Chapter 18
Characterization of Vibrational Mechanical Properties of Polyurethane Foam

Raphaël Dupuis, Olivier Duboeuf, Bertrand Kirtz, and Evelyne Aubry

Abstract Polyurethane foam (PU) is widely used in numerous comfort applications such as automotive seat cushioning and mattresses. The present paper is devoted to describe experimental techniques and identification of dynamic properties of thin flexible polyurethane foam used in automotive seats. In the experimental device, a free mass is mounted on a 0.1 m^2 of different foams used in car upholstery. The foam is the only flexible component. The device is excited with an electrodynamic shaker with frequencies varying between 10 and 200 Hz. The response of foam samples to sweep sine excitation is analyzed for different excitation acceleration amplitude (1–2.5 mm s^{-2}) and for different free masses.

In order to answer the issue of replacement, different multilayer products and single foam samples have been characterized and comparisons have been carried out. The results of this study show interesting properties in terms of dynamic behavior of multilayer products when compared to the PU foams.

Keywords Polyurethane foam • Upholstery • Dynamic behavior • Natural frequency • Filtration frequency

18.1 Introduction

In order to propose some alternative soft cellular solids usable in the automotive interior, it is necessary to have an accurate knowledge of the dynamic characteristics of the existing materials. The new European Directives such as 2000/53/CE [1] imposes strict rules concerning the recycling with an aim of 85 % of recyclable products and 95 % re useable products. These new constraints imposes car manufacturers and their partners to review the automotive specifications for the materials used in the automotive interior as the headliner facings, the loudspeaker housing, the insulation material, car upholsteries, etc. . . The materials currently used as seat upholsteries are complex materials generally composed of three layers (Fig. 18.1). The first layer is a knitted or woven fabric, for the appearance, generally made of polyester (PET). The second layer is polyurethane foam between 2 and 8 mm thickness. The third layer is usually a knitted polyamide (PA) or polyester fabric. The use of polyurethane will bring comfort in the case of flexible foams and excellent thermal insulation in the case of rigid foam [2].

The realization of automotive complex fabrics, usually done by flame lamination, produces the emission of dangerous volatile components [2], and inhibit the recyclability of this complex. Indeed, the delaminating process of these complex materials is quite impossible because traces of foam remain in the polyester or polyamide after separation of the different layers and pollute the extracted components. Some alternative products to polyurethane foam are existing, often made by a single component material (100 % polyester p.e.), leading to an easier recyclability. To be accepted by automotive original equipment manufacturer, these alternative materials must have the same mechanical characteristics, particularly in terms of humid aging and dynamic characteristics, than the replaced foam. Moreover, it must meet the requirements of the automotive industry in terms of weight, implementation and cost [3].

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In this paper, different polyurethane foams have been studied. The methods of physical and mechanical characterization of foams will be presented. First, the characterization methods and free mass vibration tests will be detailed, then the results will be analyzed and a critical analysis of the dynamic behavior of these materials will be carried out.

Many authors have published as well paper than books about foam mechanical properties. The reference is obviously the work of Gibson and Ashby [4]. Thus, they have shown that the characteristics of foams depend on various parameters such as cell morphology, size, arrangement, connections between them… Static mechanical behavior of foams has been well described by Gibson and Ashby [4], particularly in the effect of a compressive force. On the stress-strain curves of polyurethane foam, three main parts can be highlighted. First a linear elasticity at low stress followed by a long collapse plateau, and finished by a densification of the material in which the stress rises steeply.

Concerning dynamic studies on polyurethane foam, Pritz [5] has proposed in 1980 to study the complex modulus of soft materials using a free mass device. Since then, the team of Bajaj and Davies has conducted numerous studies on the polyurethane foam, both experimental [6–9] with a free mass device guided with ball bearing, and in modeling using memory integer models [8], or memory fractional models [9, 10]. Jmal has also developed an interesting approach with memory integer models [11]. All of these studies have focused on samples of thick foam (75 mm), but never to the cover of the seat.

18.2 Tested Materials

The study focused on polyurethane foams commonly used in automotive trim. The foam is soft cellular structure [8]. The cells can be modeled geometrically by a pentagon. A method of characterization [12] adapted from the VISIOCELL® method (Fig. 18.2) has been used to evaluate the average diameter of foam cells. The tested foams A and B were respectively open and closed cells.

All the parameters issued of these characterization methods are shown in Table 18.1.

Table 18.1 presents the main physical characteristics of foams studied.

