Dynamic Behavior of HDPE Fuel Tanks: Assessing Rate-Dependent Stiffness in Finite Element Analysis

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Abstract: - High-density polyethylene fuel tanks are commonly used in the automotive industry as a crucial component for transporting and storing combustible liquids. Still, predicting their dynamic behavior with high accuracy remains demanding, considering various loading conditions during a product's life. The study presented in this paper details a modal numerical analysis of the HDPE fuel tank and how different material models, rate-independent and rate-dependent, affect the final results in linear simulations. Finite Element Analysis (FEA) performed in the ANSYS software confirmed that a more detailed rate-dependent material model used during numerical analysis provides more accurate and reliable results.

Key-Words: - Finite Element Analysis, Modal Analysis, HDPE, Fuel Tank, Automotive, Rate-Dependent Materials.

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1 Introduction

The design and manufacturing of automotive fuel tanks is an essential endeavor within the automotive industry. These components are responsible for storing and delivering fuel safely, and they must withstand a variety of mechanical stresses during the vehicle's operation. The patent [1] and the article [2] discuss in detail the process of constructing and manufacturing both the frame and the fuel tank of the motorcycle. The design and production of automotive fuel tanks have been discussed in many publications. When fuel tanks, scientists take several factors related to the materials used and their required strength. Metals have been historically used for the manufacture of fuel tanks. Since 1972 plastic materials have begun to replace metal materials. The reason for this was that they have many advantages, such as less weight, no corrosion problems, less explosion damage during fire accidents, and sound and vibration damping, [3]. Researchers around the world are conducting research to find better plastic fuel barrier materials that meet increasingly stringent requirements, both because of tighter emission regulations and because fuels with very different compositions are used. In article [4], the influence of reducing the thickness of the grade of blank and changing the steel on the deformability of a lightweight automotive fuel tank was investigated. In [5] the authors describe the fuel tank made of alumina steel material, which combines the strength of steel with the corrosion resistance of aluminum. An important issue is the use of composite materials, such as plastic and carbon fiber, which offer advantages such as minimizing deformation and providing strength to the walls [6], [7]. The fuel tanks in cars are made of various materials such as plastic, polyketone, aluminum alloy, and high-pressure plastic. Plastic fuel tanks can be made from PVC resin, carboxyl nitrile butadiene rubber, polyvinyl butyrate butyral, and glass fiber, [8], [9]. Due to the unique balance of mechanical properties and high chemical resistance, polyketones (POK) are described as high-performance, multifunctional polymer materials that can be used, among others, to produce fuel tanks, [10]. Article [11] focuses on the integration of self-healing polymers or composites with cellular fillers made of wrinkled aluminum foil for fuel tanks. The analysis of fuel tanks made of high-pressure plastic has been extensively studied in the literature. Various aspects such as thermal management, failure behavior analysis, and structural optimization have been investigated, [12]. In the article [13], the authors discussed the results of the numerical structural analysis of a low-pressure hydrogen canister. Many articles describe the testing of high-pressure plastic fuel tanks. Article [8] presents the results of the static and dynamic analysis of plastic fuel tanks. In static analysis, equivalent static loads are applied to fuel tanks. However, in dynamic analysis, the time-varying loading and inertia of the fluid and fuel tanks are considered using modal transient analysis. In [14], the authors discussed the results of their research on the strength of plastic fuel tanks subjected to high-pressure tests simulating operating conditions in vehicles.

Currently, many publications contain studies on fuel tanks made of high-density polyethylene (HDPE). This material is valued for its lightness, corrosion resistance, and the possibility of forming in molding processes. In the article [15], the authors showed that increasing the density of the amorphous polyethylene regions by approximately 0.3% reduces oxygen permeability by up to 22%, without significantly changing other properties of the material. The article [16] describes research involving the use of motion tracking combined with computer vision to measure dynamic deformations in HDPE fuel tanks during collision simulations. The analysis of the influence of manufacturing technique, thickness, temperature, and strain rate on the tensile properties of HDPE is discussed in [17]. In the article [18] experimental studies of the effect of temperature on the behavior of the HDPE material were conducted, which translates into the durability and crash resistance of the fuel tank. The dynamic stiffness of high-density polyethylene and ways to model it in LS-DYNA® were shown in the article [19].

