

Shear stiffness measurement against frequency of viscoelastic materials

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Abstract

In many mechanical systems polymers are used to damp vibrations. Shims are used in brake systems to damp squeal noises occurring above 1000Hz. Shims are viscoelastic materials composed of layers of steel, rubber and glue. Although the mechanical behavior of polymers are usually characterized by DMA (Dynamic Mechanical Analysis) thanks to the time-temperature superposition principle, this principle does not hold for shims. An analyser has been designed to characterize these materials up to 3kHz without using the time-temperature superposition principle. The characterization of samples is performed under a static preload.

1 Introduction

In many mechanical systems viscoelastic materials are used to damp vibrations. In disc brake systems, the squeal noise is due to an unstable vibration occurring between 1kHz and 10kHz. For instance, shims are viscoelastic multi-layer materials used to get rid of squeal and others noises. Shims are composed of layers of steel, rubber and glue. The stiffness of such material is strongly frequency dependent.

Squeal noise occurrences of a brake system are usually predicted by a complex eigen value analysis (CEA) on a finite element (FE) model, see Chevallier [1], Fritz [2, 3]. Since viscoelasticity can lead to some counter intuitive destabilization effects, see Chevallier [1], Fritz [2, 3], disc brake FE models must account precisely for the viscoelastic behavior of materials such as shims. The Generalized Maxwell model describes well the viscoelastic stiffness of materials behaving between purely elastic and purely viscous, see Chevalier[4]. This viscoelastic model can be easily implemented in FE disc brake model, see Chevallier [1]. Some methods exist to identify the parameters of the Generalized Maxwell model based on the stiffness measurements, see Dion [5], Renaud [6]. Thus, the knowledge of shims stiffness is required from 100Hz to 10000Hz to get a predictive disc brake model.

Since shims are composed of layers of different materials such as steel and glue, the time-temperature superposition principle does not hold. Thus a direct characterization is required. Several techniques already exist. A classical one is the Oberst's beam method, see [7, 8, 9]. It consists in comparing the eigen frequency of the normal mode of the same structure with and without the viscoelastic material. Unfortunately this kind of method allows characterization only at very few frequencies, the ones of normal modes. Another technique is to measure the relaxation function of a material, see Chen [10]. However, as it is difficult to assess a true strain unit step, this technique is only accurate at low frequencies below the frequency bandwidth of squeal noise. The last option is to perform a direct characterization with a DMA analyser without using time-temperature superposition. This requires to characterize materials below the frequency of the first normal mode of the analyser which interfer with the measurement by involving samples deformation.

A new analyser has been designed to mimic the stresses of shims during a squeal noise occurrence, cf. Figure 1. This means a static normal preload representative of the braking pressure and a dynamic

shear stress representative of the unstable vibration at the root cause of the squeal. The analyser allows characterizing materials between 100 and 3000Hz. This article presents the design of this shear DMA tester, the postprocessing of the data and the measured shear stiffnesses of some shims.

