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Effect of the viscoelastic properties of the vulcanized rubber hose on the transmissibility of a small diameter pipeline system

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Abstract. Frequency response analysis is a fundamental approach for assessing a system's vibration response under operational loading, supporting design validation, performance improvement, and correction of failures related to damping or structural behavior. The combination of numerical simulations with experimental validation can significantly reduce product development time; however, oversimplified constitutive models or uncertainties in material properties, boundary conditions, or load definitions can generate discrepancies between predicted and measured responses. This work investigates a real case of a pipeline system containing a vulcanized rubber hose, aiming to improve prediction accuracy. The coupled mechanical system is modeled using the finite element method in ABAQUS to determine the transmissibility frequency response function, applying excitation at one end and measuring the response at the other. The hose is modeled as viscoelastic, with storage modulus and loss factor obtained from dynamic mechanical analysis as frequency-dependent functions. The parameters of a fractional derivative constitutive model are identified, calibrated, and validated experimentally. Finally, the study compares the dynamic behavior of non-vulcanized and vulcanized rubber specimens, demonstrating the influence of vulcanization on vibration characteristics and providing a methodology applicable to the design and optimization of more complex components and systems.

Keywords: Viscoelastic materials, Finite element method, Modal analysis, Frequency-dependent damping.

1 Introduction

The frequency response function (FRF) is widely employed to quantify how mechanical systems respond to varying excitation frequencies, providing essential insights for design validation, structural health monitoring, and failure prevention [1-2]. In many industrial applications, particularly in the automotive and manufacturing sectors, integrating numerical simulation tools with experimental validation has become standard practice [3 - 4]. This approach enables virtual testing and iterative refinement before physical prototyping, significantly reducing development time and associated costs.

However, achieving reliable numerical predictions depends critically on the accurate characterization of the materials and components involved [5]. Viscoelastic materials, such as vulcanized rubber used in flexible pipelines, pose particular modeling challenges due to their time- and frequency-dependent behavior. Classical constitutive models based on integer-order differential equations, such as the Maxwell and Kelvin-Voigt models, offer a solid analytical foundation and are widely adopted in engineering practice [6]. Nonetheless, capturing the full dynamic response of real materials often requires multiple elements or complex model arrangements, increasing the difficulty of parameter identification [6-11]. This gives rise to a modeling paradigm: while simpler formulations may lack the fidelity needed for precise prediction, overly complex models can be impractical due to the labor-intensive effort required for accurate calibration. Striking the right balance between accuracy and computational or experimental feasibility remains a central challenge in viscoelastic modeling [12]. To address these limitations, fractional derivative models have emerged as powerful tools for representing viscoelastic

behavior across a broad frequency range. These models incorporate non-integer order derivatives, capturing the hereditary and damping characteristics intrinsic to polymeric materials, and often yield improved agreement with experimental observations [5].

This paper presents a comprehensive study on the effect of viscoelastic properties of vulcanized rubber hoses on the transmissibility of a small-diameter pipeline system, typical of automotive heating, ventilation, and air conditioning (HVAC) applications. Finite Element Method (FEM) simulations are conducted using ABAQUS, with the hose's viscoelastic behavior modeled via a fractional derivative constitutive law. The numerical model is calibrated and validated against experimental frequency response data obtained from controlled excitation tests. The results demonstrate enhanced predictive accuracy, highlighting the potential of fractional viscoelastic modeling in engineering design. Furthermore, the methodology developed provides a systematic framework applicable to future analyses involving complex components and advanced materials.

2 Literature Review

2.1 Classical Viscoelastic Models

The mechanical behavior of viscoelastic materials is governed by both elastic and viscous characteristics, leading to time- and frequency-dependent responses under dynamic loading. Classical viscoelastic models, such as the Maxwell, Kelvin-Voigt, and Standard Linear Solid (Zener) models, have been extensively adopted due to their simplicity and clear physical interpretation.