2 Problem Formulation

To estimate the dynamic response of the structure and obtain eigenfrequencies and mode shapes, finite element analysis, and linear dynamics are used, but when large assemblies are investigated simplifications are demanded by the software. Individual parts simulations are straightforward to adjust, but with a whole assembly, there are contacts between the parts. With contact, where interfaces are fixed one to another this is still not an issue, but when friction-based contacts are in place it is challenging to model with simplification restraints. Linear dynamics do not allow the engineers to mimic those phenomena in software, so contacts, where parts can separate or undergo frictional interactions can not be simulated.

Also, thermoplastics tend to be nonlinear even in its mainly elastic response range. With that additional accuracy errors right at the beginning of the analysis preparation are introduced since the elastic material model is commonly used during modal analyses. This poses a significant challenge loading characteristics including high strain rate cases, such as rapid mechanical loading. In such situations, the assumption of linear elasticity in modal analysis may not hold, and more advanced material models, capable of capturing nonlinear responses, become necessary for accurate simulations. Of course, the material models used in numerical modal construction do not support nonlinearities, which requires that the numerical model of the object be tuned and prepared in such a way as to ensure these discrepancies. Furthermore, relying solely on static tensile test material data may not provide a complete and realistic representation of how soft materials such as HDPE respond to dynamic loading conditions. These materials often exhibit rate-dependent material properties, meaning their mechanical behavior changes with the rate at which they are loaded or deformed. To accurately reflect the rate-dependent effects mentioned above, advanced material models, such as the viscoelastic model, should be used during FEM simulations.

In ANSYS software, viscoelasticity is modeled by a generalized Maxwell solid. In one-dimensional representation, it is a spring element with some spring and dashpot Maxwell elements in parallel, which is shown in Figure 1.

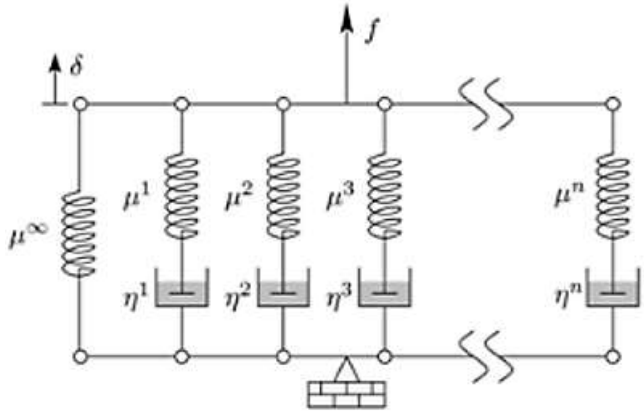

Fig. 1: Schematic of a generalized Maxwell model consisting of n Maxwell elements connected in parallel

The relaxation time τ^i in this model is given by:

$$\tau^i = \frac{\eta^i}{\mu^i} \tag{1}$$

where:
η^i – dashpot viscosities,
μ^i – spring stiffnesses,
i – i-th Maxwell element.

The generalized Maxwell model and its constitutive model in three dimensions are given by:

$$\sigma(t) = \int_0^t 2G(t-\tau)\frac{de}{d\tau}d\tau + I\int_0^t K(t-\tau)\frac{d\Delta}{d\tau}d\tau \tag{2}$$

where:
$\sigma(t)$ – Cauchy stress,
G – relaxation modulus,
τ – past time,
e – deviatoric strain,
I – identity tensor,
K – relaxation modulus,
Δ – volumetric strain.