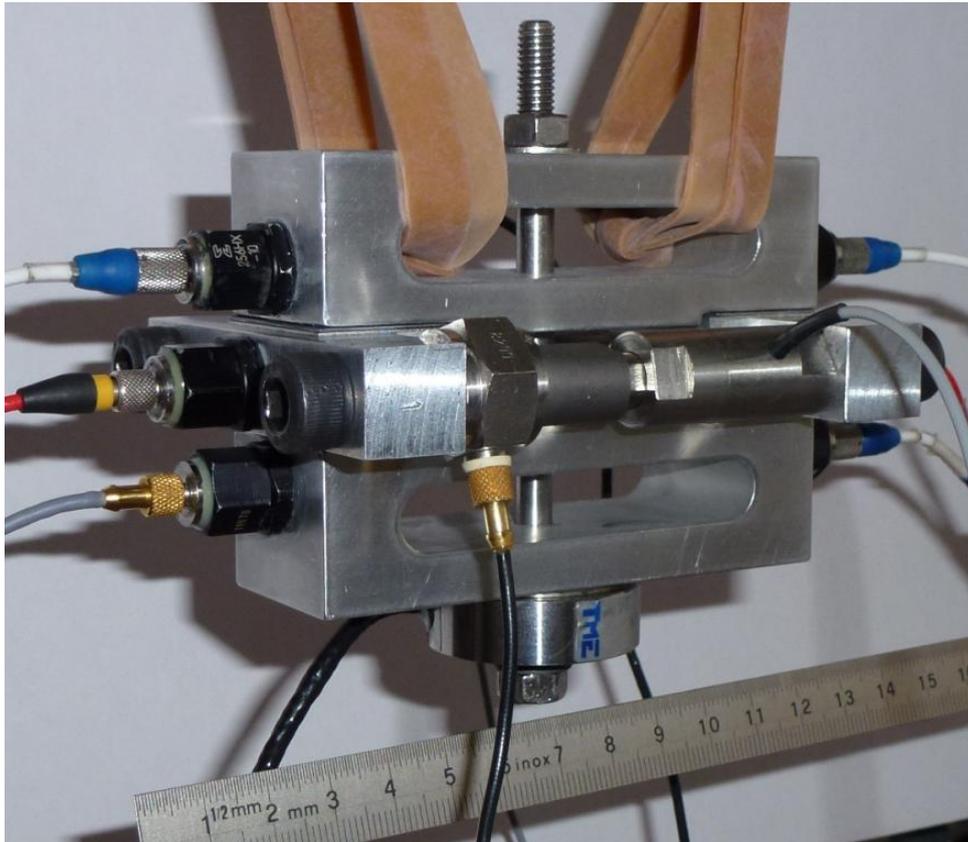


Figure 1: DMA analyser for shear characterization

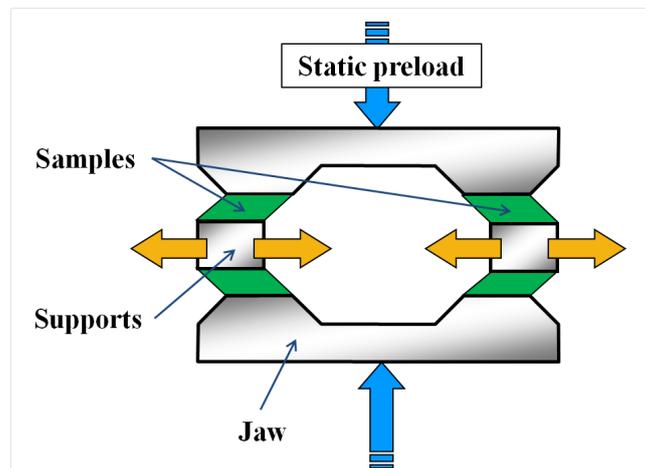


Figure 2: Operating principle of the shear DMA analyser

2 Design of the analyser

The operating principle of the shear DMA analyser is shown in Figure 2. It is almost symmetrical and requires four samples for one characterization. Thereby the measured complex shear stiffness is the mean value among four samples. The analyser (cf. Figure 1) is hung by rubber bands for any

vibration of environment could not interfere with the measurement. Six piezoelectric accelerometers measure the tangential acceleration of the top face and the bottom face of each sample. Then, the shear deformation of each sample is measured by integrating the acceleration measurements.

Samples are rectangles of 20mm by 30mm with variable thickness depending on the shim. Each sample is pressed between one support and one jaw. This pressure is applied by a M6 screw and is measured with a static force sensor (cf. Figure 1). The maximum preload is 5000N and corresponds to a pressure on samples of 4MPa. Recall that eventually no DMA tester allow direct characterization above 1000Hz with a static preload.

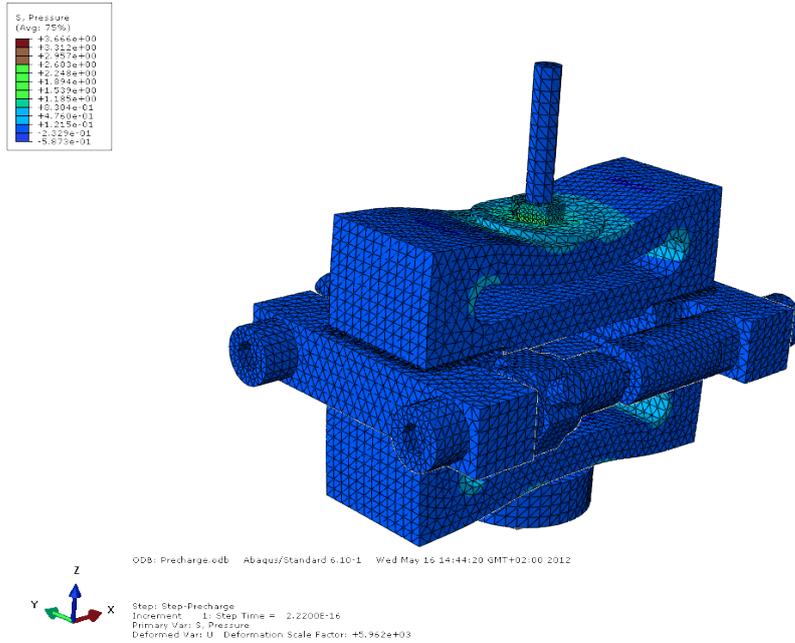


Figure 3: Whole deformation of the shear DMA analyser induced by the normal preload applied thanks to the M6 screw.

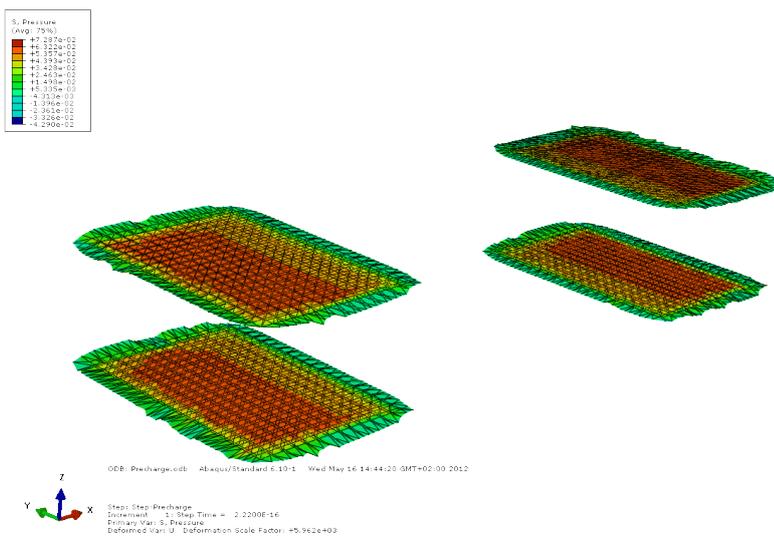


Figure 4: Pressure undergone by the four samples due to the normal preload applied thanks to the M6 screw.