The Maxwell model, comprising a spring and a dashpot in series, is suitable for modeling stress relaxation but inadequately captures long-term creep behavior. Conversely, the Kelvin-Voigt model, based on a parallel spring-dashpot configuration, effectively represents creep but fails to describe stress relaxation accurately. The Zener model, or Standard Linear Solid, combines both arrangements and serves as a more complete representation of viscoelastic behavior in the linear regime [6].

To address the limitations of these basic models in capturing complex material responses, generalized models based on Prony series expansions are often employed. These models, such as the Generalized Maxwell Model (GMM) and the Generalized Kelvin-Voigt Model, consist of multiple elements with different time constants. This enables the modeling of broad relaxation or retardation spectra, which are typical in polymers and elastomeric materials [9].

Despite their analytical robustness, classical models present practical limitations. The need for many elements to fit a wide frequency range leads to a large number of parameters, complicating calibration and reducing computational efficiency [11]. In applications involving dynamic behavior, such as vibration analysis of rubber hoses in automotive pipelines, these drawbacks become particularly critical, motivating the search for more compact yet accurate modeling frameworks.

2.2 Fractional Derivative Models in Viscoelasticity

Fractional derivative models have emerged as a powerful alternative to classical formulations in recent decades. These models use non-integer order derivatives to describe stress-strain relationships, enabling the capture of material memory effects and complex damping behavior with fewer parameters. The foundational work by Koeller [5] demonstrated the applicability of fractional calculus to viscoelasticity, showing that a single fractional element could reproduce both creep and relaxation phenomena over broad timescales. Similarly, Bagley and Torvik [6-7] developed fractional versions of the classical Maxwell and Kelvin models, proving that these formulations could approximate experimental data more effectively than traditional integer-order models. Fractional viscoelastic models offer several advantages: i) They inherently represent power-law behavior observed in many polymers; ii) Fewer parameters are required compared to Prony series; iii) They exhibit smooth transitions between elastic and viscous regimes.

Fractional derivative models provide a compact means of representing relatively weak frequency-dependent properties in the frequency domain. For example, a single material complex modulus might be represented as:

$$E^*(i\omega) = \frac{E_0 + bE_\infty(i\omega)^m}{1 + b(i\omega)^m} \tag{1}$$

where E_0, E_∞, b, and m are material properties, with m being the slope of the loss factor on a log-log plot versus frequency, at frequencies below that at which peak damping is observed. Values for m range from nearly 0 to 1, with 0.5 being typical, Lesieutre [13]. These benefits make fractional models particularly suitable for simulating polymeric materials subjected to dynamic loading, including elastomeric components like hoses, seals, and bushings. Despite their advantages, these models introduce new challenges, especially regarding numerical implementation and physical interpretation of fractional parameters. However, recent advances in computational mechanics and optimization have made them increasingly accessible for engineering applications.

2.3 Parameter Identification and Model Calibration

A central challenge in viscoelastic modeling is the identification of constitutive parameters that accurately reflect material behavior under operational conditions. In classical models, this process often involves fitting multi-element Prony series to experimental data using regression or optimization algorithms. However, as the number of elements increases, the parameter space becomes highly dimensional and nonlinear, making identification sensitive to initial guesses and local minima [10]. These difficulties are further exacerbated by the experimental noise, variability in material batches, and temperature effects.

In the case of fractional derivative models, although fewer parameters are typically required, they often lack direct physical interpretation, and the fitting process can involve non-convex optimization. Several studies have proposed using hybrid algorithms (e.g., GA-BFGS, particle swarm, differential evolution) and frequency-domain fitting to overcome these issues [12,14]. Experimental techniques such as Dynamic Mechanical Analysis (DMA), FRF measurements, and relaxation tests are essential tools for feeding accurate data into the calibration process.

