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Olivier Duboeuf, Raphaël Dupuis, Evelyne Aubry, Marc Lauth

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Harmonic Vibration Test for the Analysis of the Dynamic Behaviour of Polyurethane Foams

O. Duboeuf

Laboratoire MIPS, Université de Haute Alsace, 12 rue des frères Lumière, Mulhouse 68093, France
Laboratoire R&D Foam Chemistry, Faurecia Automotive Seating, 17 rue de la Forge, Lure 70202, France
e-mail: olivier.duboeuf@uha.fr

R. Dupuis, E. Aubry

Laboratoire MIPS, Université de Haute Alsace, 12 rue des frères Lumière, Mulhouse 68093, France

M. Lauth

Laboratoire R&D Foam Chemistry, Faurecia Automotive Seating, 17 rue de la Forge, Lure 70202, France

Abstract The main goal of this paper is to describe experimental techniques and identification of dynamic properties of flexible polyurethane foam. Indeed, automotive seat comfort level is established with considering quasi-static—density core, hysteresis loss and compression stress— and dynamic— transmissibility and damping— properties of flexible polyurethane foams. Our dynamic system, modeled as a single degree-of-freedom system, is composed of an experimental device with a free mass on the top and a shaker on the basement. The first one, a rigid block, is mounted on a $100 \times 100 \times 50$ mm cube sample of foam material and the second one excites the device with harmonic vibration. The steady-state response of a polyurethane foam sample—after the same number of cycles—to harmonic vibration is analyzed for different excitation amplitude level and for different initial compression level, corresponding respectively to various road surface conditions and to various apparent-mass. The transmitted vibration between the shaker and the free mass is measured to determine the damping effect and the filter band of polyurethane foam, and enables to trace the Bode magnitude and phase plots of the dynamic stiffness function of the system. The results presented here compare three types of foams.

Keywords Polyurethane foams • Dynamic behavior • Dynamic stiffness function • Harmonic vibration • Bode plots

10.1 Introduction

Comfort in automotive applications is not just driving pleasure; it is the best player for the safety and health of passengers of the vehicle. For example, an uncomfortable seat transmits vibrations from the road, the engine, and the frame to the occupant and therefore can lead to back and neck pain due to poor filtration. The effect of these vibrations on health is a known phenomenon and has been already studied by many Scientists [1]. But the remaining key point is still “how can we make them more comfortable?”

A full seat consists of a frame, foam paddings and a headrest. Flexible polyurethane foam (PU foam) is very often used in automotive seat padding comfort application. Indeed, PU foam is characterized by a large spectrum of mechanical properties [2] such as: low density, the ability to absorb the strain energy and low stiffness. Moreover, by modifying the chemical formulation of foam, it is also possible to impact upon the static and dynamic mechanical properties, and consequently upon the comfort of seat users.

Using the mechanical field, we can study foam by four different ways: static behavior [2–4], quasi-static behavior [5–8], dynamic behavior [8–12] and ageing behavior [13, 14]. All these ways are a part of the comprehension of behavior of automotive seating, together with other test such as approach comfort, ride comfort and overall durability of seat. To control the vibration transmitted to the seat and then to increase the comfort, we need to model a complex mechanical behavior of polyurethane foams and therefore to identify its dynamic and quasi-static properties. In our study, using our harmonic vibration test method, three kinds of foams with similar properties are tested. This paper explains the test method and operation results we have obtained.

10.2 Experimental Study: Tested Materials

In this work, we study polyurethane foams, designed by Foam A, B and C, large used in automotive seating application and whose chemical, morphological and mechanical properties are shown in Table 10.1. As you can notice those characteristics are similar in term of chemistry, only the quantity of reinforcing particulate copolymer polyol (CPP) is different. Copolymer polyol plays a great role in polyurethane foam formulation. It is a “grafted” polyol, used to improved hardness, strength, foam processing, and cell opening. It also increases the cross-linking degree [15].