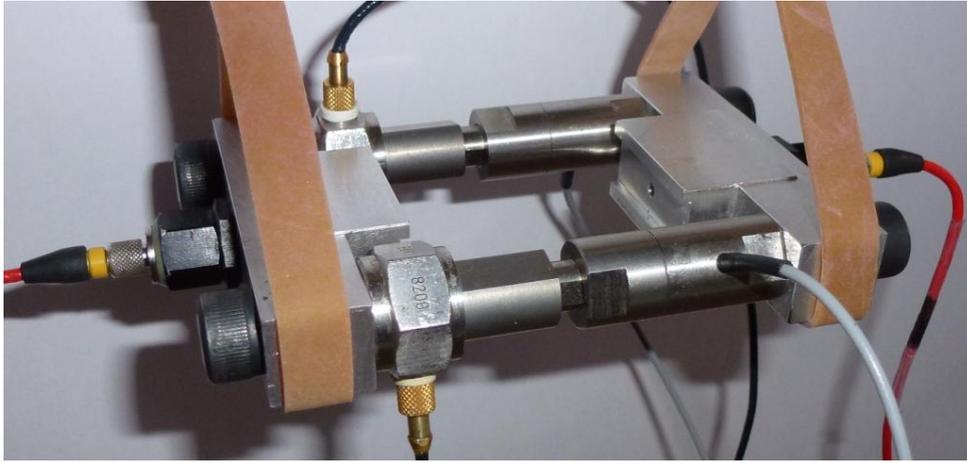


Figure 5: Actuation chain

Figures 3 and 4 are the results of a Finite Element model simulating the normal preload. They show the deformation of the shear DMA analyser and the pressure undergone by samples. The normal preload of the shear DMA analyser is almost uniform on the whole sample surface. This uniformity is ensured by the slot in the jaw's shape. This design of the jaw also greatly reduces the coupling between the normal load and the shear load on the samples.

When characterizing samples, the dynamic excitation is obtained by moving the supports apart with piezoelectric actuators. In contrary to the Oberst beam test, this shear DMA tester allows pure shear deformation of samples without bending. Then, the stiffness is measured directly and no Finite Element model is required for comparison. The forces generated by the two actuators are measured with two piezoelectric force sensors. The actuation chain alone is shown in Figure 5.

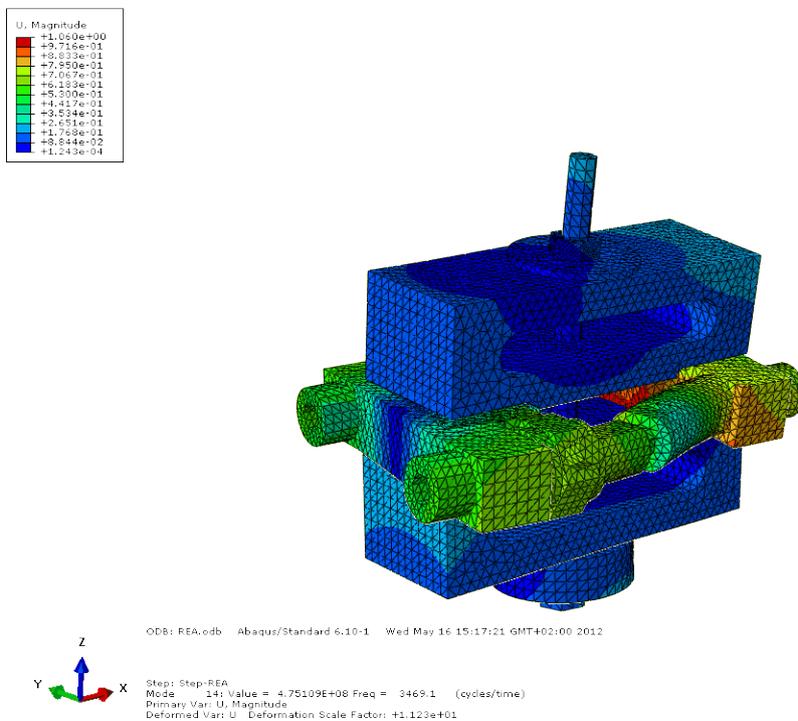


Figure 6: Mode shape of the first eigen mode interfering with measurements. It occurs around 3500Hz depending on the shear stiffness of samples.

The upper limit frequency of characterization is given by the frequency of the first normal mode of the analyser which interfer with the measurement. Actually, interferences occur when a normal mode involves samples deformation or sensors motion. The higher this eigen frequency occur, the larger is the frequency bandwidth of characterization. The first interfering eigen mode involves the deformation of the actuation chain. Figure 6 shows its mode shape. This eigen mode generally occurs about 3500Hz and limits the characterization to a frequency about 3000Hz.