2.4 Applications in Rubber Components and Pipeline Systems

Rubber components such as hoses, mounts, and bushings are widely used in the automotive industry due to their ability to absorb vibrations and accommodate mechanical displacements. However, their nonlinear, frequency-dependent behavior, especially under dynamic loads, makes accurate modeling a nontrivial task. Several studies have investigated the application of viscoelastic modeling to rubber-like materials. Ali et al. [15] compared classical hyperelastic models, such as neo-Hookean, Mooney-Rivlin, Yeoh, and Ogden, based on their ability to fit uniaxial stress-strain data. The study found that while simpler models are useful for small deformations, more complex ones like Ogden and Yeoh offer better accuracy across a wider range of strains. Complementing this, Zhou et al. [16] provided a comprehensive review of viscoelastic damping materials (VDMs), highlighting their classification, application methods, and mathematical modeling. The authors emphasized the importance of selecting appropriate constitutive models, such as Maxwell, Voigt, and fractional derivative models, to accurately capture the frequency- and temperature-dependent behavior of VDMs in structural vibration control.

In pipeline systems, flexible hoses made of rubber are commonly used in air conditioning, fuel delivery, and hydraulic subsystems. These components are particularly sensitive to vibration-induced fatigue and resonance phenomena. Accurate prediction of their transmissibility is essential for ensuring long-term durability and passenger comfort. Wijaya et al. [4] conducted a numerical and experimental investigation into the dynamic behavior of automotive air conditioning (A/C) hoses, focusing on the effects of engine-induced vibrations. Using finite element modeling and modal testing, the study identified that bending and swing modes dominate the hose's dynamic response, with the highest stress concentrations occurring in the reinforced braid layers and at the nipple connections. The authors employed a Mooney–Rivlin hyperelastic model to represent the rubber material and demonstrated that the middle rubber layer experiences the highest strain, while the outer braid layer is most susceptible to stress-induced failure.

The integration of FEM simulations with experimentally calibrated viscoelastic models has become a standard approach in such applications. When enhanced by fractional derivative formulations, these models can yield significantly improved correlation with measured frequency response data.

3 Methodology

3.1 Experimental Procedure

The dynamic behavior of the rubber hose was characterized through frequency response tests on two configurations: a straight pre-vulcanized specimen and a curved post-vulcanized specimen extracted from the automotive HVAC pipeline. The curved configuration introduced intentional geometric complexity, reproducing the actual component's shape and allowing assessment of its influence on the dynamic response.

In the first configuration, a 200 mm pre-vulcanized straight hose was clamped over 10 mm at one end and mounted vertically on a Sentek L1024M-PA115 electrodynamic shaker, as shown in Fig. 1 (left). The excitation signal had a constant amplitude of 9.81 m/s² over the frequency range of 15–500 Hz, which is commonly adopted for vibration assessment in automotive applications. A uniaxial accelerometer was positioned 20 mm from the free end recorded the response. The measured data were processed to obtain the frequency response function, including both real and imaginary components. The experimental setup is shown in Fig. 1 (right).

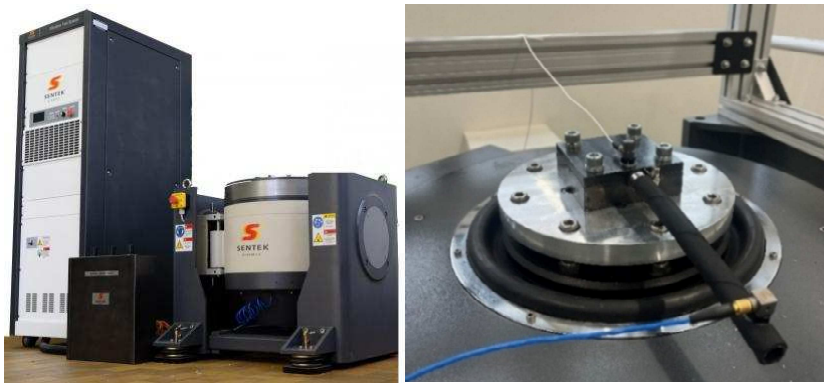


Figure 1. Frequency response test setup: (left) shaker; (right) pre-vulcanized hose.