Density, compression stress and resilience are determined by the methods recommended in standards ASTM D3574 [16]. The average cell size is determined through the Microvision-Ellix device and an adaptation of “Visiocell” method detailed in the study of Ju [17].

10.3 Experimental Methodology

All the tests presented in this paper have been carried out on a vibration-testing device, shown in Fig. 10.1. It is composed by a shaker on the basement (INSTRON 8800), a bottom plate fixed on the basement and a sliding top plate guided in a single direction of translation by four guides. To limit the internal friction of the stems on the guides (e.g. ball bearings), our experimental setup uses air bearing. The friction coefficient is then practically zero. Between the two plates, a cubic sample of foam is fixed.

The actuator is used to create the excitation signal whose characteristics will be given later. During the tests, the displacement of the bottom plate $x_{bottom}(t)$ (displacement under the foam sample) and the displacement of the sliding top

Table 10.1 Chemical, morphological and mechanical foams characteristics

| Designation | Foam A | Foam B | Foam C |
|--|------------------------------|------------------------------|------------------------------|
| Foam types | Flexible | Flexible | Flexible |
| Isocyanate | TDI-LVOC | TDI-LVOC | TDI-LVOC |
| Polyol—CPP rate | Polyol PA— 15 parts | Polyol PA— 30 parts | Polyol PA— 55 parts |
| Water rate | 3.5 parts | 3.5 parts | 3.5 parts |
| Fabrication process | Molded | Molded | Molded |
| Type of cells | Open | Open | Open |
| Dimensions ($L_0 \times l_0 \times h_0$) m^3 | $0.1 \times 0.1 \times 0.05$ | $0.1 \times 0.1 \times 0.05$ | $0.1 \times 0.1 \times 0.05$ |
| Density ($kg \cdot m^{-3}$) | 45 | 46 | 46 |
| Compression stress (kPa) | 5.8 | 8.1 | 10.4 |
| Resilience (%) | 81 | 78 | 74 |
| Average cell size (μm) | 424 | 428 | 430 |

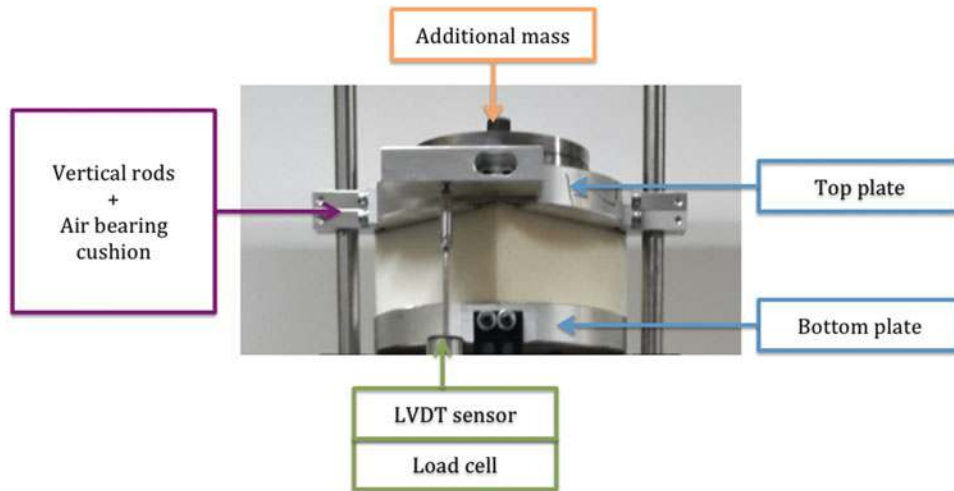


Fig. 10.1 Testing device

Table 10.2 Initial compression levels for three tests

| Test | Designation (%) | Foam A | Foam B | Foam C |
|--------|--|--------|--------|--------|
| Test 1 | Initial compression level for preload M1 | 3.0 | 2.5 | 1.5 |
| Test 2 | Initial compression level for preload M2 | 15.0 | 7.5 | 5.0 |
| Test 3 | Initial compression level for preload M3 | 33.5 | 16.5 | 8.0 |