To characterize shims, samples are first positioned manually between jaws and supports. When possible shims are stuck on jaws. Then, the preload is applied thanks to the screw. Second, a stepped sinus excitation is performed with a rate of 12 frequencies per octave. The excitation time of samples has to last as short as possible in order not to warm the material. For each single frequency, the level of excitation is controlled with the sample's strain. Finally the data acquired during the test are postprocessed in the Matlab environment.

3 Data postprocessing

To postprocess the data obtained during shear stiffness characterization of the samples, the effects of jaws deformations and the inertia efforts must be corrected. The shear DMA analyser is designed to work at frequencies lower than its first normal mode. Thus deformable parts are modelled with springs. Above a few hundred Hertz, even small displacements of lightweight parts can lead to inertia efforts comparable to the shear efforts. For example, a sinusoidally moving mass of 100g with a displacement amplitude of $1\mu\text{m}$ at 1000Hz leads to an inertia effort of $|F| = |M\Gamma| = M(2\pi f)^2 X = 10^{-1} \times (2\pi \times 1000)^2 \times 10^{-6} \simeq 4\text{N}$. At 5000Hz, the same mass leads to an inertia effort around 100N. Thus attention must be paid to masses modelling, especially for the actuation chain shown in Figure 5.

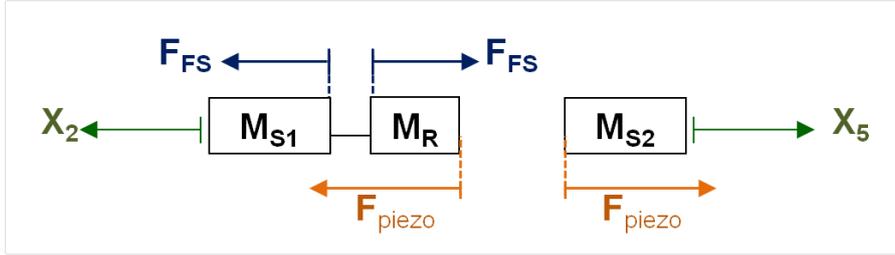


Figure 7: Rheological modelling of the actuation chain

The actuation chain is composed of two supports, both with one accelerometer, two dynamic force sensors, two links and two piezoelectric actuators. The force sensors and the actuators are both composed of a piezoelectric part linking two masses. Thus, the force sensors measure a force between two masses and the actuators generate a force between two masses. Thereby, the actuation chain is modelled by three masses: M_{S1} , the left support, M_R the link and M_{S2} the right support. These three masses are separated by the piezoelectrical part of the sensors and the actuators. The actuation chain modelling is shown in Figure 7. Let $\omega = 2\pi f$ denote the angular frequency, let $\Gamma = -\omega^2 X$ denote the Fourier transform of the acceleration and let F denote the Fourier transform of the force. Then, the fundamental principle of the dynamics give Equation (1):

$$\begin{cases} M_{S1}\Gamma_2 = F_{\text{FS}} \\ M_R\Gamma_2 = -F_{\text{FS}} + F_{\text{piezo}} \\ M_{S2}\Gamma_5 = F_{\text{piezo}} \end{cases} \quad (1)$$

The total weight of the actuation chain is:

$$M_{\text{total}} = M_{S1} + M_R + M_{S2} = 290\text{g} \quad (2)$$

From Equation (1) and (2), one obtains the masses equations (3) against frequency. A test has been led between 1000 and 2000Hz on the actuation chain alone as shown in Figure 5. The values are

