and Vibration Control," *International Journal of Solids and Structures* **38:**8065–8092 (2001).

13. Gaillard, C.L., and Singh, R., "Dynamic Analysis of Automotive Clutch Dampers," *Applied Acoustics* **60:**399–424 (2000).

14. Zhang, J., and Richards, C.M., "Parameter İdentification of Analytical and Experimental Rubber Isolators Represented by Maxwell Models," *Mechanical Systems and Signal Processing* **21:**2814–2832 (2007).

15. Zhang, J., and Richards, C.M., "Dynamic Analysis and Parameter Identification of a Single Mass Elastomeric İsolation System Using Maxwell-Voigt Model," *ASME Journal of Vibration and Acoustics* **128:**713–721 (2006).

16. Lakes, R., *Viscoelastic Solids*, CRC Press, Boca Raton, FL (1998).

17. Ewins, D.J., *Modal Testing: Theory and Practice*, Research Studies Press, Baldock, UK, (1986).

18. McConell, K.G., *Vibration Testing, Theory and Practice*, Wiley, New York (1995). ■