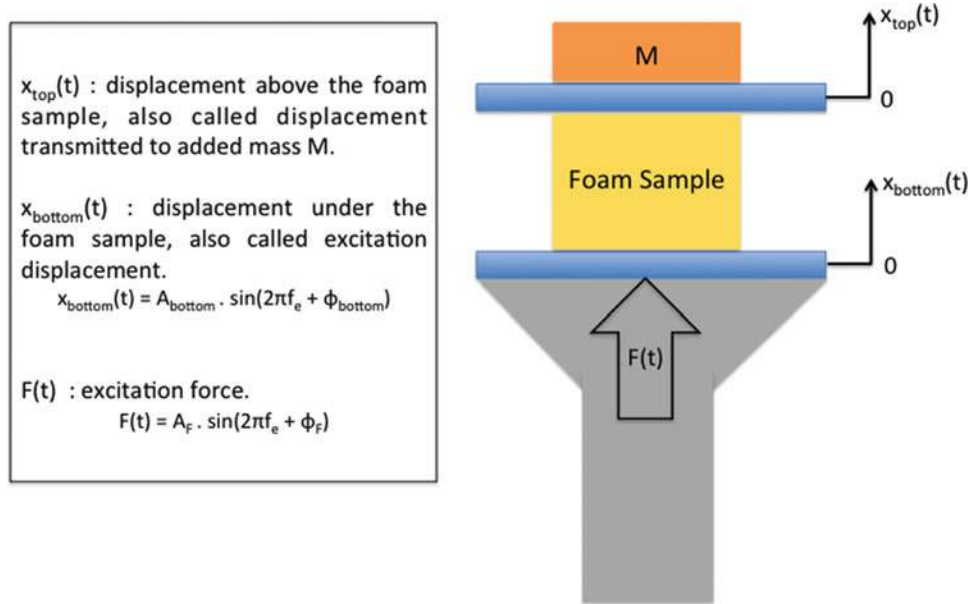
**Fig. 10.2** Schematization of the testing procedure

plate $x_{top}(t)$ (displacement above the foam sample) are measured with LVDT linear sensors. We also measured the excitation force under foam sample $F(t)$ with a load cell placed between the actuator and the base plate.

Actually, the initial compression level of the foam car seat is a function of the occupant weight. In this study, we compare the three foams for three “persons” (about 5th, 50th and 90th percentile), so for three preload above the sample. As a result, put the same additional mass M on the three samples induce different initial compression levels (Table 10.2) due to different compression stress.

The harmonic vibration test consists in shaking the bottom plate with a sinusoidal signal. The excitation frequency f_e is varying from initial value $f_{min} = 1$ Hz to final value $f_{max} = 20$ Hz by raising step of 0,5 Hz. The foam is excited for a significant amount of cycles at each frequency to achieve a steady state (about 100 cycles). Then, the three measurements (displacement of the sliding top plate, displacement of the bottom plate and excitation force under foam sample) are recorded during 100 cycles. A Fourier Transforms are finally realized on each signal recorded. To make sure the repeatability of our tests, each trial is carried out at least three times, always with a new sample of foam from the same population.

The Fig. 10.2 displays a schematization of the experimental test device, signals and procedure.

In this work, all samples used in harmonic vibration test have the same mechanical and environmental histories: they are virgin, extracted from the core of a new foam molded block ($0.4 \times 0.4 \times 0.07$ m) produced in laboratory, cut to the following dimensions $0.1 \times 0.1 \times 0.05$ m and being conditioned during at least 24 h in a climate room (temperature at $23 (\pm 2)$ °C and relative humidity at $50(\pm 5)$ %).