$G(t)$ with $K(t)$ are the Prony series shear and bulk relaxation moduli, respectively defined:

$$G(t) = G_0\left[\alpha_\infty^G + \sum_{i=0}^{n_G} \alpha_i^G \exp(-\frac{t}{\tau_i^G})\right] \quad (3)$$

$$K(t) = K_0\left[\alpha_\infty^K + \sum_{i=0}^{n_K} \alpha_i^K \exp(-\frac{t}{\tau_i^K})\right] \quad (4)$$

where:
G_0, K_0 – relaxation moduli at t = 0,
n_G, n_K – number of Prony terms,
α_i^G, α_i^K – relative moduli,
τ_i^G, τ_i^K – relaxation time.

3 Problem Solution

HDPE is the material from which the fuel tank is made. A very important issue that should be considered during the dynamic analysis of structures made of HDPE or other polymers is the behavior of these materials depending on the rate of loading. The rate dependence means that the mechanical properties of a material change with the rate at which it is loaded or deformed. In the context of FEA, where simulations are employed to predict structural responses to dynamic loads, it is essential to account for this rate-dependent behavior. Even in quasi-static simulations, where the loading conditions are relatively slow and gradual, the use of a simple elastic material model may prove inadequate when dealing with materials such as HDPE. This inadequacy arises primarily from the plastic nature of the material. HDPE, like many polymers, exhibits a nonlinear stress-strain response, especially at higher stress levels. This results in poor accuracy of the linear material model even at the elastic range. Another topic is the dynamic stiffness of the material, but that can be addressed through damping adjustments during the modal analysis. With the shortcomings of the elastic model, engineers have to use more complex models within the linear dynamics. One of those models is the viscoelastic model. Thanks to the properties of the dataset required to create this model, it can capture the behavior of the material more accurately, including damping effects and dynamic stiffness in the frequency domain. A viscoelastic model incorporates both elastic (Hookean) behavior, which represents instantaneous deformation, and viscous (dashpot) behavior, which accounts for time-dependent deformation or energy dissipation. With this model, it is possible to significantly reduce the inaccuracy of the material model and build more robust numerical models of the investigated structures.

To acquire the dataset needed for the viscoelastic model Dynamic Mechanical Analysis (DMA) is used. During his test, the specimen is loaded with a specified frequency. The dataset acquired after the analysis provides the storage and loss modulus within the frequency domain.

The simulation included both the fuel tank and the mounting frame used during the experimental test. Minor details, like markings or welding joints were simplified. The tank shell was represented by a surface model with constant thickness and some noncritical components of the assembly were changed to mass points. Figure 2 shows simplified geometry. All calculations were performed using ANSYS 2022R2.

To compare material model differences two identical simulations were performed. One used an elastic material model for the HDPE components and the second one used a viscoelastic material model.

Fig. 2: The fuel tank geometry used in simulations

The results of the numerical analyses were compared with the experimental test data. In this test, accelerometers were placed on the structure to monitor the amplitude in the range of frequency 3-100 Hz. Results from the simulations provide the amplitude measured at the same locations. Figure 3, Figure 4 and Figure 5 show the comparison of those tests. The analysis of the obtained results allows us to conclude that the introduction of a viscoelastic material model significantly improved the accuracy of the simulation results in comparison with the standard elastic model. In particular, the frequencies corresponding to the maxima in the data closely align with the experimental test results, reflecting a significant improvement in the predictive capabilities of the viscoelastic material model.

In particular, in Figure 3, the G-force values and the overall shape of the curve present a substantial enhancement in the accuracy of the simulation data at that specific point in the frequency spectrum. In Figure 4 we observe slight improvement; both amplitude and frequency values are closer to the conducted sine sweep test. However, not all the points on the model showed very promising results. Figure 5 shows no major improvement, especially the amplitude shows no signs of advancement.