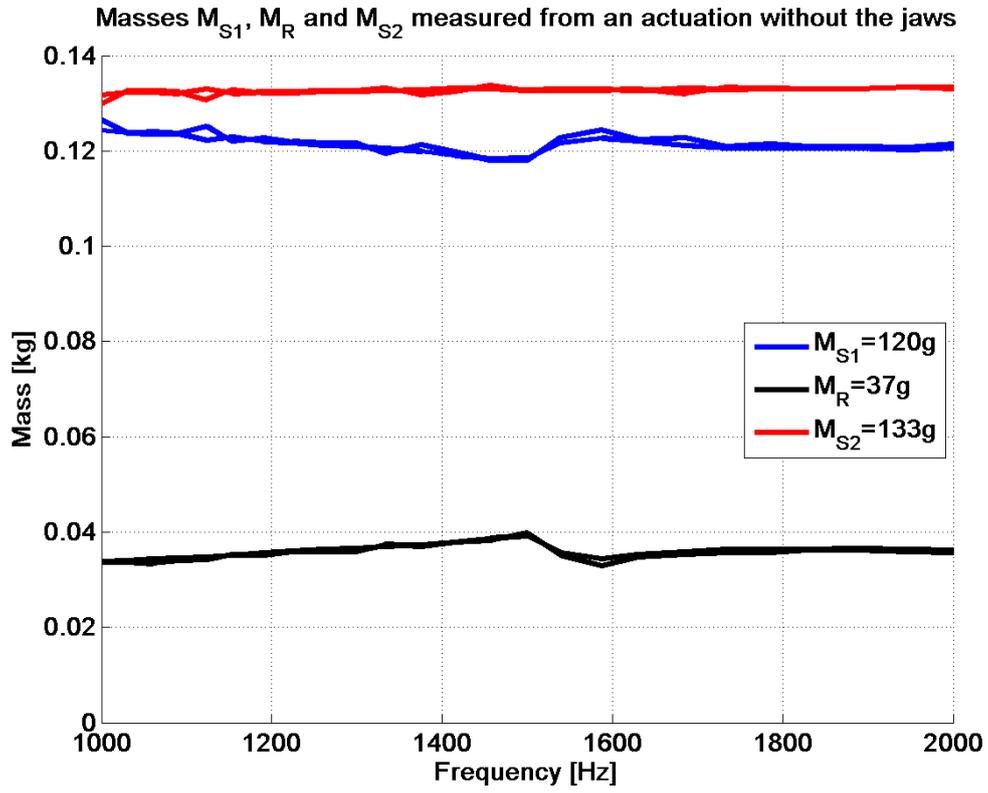


Figure 8: Supports masses identification

plotted in Figure 8. As expected the masses values are constants.

$$\begin{cases} M_{S1}(f) = \frac{F_{FS}}{\Gamma_2} \simeq 120\text{g} \\ M_R(f) = M_{total} \frac{\Gamma_5}{\Gamma_2 + \Gamma_5} - M_{S1} \simeq 37\text{g} \\ M_{S2}(f) = M_{total} \frac{\Gamma_2}{\Gamma_2 + \Gamma_5} \simeq 133\text{g} \end{cases} \quad (3)$$

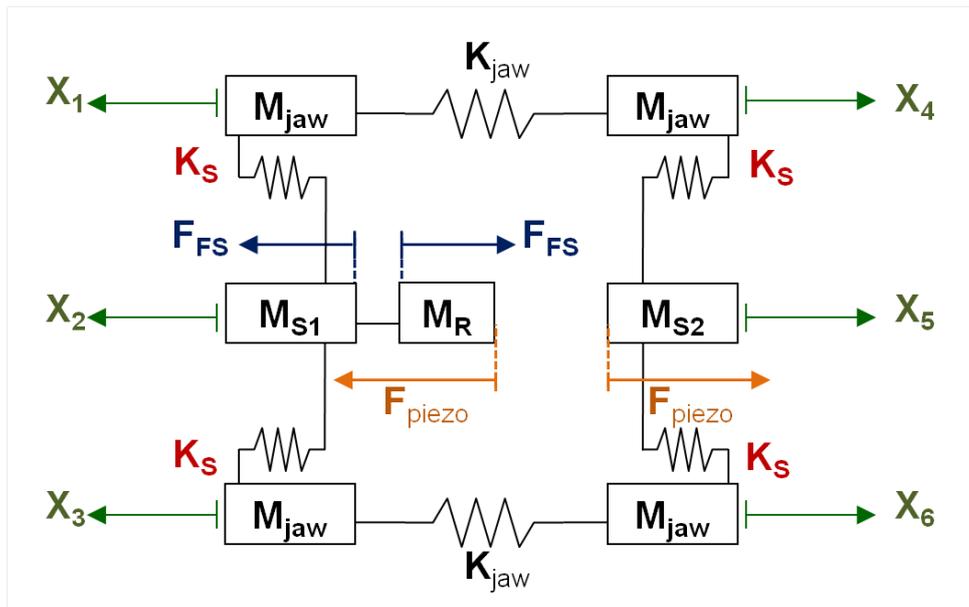


Figure 9: Rheological modelling of the shear DMA analyser

The rheological model of the shear stiffness shear DMA tester is shown in Figure 9. Although the jaws are modelled by two identical masses, M_P , linked by a spring K_{jaw} , these parameters have no influence in the following postprocess. From the analyser model shown in Figure 9, the fundamental principle of the dynamics give Equation (4):

$$\begin{cases} M_{S1}\Gamma_2 = -K_S(2X_2 - X_1 - X_3) + f_{FS} \\ M_{S2}\Gamma_5 = -K_S(2X_5 - X_4 - X_6) + f_{FS} + M_R\Gamma_2 \end{cases} \quad (4)$$

Thus, the mean shear stiffness of the four samples K_S is obtained according to Equation (5):

$$K_S = \frac{\omega^2((M_{S1} - M_R)\Gamma_2 + M_{S2}\Gamma_5 - 2F_{FS})}{2\Gamma_2 + 2\Gamma_5 - \Gamma_1 - \Gamma_3 - \Gamma_4 - \Gamma_6} \quad (5)$$

The mean deformation and the mean force undergone by the four samples are given by Equation (6):

$$\begin{cases} X_{\text{mean}} = -\frac{1}{4\omega^2}(2\Gamma_2 + 2\Gamma_5 - \Gamma_1 - \Gamma_3 - \Gamma_4 - \Gamma_6) \\ F_{\text{mean}} = -\frac{1}{4}(M_{S1} - M_R)\Gamma_2 + M_{S2}\Gamma_5 - 2F_{FS} \end{cases} \quad (6)$$