The second test evaluated the effect of geometric complexity using a post-vulcanized curved hose segment, with the original geometry preserved according to the CAD model. A uniaxial accelerometer was placed near the excitation point, and the same shaker and excitation parameters (9.81 m/s², 15–500 Hz) were applied. This configuration enabled characterization of dynamic transmissibility and structural response under conditions closely replicating the operational system. Figure 2 shows the experimental setup, the CAD model of the hose, and the superimposition of the CAD geometry on the setup, highlighting the geometric representativeness of the computational model.

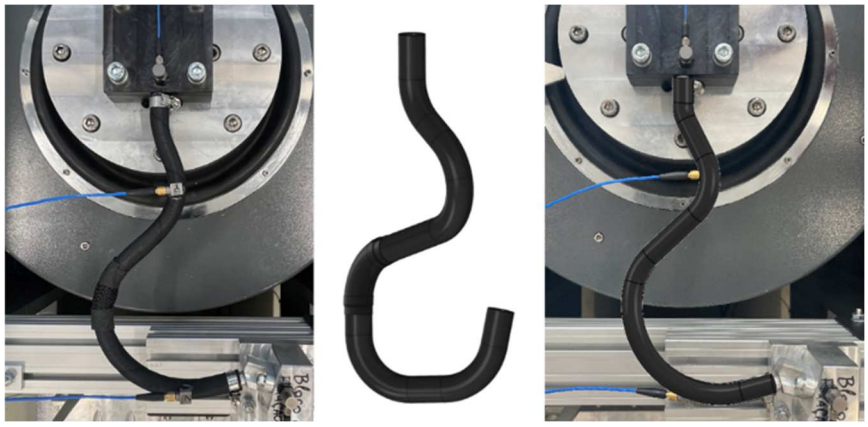


Figure 2. Frequency response test setup of post-vulcanized curved hose.

3.2 Numerical Modeling and Parameter Identification

The finite element simulations were carried out in Abaqus, replicating the experimental setup through a detailed structural model. The hose was discretized using first-order quadrilateral shell elements (S4R), with mesh sizing based on the specimen's average diameter, total length, and measured wall thickness. Boundary conditions reproduced the test configuration, with a fully clamped constraint at one end and a concentrated point mass at the opposite end to represent the accelerometer. The hose was modeled as a three-layer composite with a rubber–polyamide–rubber stacking sequence, consistent with its actual internal structure. The rubber layers were defined as viscoelastic materials governed by a fractional derivative constitutive law, while the polyamide layer was modeled as linear elastic with Rayleigh damping. Layer thicknesses, measured directly with a caliper, were 1.6 mm for the outer rubber, 0.75 mm for the polyamide, and 1.25 mm for the inner rubber, resulting in a total wall thickness of 3.6 mm. These values were kept constant throughout the optimization process.

To calibrate the viscoelastic parameters of the rubber layers and the Rayleigh damping coefficients of the polyamide layer, an automated optimization routine was developed. The optimization was performed using the Archive-based Micro Genetic Algorithm (AMGA), a multi-objective exploratory technique well-suited for highly non-linear, discontinuous, and constrained search spaces, as in the present problem. AMGA applies standard genetic operators (mutation and crossover) while maintaining a search history and employing a three-tier fitness evaluation: domination level within the population, contribution to the search history, and solution diversity. The process iteratively modified the material parameters, generating new Abaqus input files via MATLAB, running the simulations, and extracting the FRF for comparison with experimental curves. The optimization aimed to minimize the difference between simulated and measured FRFs. This approach ensured a robust calibration for both configurations.

4 Results

After the initial experimental stage, it was possible to obtain the amplitude–frequency FRF within the 5–2000 Hz range for both the straight and curved hose configurations. From these measurements, the real, imaginary, and magnitude components of the FRF were extracted, providing a complete representation of the system's dynamic response. These curves served as input for the Isight-based optimization procedure aimed at calibrating the viscoelastic parameters of the hose model. During the optimization, the elastic modulus of the polyamide layer was kept constant at 65 MPa, with a Poisson's ratio of 0.2, and the fractional derivative order m was fixed at 0.5, ensuring that the calibration process focused exclusively on the viscoelastic behavior of the rubber layers.