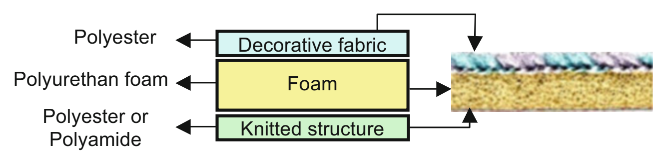

Fig. 18.1 Automotive complex composition

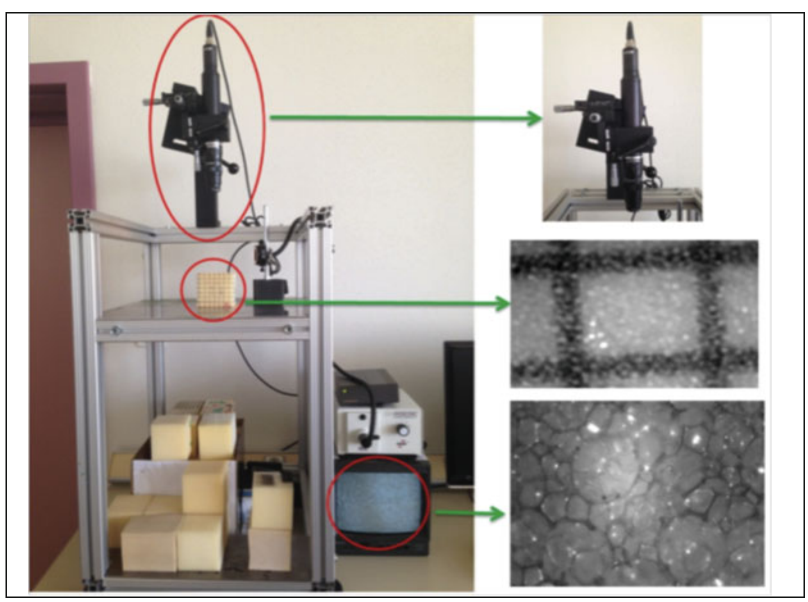

Fig. 18.2 Polyurethane foam structure [12]

For each foam, we applied the experimental methodology to determine the compression behaviour presented in 2009 [13] and we calculated the energy of the hysteresis and the maximum stress at 50 % of initial thickness deformation at the fourth cycle (Table 18.2).

18.3 Experimental Methodology

All the tests have been carried out on an electrodynamic shaker (LDS V455, Bruel and Kjaër) driven by a vibration control system (COMET, Bruel and Kjaër) (Fig. 18.3). The foam plates are glued by a perfectly hardening adhesive (3M™ Double Coated Tape 9832) to thin metal plates, which are bolted on the base of the shaker and on the free mass to prevent the free mass from losing contact with the foam during vibration. In order to vary the compression level, additional weights can be placed on the top mass (Fig. 18.3).

The frequency of excitation was varied from 10 to 200 Hz with a 1 oct/min sweep rate, with constant input acceleration, and the amplitude and phase of the response was recorded. Two piezoelectric CCLD accelerometers (type 4507B, Bruel and Kjaër) were used to measure the input acceleration of the shaker and the output response of the free mass. The amplitude and phase responses were recorded for four additional free mass (1.0, 1.6, 2.2 and 2.8 kg) in order to modify the foam compression levels and four excitation acceleration amplitudes (1.0, 1.5, 2.0 and 2.5 m/s^2 peak amplitude).

The test procedure is the following: according to the recommendations given by White et al. [6], the sample is first loaded during 30 min to reach his static steady state. Then, the system is excited at constant acceleration amplitude at a 10 Hz

Table 18.1 Physical characteristics of tested foams

Designation	Foam A	Foam B
Foam types	Flexible	Flexible
Isocyanate	TDI polyester	TMDI
Fabrication process	Slabstock	Slabstock
Type of cells	Closed	Open
Dimensions ($L_0 \times l_0 \times h_0$) m^3	$0.1 \times 0.1 \times 0.004$	$0.1 \times 0.1 \times 0.004$
Density ($kg\ m^{-3}$)	45.2	46.1
Average longitudinal cell size (μm)	190	348
Average transversal cell size (μm)	117	241

Table 18.2 Compression behaviour properties of tested foams

Designation	Foam A	Foam B
Energy dissipated during the 4th cycle of compression (J)	1.9	1.45
Maximum stress at 50 % of initial thickness deformation at the fourth cycle (kPa)	11	6.7