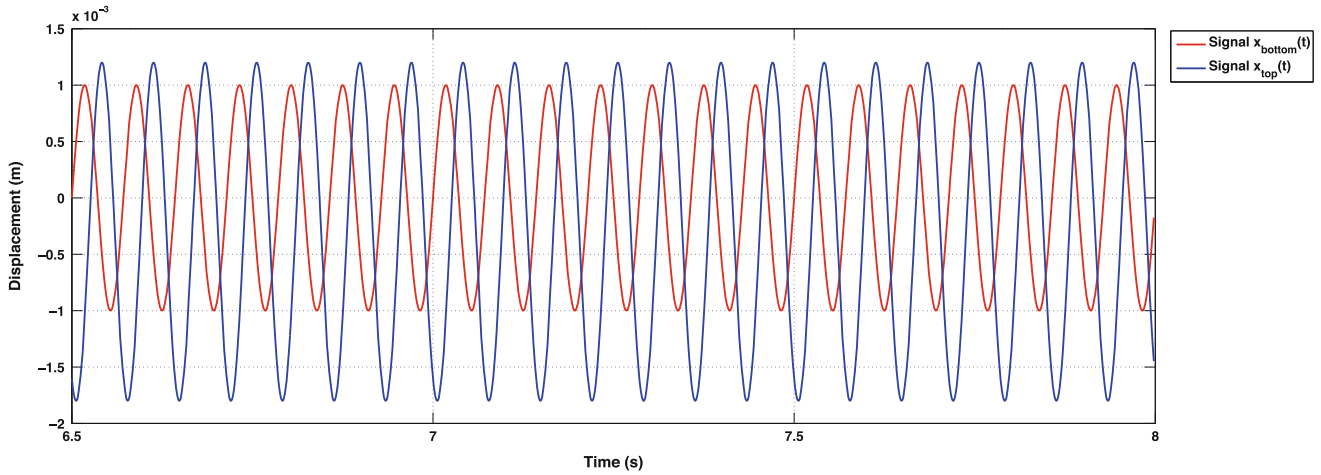


Fig. 10.3 Difference between $x_{top}(t)$ and $x_{bottom}(t)$ at 14 Hz

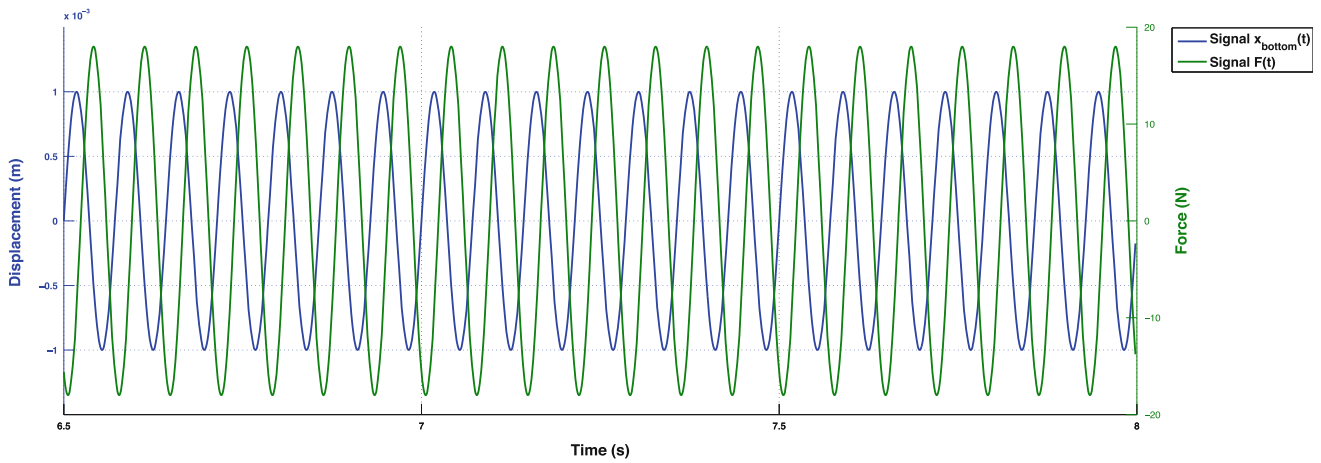


Fig. 10.4 Difference between $x_{top}(t)$ and $F(t)$ at 14 Hz

10.4 Results and Discussions

10.4.1 Time Domain Analysis

At first, to prove that the dynamic behavior of the polyurethane foam is complex, we observed the two temporal signals recorded. On the one hand, we have the excitation displacement (displacement under the foam, $x_{bottom}(t)$) and on the other hand, we have the displacement transmitted to the free mass (displacement above the foam, $x_{top}(t)$). They have both the same main frequency in the steady state, but the second one present a permanent and constant offset to the initial position. This offset depends on the frequency value. This offset is due to several facts. Indeed, after each loading and unloading cycle, we can observe an accumulation of residual strain. This phenomenon is also observable in the quasi-static behavior (Fig. 10.3).