In the first optimization stage, the parameters obtained were: $\alpha = 0.5$ and $\beta = 1\times10^{-6}$, Rayleigh damping coefficients for the polyamide layer, and viscoelastic properties of the rubber hose being $b = 0.00225$, $E_0 = 75$ MPa, $E_\infty = 85$ MPa, with $m = 0.5$ maintained constant. The optimization sought to minimize the discrepancy between experimental and numerical FRFs, particularly around resonance peaks where damping effects are more pronounced. A good agreement between the experimental and simulated results can be observed, with an R^2 value of 0.7792 for the magnitude curve, indicating convergence of the predicted response toward the measured data. The resulting calibrated curves, comparing experimental and simulated FRFs, are presented in Fig. 3.

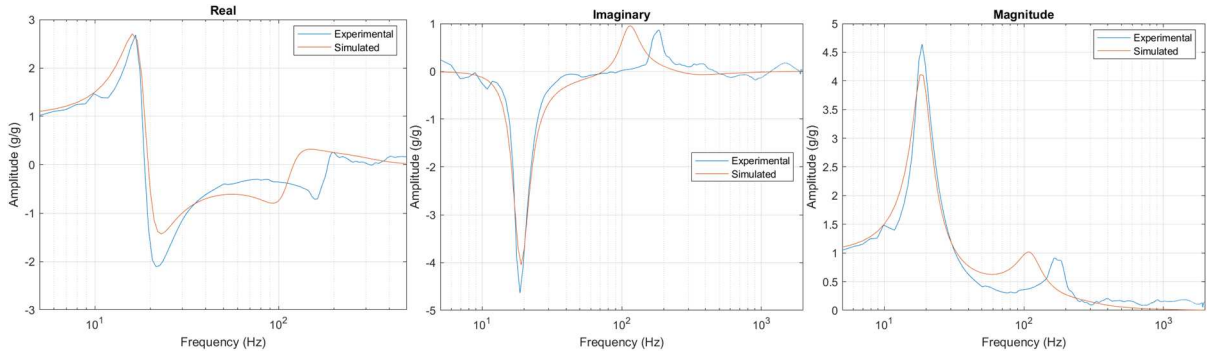


Figure 3. Comparison of the FRFs of the pre-vulcanized hose.

Proceeding with the post-vulcanized curved hose configuration, the experimental procedure followed the same excitation and acquisition methodology. The calibrated parameters obtained in this stage were: $\alpha = 120$, $\beta = 15\times10^{-5}$, $b = 0.002175$, $E_0 = 135$ MPa, $E_\infty = 975$ MPa, with $m = 0.5$ maintained constant. As in the previous case, optimization aimed to minimize the discrepancies between experimental and simulated FRFs, with particular attention to the resonance peaks where viscoelastic damping has a major influence on the dynamic response. A high level of agreement was achieved, with an R^2 value of 0.9202 for the magnitude curve, indicating strong convergence between predicted and measured results, despite the added geometric complexity. Figure 4 presents the comparison between simulated and experimental FRFs.

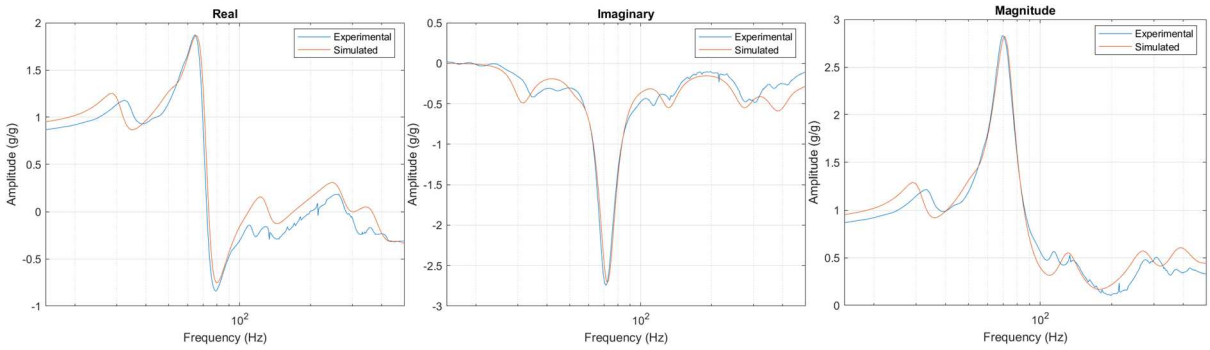


Figure 4. Comparison of the FRFs of the post-vulcanized curved hose.