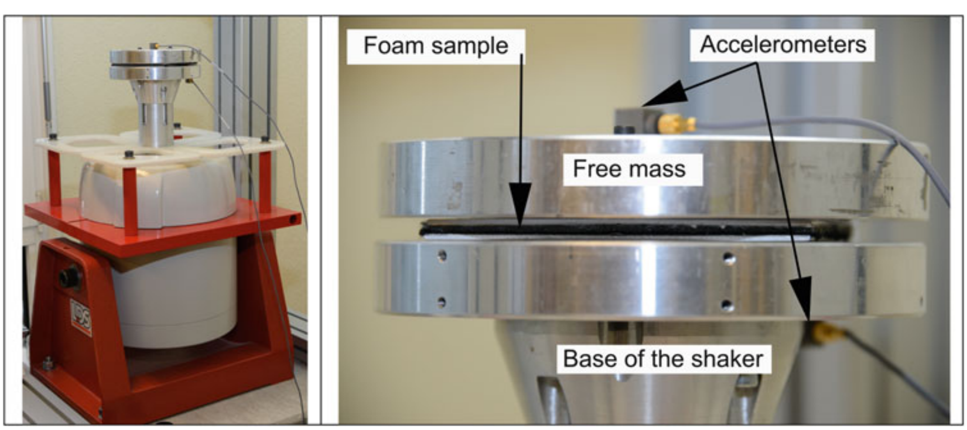

Fig. 18.3 LDS shaker and free mass system

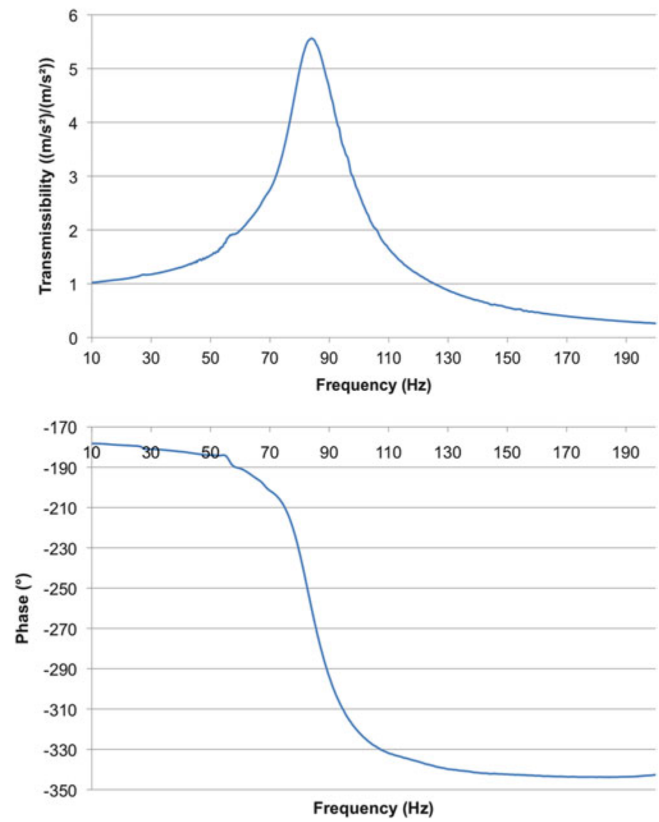

Fig. 18.4 Classical transmissibility–frequency and phase–frequency curves of polyurethane foam

frequency during 10 min. At least, the sweep sine is applied from low to high frequency and then from high back to low frequency.

At the end of the test, the transmissibility is calculated and plotted (Fig. 18.4), and we can calculate the natural frequency, the Q factor, the gain at the resonance and the filtration frequency.

18.4 Results and Discussions

For each mass and each excitation acceleration level, we measured the natural frequency, the filtration frequency, the magnitude at resonance, and we calculated the stiffness of each foam. The results were plotted curves (Figs. 18.5, 18.6, 18.7 and 18.8).

The first parameter we analyzed is the stiffness (Fig. 18.5). We can notice that for foam B, whatever the mass we applied and whatever our excitation acceleration level, the stiffness is quite constant, excepted for the heaviest mass and highest acceleration. This can be explained by the structure of open cellular foam B. For the foam A, according to our testing conditions, the stiffness is not constant. When we load the foam with our lowest mass, we can observe that the stiffness is more important. Our excitation acceleration level of excitation doesn't seem to have a great influence on the stiffness of foam A. For each level of mass, the stiffness doesn't vary when the excitation acceleration level changes. This can be explained by the highly nonlinear comportment of closed cell polyurethane foams described by Gibson and Ashby [4].