The evaluation two temporal signals recorded could also be with the excitation force under the foam $F(t)$ and the displacement transmitted to the free mass $x_{top}(t)$. In the same way, there is an offset between 0 and $\frac{\pi}{2}$ at various excitation frequencies, due to the viscoelastic behavior of the polyurethane foam (Fig. 10.4).

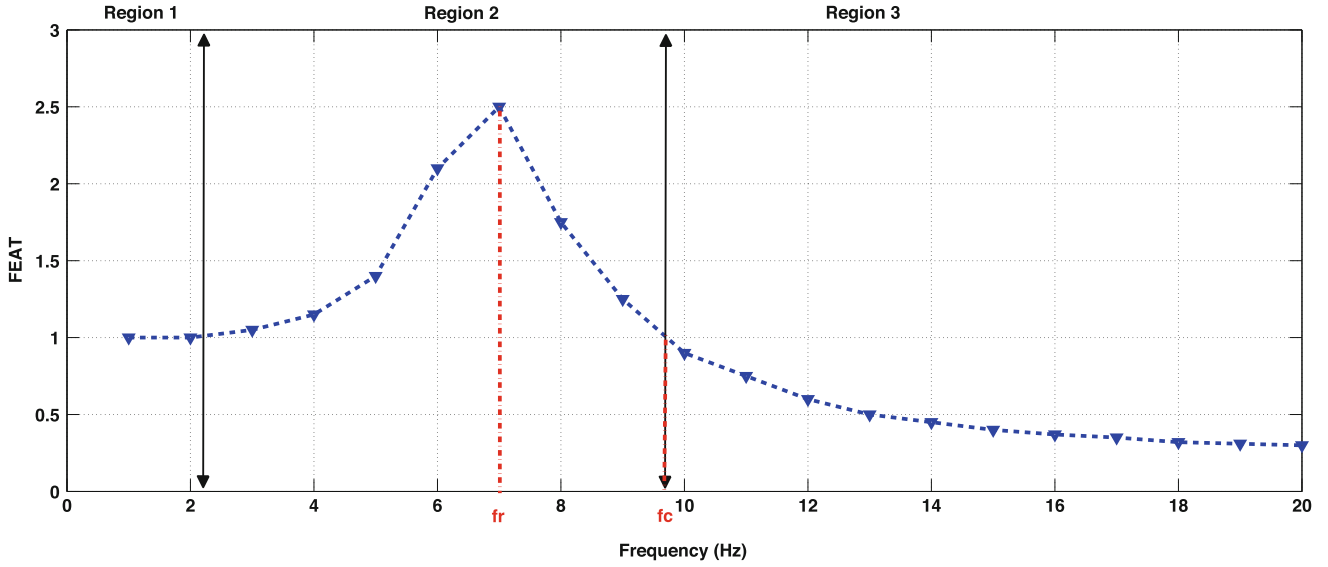


Fig. 10.5 Example for a FEAT ratio

10.4.2 Frequency Response Analysis

There are several methods to evaluate the comfort of a car seat. For example, automotive OEM's calculate the ratio between the vibration level above the car seat (on the passenger) and the excitation at the basement of the seat (due to engine, structure and road vibrations) [18]. This one is known as "SEAT factor" (Seat Effective Amplitude Transmissibility). All information about this method to evaluate seat comfort is detailed in ISO 2631-1 standard [19].