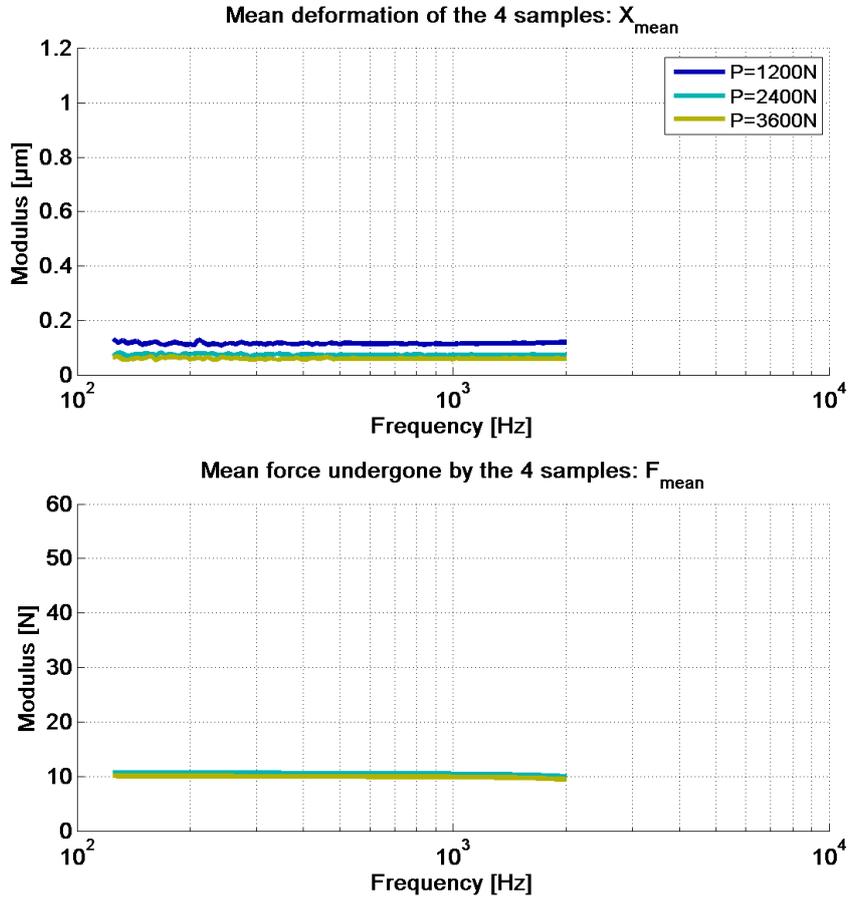


Figure 10: Mean deformation X_{mean} and mean effort F_{mean} undergone by the interface between the supports and the jaws (without any samples)

4 Confidence limit

The measured shear stiffness K_S obtained from Equation (5) is composed of two stiffnesses in serie: the shear stiffness inside the sample K_{shim} and the shear stiffness of the analyser itself K_{analyser} .

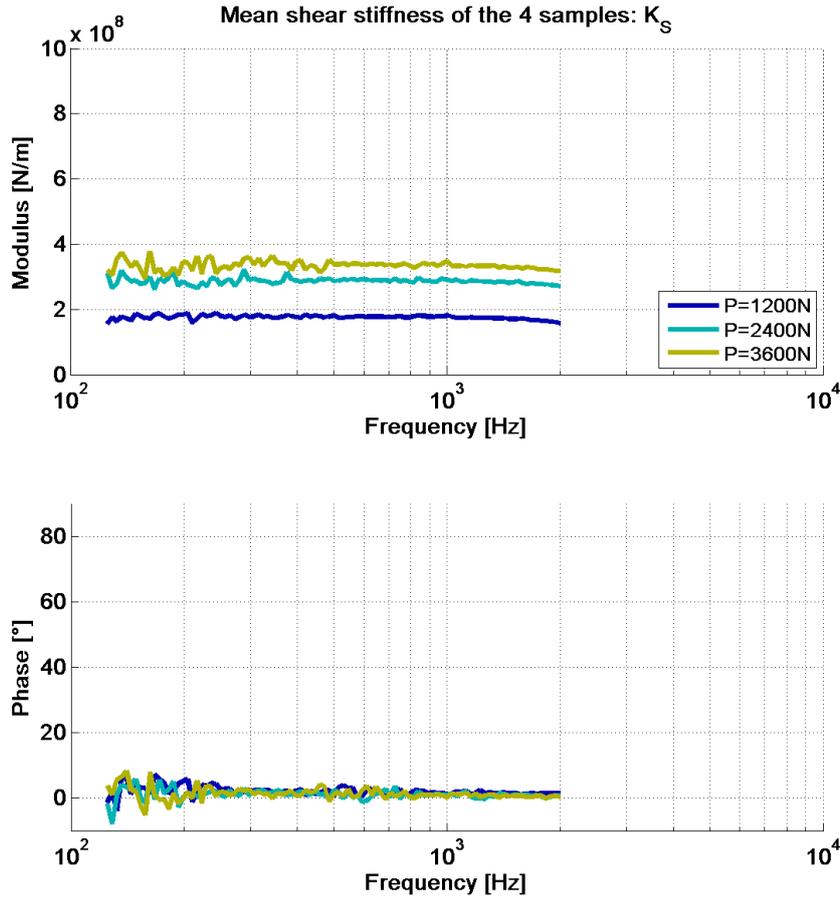


Figure 11: Mean shear stiffness K_{analyser} of the interface between the supports and the jaws (without any samples)