Figure 5 presents the real, imaginary, and magnitude components of the viscoelastic modulus of the pre-vulcanized (left) and post-vulcanized (right) hose as functions of frequency, obtained after parameter optimization. These curves illustrate the frequency-dependent behavior of the material, reflecting both storage and loss moduli captured by the fractional derivative model. The post-vulcanized hose exhibits higher stiffness compared to the pre-vulcanized specimen, indicating that vulcanization significantly increases rubber rigidity, particularly at higher frequencies.

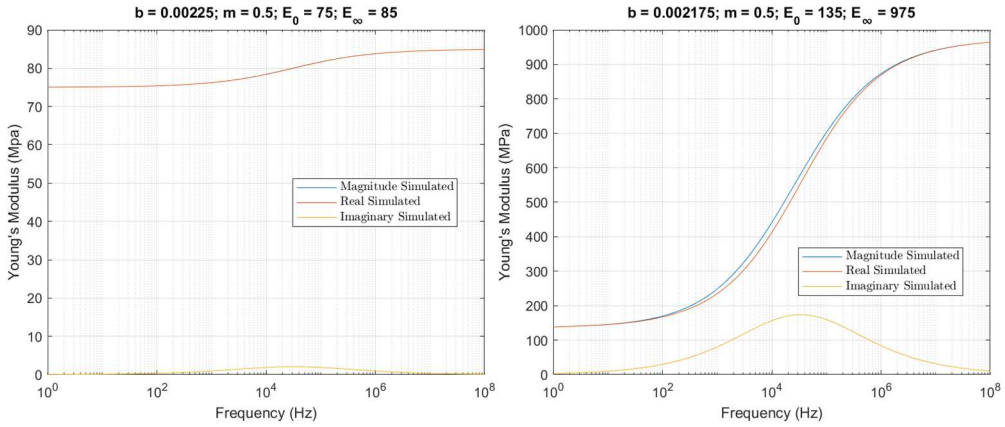


Figure 5. Frequency response of pre-vulcanized (left) and post-vulcanized (right) hose modulus.

The fractional derivative model effectively represented the hose's viscoelastic properties, achieving good correlation between experimental and numerical FRFs, especially at the first resonance peak where damping effects are most critical. This approach allows the development of more accurate simulation frameworks capable of capturing viscoelastic effects, improving predictions of loads and dynamic responses throughout the component's service life. Moreover, the results highlight that the increase in hose stiffness after vulcanization is further influenced by its curved geometric conformation, demonstrating the combined effects of material treatment and component geometry on dynamic behavior.

5 Conclusions

T This work presented an experimental–numerical methodology for the viscoelastic characterization of automotive rubber hoses using a fractional derivative constitutive model. The approach combined frequency response measurements in both pre-vulcanized straight and post-vulcanized curved configurations with finite element simulations in Abaqus for automated parameter calibration.

The AMGA proved effective in handling the highly non-linear, multi-modal search space of the parameter identification process, enabling accurate calibration of both viscoelastic and damping properties. Comparison between experimental and numerical frequency response functions demonstrated that the proposed modeling strategy captures the main dynamic characteristics of the hose, with high correlation near resonance peaks, where viscoelastic effects are most significant.

The results also showed an increase in stiffness after vulcanization and geometric conformation to the curved shape, highlighting the importance of incorporating the manufacturing process effects into numerical models. The validated fractional derivative model provides a robust foundation for predicting the dynamic response of rubber hoses under operational loading conditions, supporting more reliable durability assessments and optimized design for service life performance.

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