In the same way, our laboratory uses a ratio to determine the ability of the foam to reduce vibrations. This ratio is known as "FEAT factor" for "Foam Effective Amplitude Transmissibility" which is calculated following a sinusoidal excitation at constant amplitude and constant frequency for each initial compression level [8]. FEAT ratio is:

$$FEAT(A_{bottom}, f_e) = \frac{RMS_{top}}{RMS_{bottom}} = \sqrt{2} \frac{RMS_{top}}{A_{bottom}} \quad (10.1)$$

where:

- RMS_{top} is the root mean square values of free mass displacement above the foam sample.
- A_{bottom} is the amplitude of the excitation sinusoidal signal.

As shown on the Fig. 10.5, we can divide the FEAT representation into three regions. In the first one, FEAT ratio is equal to one. The foam has a rigid body behavior. The vibration is transmitted through the foam without amplification or attenuation. Then, FEAT ratio is greater than 1. The level of vibration transmitted by the foam is amplified. This region could be divided into two sub-regions: FEAT ratio is growing up from one to a maximal value, the natural frequency f_r , in the resonance region and then, it is decrease until the value one, the filtration frequency f_c . All the frequency between 1 Hz and the filtration frequency is the bandwidth. In the bandwidth, the foam is always transmitting or amplifying the excitation signal. It is the worst frequency region for a passenger on a seat. The third region is the most interesting and attractive for passengers. Indeed, the FEAT ratio is under one, so the level of vibration transmitted by foam is lower than the excitation level. This is the foam vibration damping power.

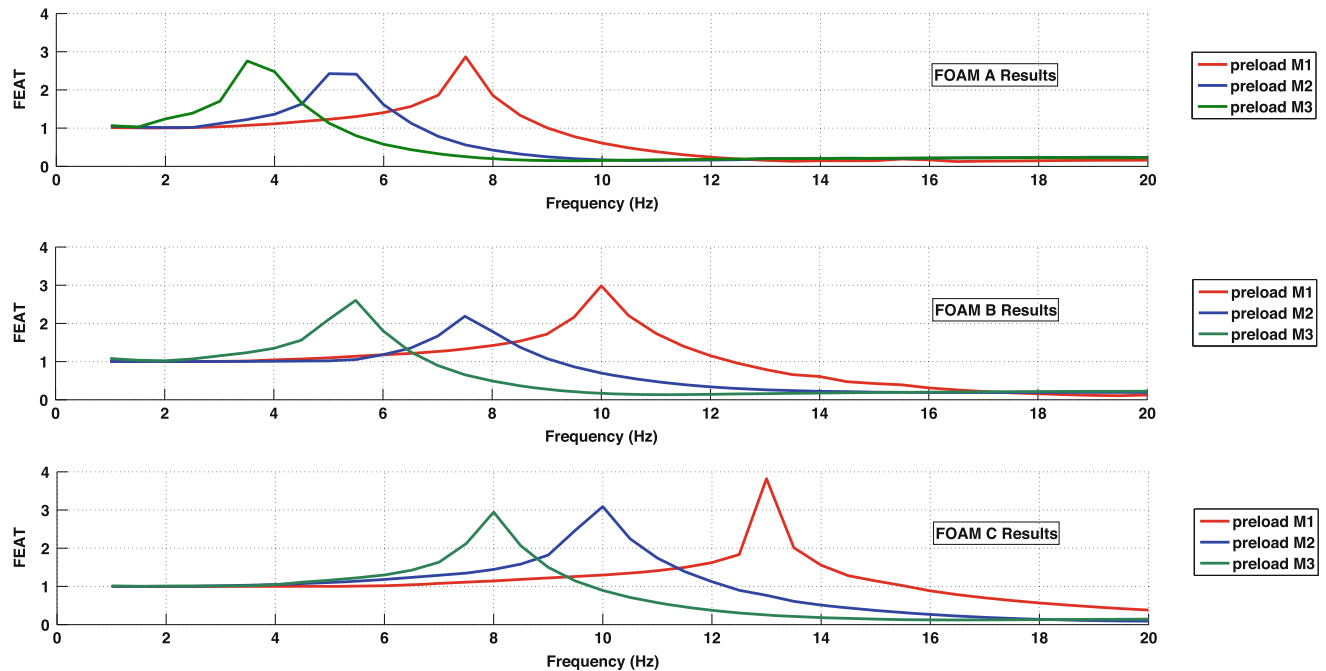
All the test presented here has been proceed on the three foams A, B and C. Table 10.3 presents the dynamic characteristics resulting of the harmonic vibration tests and Fig. 10.6 shows this results.