Concerning the natural frequency (Fig. 18.6), when we use our two heaviest masses (2.2 or 2.8 kg), the natural frequency is comprised inside the 0–50 Hz band which is the frequencies classically excited in automotive seat. In addition, the filtration frequency of foam B is lower than 50 Hz. That means that foams never filter, and sometimes amplifies the vibrations of the seat.

The results of filtration frequency are presented in Fig. 18.7. We observe that the filtration frequency is quite constant for foam B, into the band of masses and excitation acceleration level we choosed. The foam A presents a constant filtration

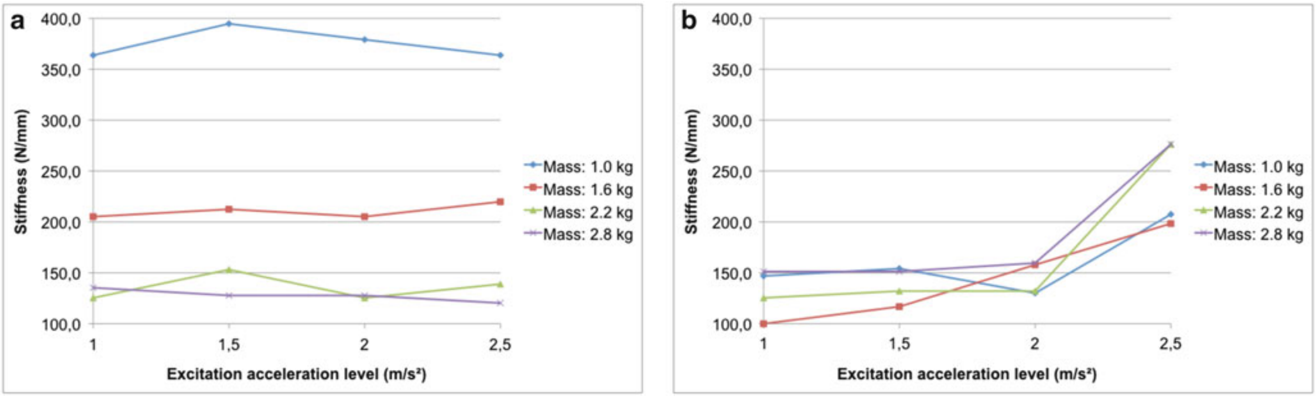

Fig. 18.5 Stiffness of foam A (**a**) and B (**b**)

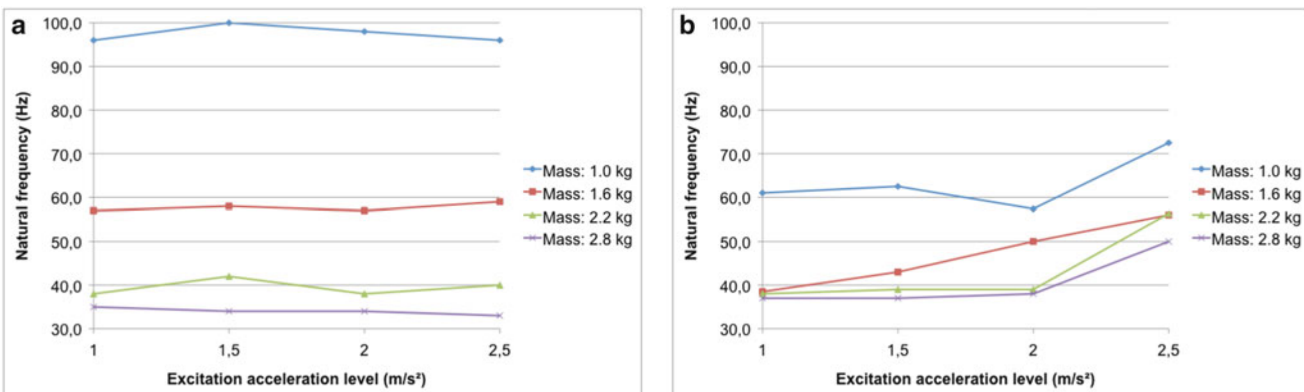

Fig. 18.6 Natural frequency for foam A (**a**) and B (**b**)