The analyser shear stiffness is due to the deformation of the supports, of the jaws and of the contact interfaces as well, thus:

$$K_S = \frac{K_{\text{shim}}K_{\text{analyser}}}{K_{\text{shim}} + K_{\text{analyser}}} \quad (7)$$

A test has been led without any samples in order to measure the shear stiffness of the analyser, thus, in this test, $K_S = K_{\text{analyser}}$. The mean deformation and the mean effort undergone by the interfaces is shown in Figure 10 for three different preloads. The modulus and the phase of the complex stiffness K_{analyser} is shown in Figure 11. It depends on the static preload because of the surfaces misalignment and roughness. Thus, high static preload ensure that entire surface is in contact, not only asperities. Since in real life, shims are stuck on pads, they also present a stiffness due to surface roughness. Thus, the real K_{analyser} intrinsic to the analyser is obtained for the higher preload at 3600N and $K_{\text{analyser}} \simeq 350 \times 10^6 \text{N/m}$.

From Equation (7), one obtains the shear stiffness inside the sample:

$$K_{\text{shim}} = \frac{K_{\text{analyser}}K_S}{K_{\text{analyser}} - K_S} \quad (8)$$

Equation (8) points out that for K_S being almost equal to K_{shim} , the analyser has to be several times stiffer than the samples to be characterized: $K_{\text{analyser}} \gg K_S \Rightarrow K_{\text{shim}} \simeq K_S$. According to Equation (8), assuming $K_{\text{analyser}} = \alpha K_S$ leads to $K_S = (1 - \frac{1}{\alpha})K_{\text{shim}}$. This means that K_S can be considered as K_{shim} with a relative error of $1/\alpha$: 10% for $K_S = 35 \times 10^6 \text{N/m}$ and 1% for $K_S = 3.5 \times 10^6 \text{N/m}$.

5 Results

A shim has been characterized thanks to the shear DMA analyser with and without its layer of adhesive (glue). Three kinds of static preload have been applied: 1200N, 2400N and 3600N. Two dynamic deformation amplitude have been applied: $0.2\mu\text{m}$ and $1\mu\text{m}$. The deformation amplitude of samples has been controlled. Figures 12 and 13 show the mean deformation and the mean effort undergone by the four samples with and without their adhesive layer.

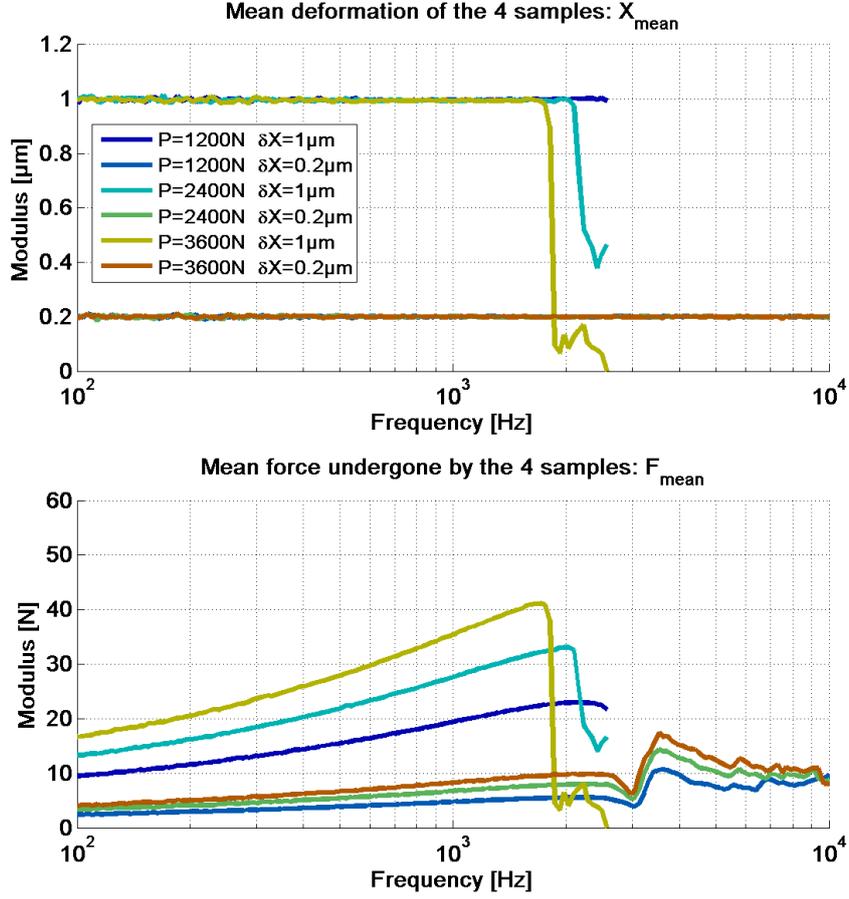


Figure 12: Mean deformation and mean effort undergone by MSC5048 samples without adhesive

The actuators were driven with a linear voltage amplifier. When the required current was over the limit of the amplifier, the target of dynamic deformation amplitude was not reached (see Figures 12 and 13). This happens especially at high frequency and high displacement amplitude. When an actuator breaks the amplitude also falls as in Figure 13.