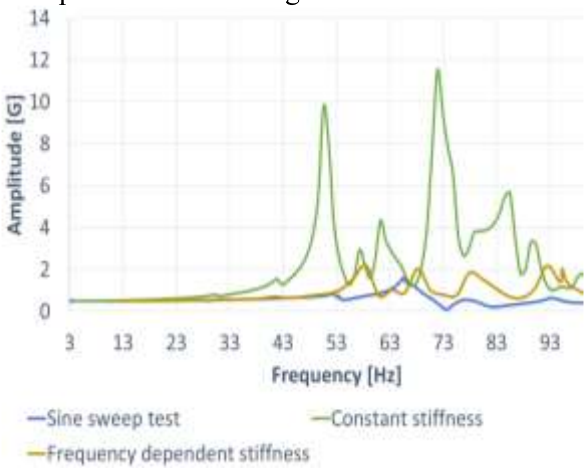

Fig. 3: Acceleration compared during sine sweep

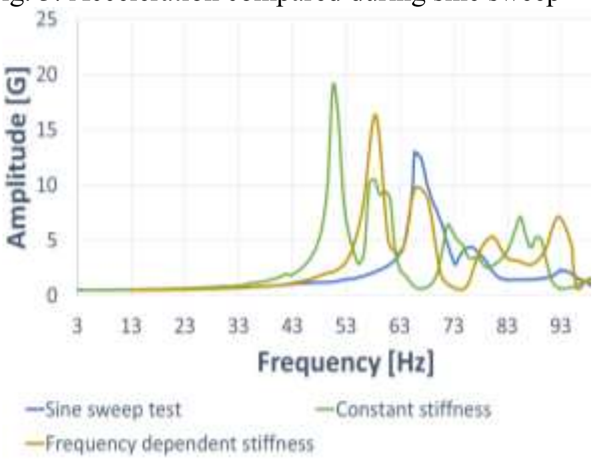

Fig. 4: Acceleration compared during sine sweep

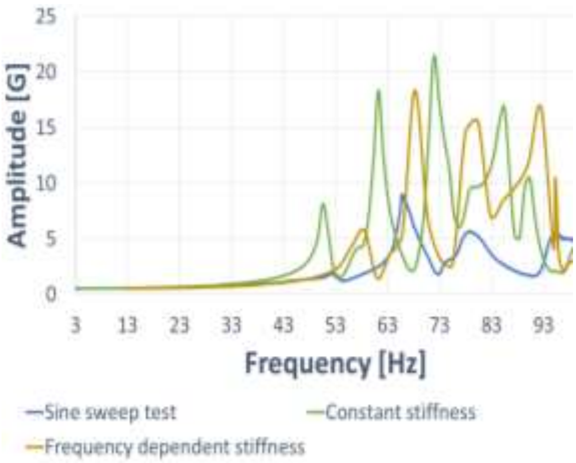

Fig. 5: Acceleration compared during sine sweep

4 Conclusion

In conclusion, this study has provided valuable insights into the dynamic response of High-Density Polyethylene (HDPE) fuel tanks during modal analysis. By conducting detailed simulations closely mirroring real-world experimental modal analysis, we sought to evaluate the performance of the viscoelastic material model in comparison to the standard elastic model. Our findings demonstrate the effectiveness of the viscoelastic material model in improving the accuracy of the simulation results, particularly in terms of aligning the frequencies of the maxima with the experimental data. However, despite these promising advancements, it is imperative to acknowledge that the general reliability of the simulation results remains below the desired standard for reliable use in the development process. Further investigation is warranted to address the existing discrepancies and refine the accuracy of the model. This scientific assessment underscores the value of incorporating viscoelastic material models during modal simulations, especially when dealing with rate-dependent materials such as HDPE, and underscores the importance of ongoing research to refine the simulation methodology, ultimately contributing to more reliable and precise numerical models.

Future research in this domain should primarily focus on enhancing the computational efficiency of geometry models capable of representing the variable wall thickness of the fuel tank. Furthermore, a crucial aspect for future investigation involves exploring and characterizing damping parameters in the context of modal analysis. Damping is a critical factor in understanding how energy dissipates within a structure under dynamic loading conditions. This knowledge is invaluable for refining the accuracy of the simulation and aligning it with real-world behavior.

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