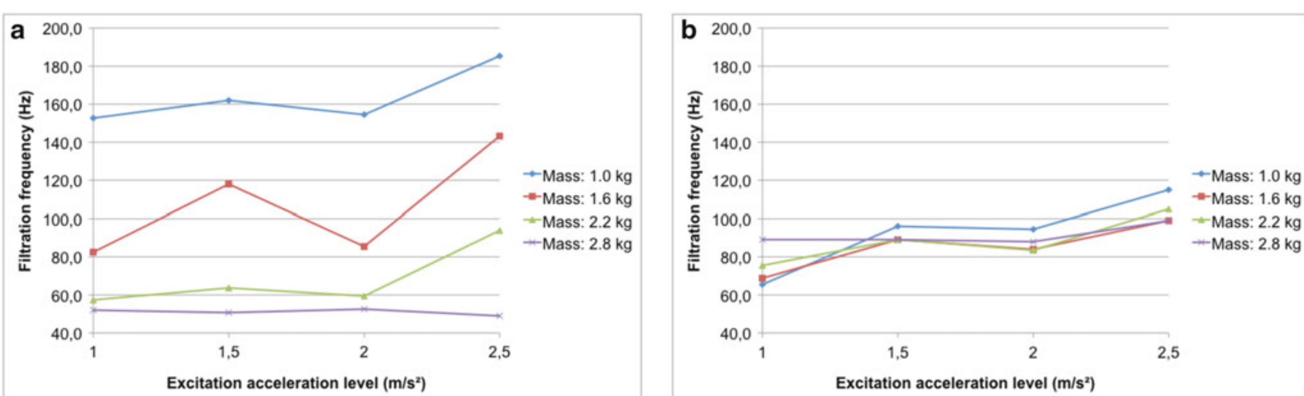

Fig. 18.7 Filtration frequency for foam A (**a**) and B (**b**)

frequency when our excitation acceleration level is varying between 1 and 2.5 m/s^{-2}, but at the opposite, the filtration frequency is highly dependant of the mass. For the masses of 1.0 or 1.6 kg, the filtration frequency are lower than for masses of 2.2 or 2.8 kg.

In term of maximal transmissibility (Fig. 18.8), the two foam types show an important level of amplification. The mass and the acceleration level of excitation don't seem to have influence on the maximal transmissibility for each type of foam. We can suppose that the maximal transmissibility is correlated to a material parameter, like the size cell for example.

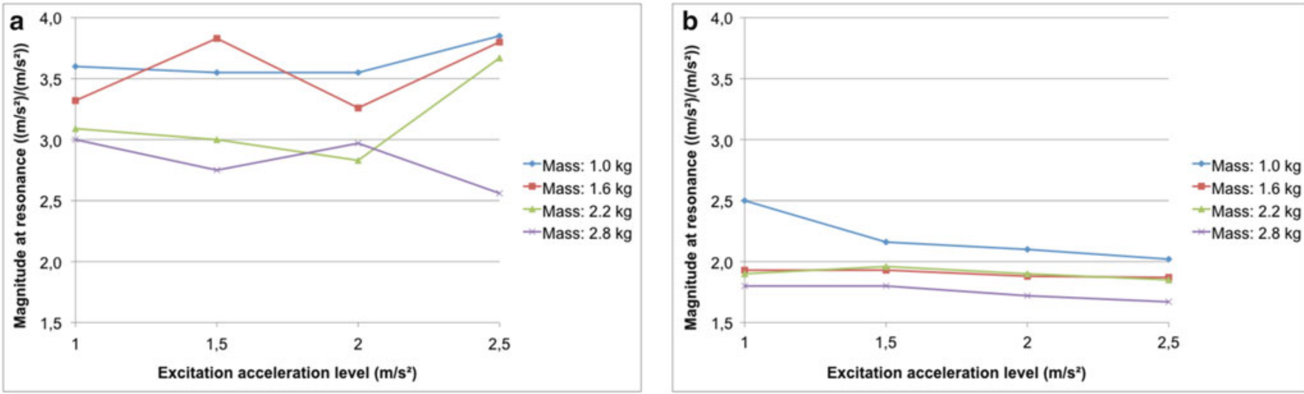

Fig. 18.8 Magnitude at resonance for foam A (**a**) and B (**b**)

18.5 Conclusions

In this study, a method for testing the vibrational mechanical properties of thin soft cellular materials used in automotive upholsteries has been developed and detailed. This method has been used to test two types of polyurethane foams. The results showed that the tested polyurethane foams have different behavior probably due to the type of cells (open or closed). The results demonstrate the inability of thin foams to filter the vibration transmitted to the seat. Indeed, the natural frequencies and the filtration frequencies are in the band of 0–50 Hz classically excited at the base of the seat. The results also highlight that the transmissibility is absolutely not negligible for all the accelerations and preload charges on the foams.

These results have to be confirmed by testing other foams, and will allow us to fully characterize new eco friendly materials dedicated to replace the current polyurethane foams.

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