As it was explained before, reinforcing particulate copolymer polyol (CPP) is used to increase the cross-linking degree. We can observe an impact on the compression stress and the resilience after four cycles. A higher content of copolymer polyol into the formulation will lead to harder foam characterized by a higher compression stress and a lower resilience.

Moreover, compression stress and resilience are immediately in relation with dynamic results. Indeed, the FEAT ratio is greater when the resilience is lower, and the natural frequency is lower when the compression set is lower too.

Table 10.3 Dynamic characteristics of our foams for different preload

| Dynamic results | Foam A | | | Foam B | | | Foam C | | |
|---------------------------------|--------|------|------|--------|------|------|--------|--------|--------|
| Preload (kg) | M1 | M2 | M3 | M1 | M2 | M3 | M1 | M2 | M3 |
| Natural Frequency f_r (Hz) | 7.5 | 5.3 | 3.7 | 10.0 | 7.2 | 5.4 | 13.0 | 10.0 | 8.0 |
| Maximal FEAT value | 2.5 | 2.4 | 2.6 | 2.7 | 2.6 | 2.4 | 3.1 | 2.8 | 2.6 |
| Filtration frequency f_c (Hz) | 9.0 | 6.7 | 5.2 | 12.4 | 9.2 | 6.8 | 15.5 | 12.3 | 9.7 |
| Stiffness (N/m) | 6662 | 4353 | 2659 | 11891 | 8277 | 5820 | 20,077 | 15,634 | 12,602 |
| Damping (N.s/m) | 37.2 | 39.2 | 46.2 | 31.9 | 44.4 | 50.6 | 33.1 | 42.2 | 48.1 |

**Fig. 10.6** FEAT ratio for each foams at different preload

As shown in Table 10.3, dynamic characteristics of foam are in relation with stiffness and damping effect. A foam, whose CPP rate level is low, will have a shorter bandwidth and therefore better vibration filtration power. In the opposite side, the amplification at natural frequency will be smaller. A foam with a high CPP rate level will have a greater bandwidth so a lower vibration filtration power.

In addition, the loading upon a seat (i.e. the initial compression level, representing normal human weight on cushion) changes its physical characteristics. As we know, stiffness is directly function of both the mass and the natural frequency. In addition, damping is also related to the mass, the natural frequency and the quality factor (in relation with the maximum value FEAT). Therefore, loader the seat will be charged, lower will be its natural frequency and filtration frequency.

10.5 Conclusions

This experimental study shows that the dynamic behavior of our polyurethane foams has a complex behavior. The study of the influence of the copolymer polyol in the initial formulation shows that the natural frequency and filtration frequency have been improved while the copolymer polyol rate is lower, for a specified compression stress.

In addition, the amplitude level of the excitation as well the initial quasi-static compression level given by the customer passenger are also following the same trade. Thus, the choice of the polyurethane foam for a given application must be carried out through a statistical study of the real solicitation conditions (range of dominant frequency of excitation, the highly probable excitation levels, etc.).

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