Figures 14 and 15 show the modulus and the phase of the complex shim stiffness. No filters have been applied on data for possible smoothing. A 0° phase means purely elastic material without damping and a 90° phase means purely viscous without elasticity. The shear stiffness modulus and phase at 1000Hz are given Table 1 for the different preloads and dynamic deformations. The stiffness values are given in N/m. To get the equivalent coefficient G_{shim} , one must use the following formulae: $G_{\text{shim}} = K_{\text{shim}} \times e/S$ with S the surface and e the thickness.

According to Table 1, increasing the static preload leads to an increase of the shear stiffness modulus but does not really affect the phase. Then, increasing the amplitude of deformation leads to a decrease of the shear stiffness modulus and to an increase of phase.

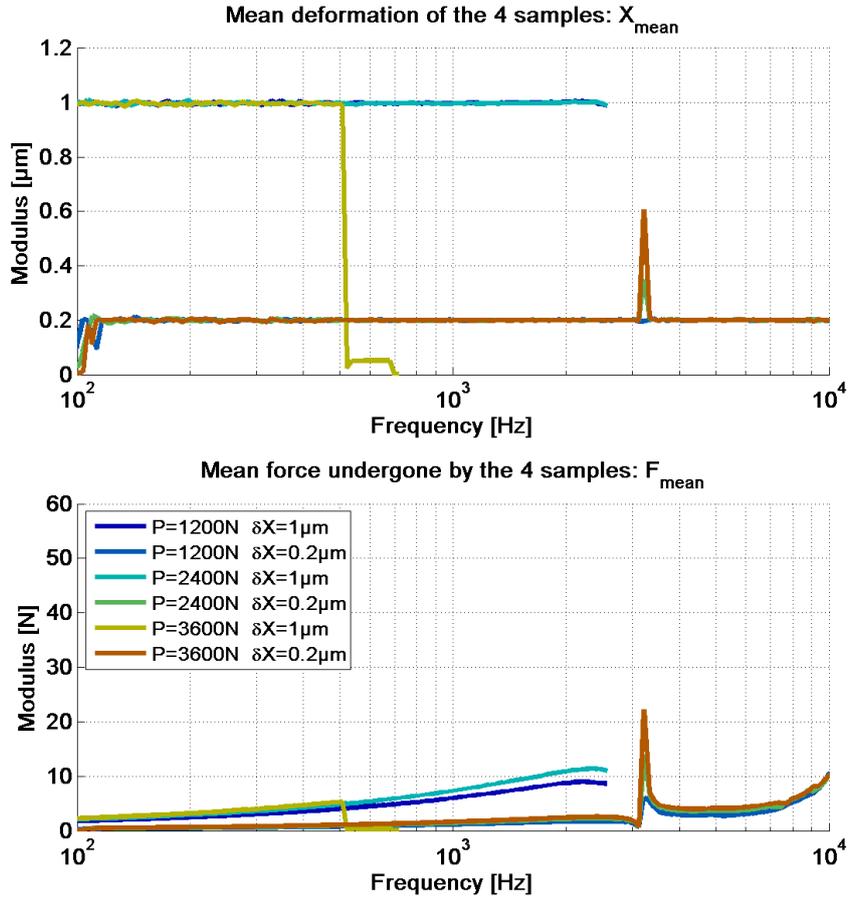


Figure 13: Mean deformation and mean effort undergone by MSC5048 samples with adhesive

Preload	Dynamic deformation amplitude	shim without adhesive		shim with adhesive	
$P = 1200\text{N}$	$0.2\mu\text{m}$	$K = 47E6\text{N/m}$	$\phi = 31.1^\circ$	$K = 12E6\text{N/m}$	$\phi = 52.5^\circ$
$P = 1200\text{N}$	$1\mu\text{m}$	$K = 39E6\text{N/m}$	$\phi = 37.8^\circ$	$K = 12E6\text{N/m}$	$\phi = 52.4^\circ$
$P = 2400\text{N}$	$0.2\mu\text{m}$	$K = 67E6\text{N/m}$	$\phi = 30.6^\circ$	$K = 15E6\text{N/m}$	$\phi = 54.6^\circ$
$P = 2400\text{N}$	$1\mu\text{m}$	$K = 56E6\text{N/m}$	$\phi = 36.9^\circ$	$K = 15E6\text{N/m}$	$\phi = 54.3^\circ$
$P = 3600\text{N}$	$0.2\mu\text{m}$	$K = 84E6\text{N/m}$	$\phi = 30.0^\circ$	$K = 16E6\text{N/m}$	$\phi = 55.2^\circ$
$P = 3600\text{N}$	$1\mu\text{m}$	$K = 72E6\text{N/m}$	$\phi = 36.2^\circ$	unavailable*	

Table 1: Shear stiffness modulus K and phase ϕ of each sample at 1000Hz. Some data is unavailable because an actuator has broken during the test.

6 Conclusion

The need for improving disc brake models with the real constitutive law of shims leads us to design a shear DMA analyser. It does not rely on the time-temperature superposition principle. It is one rare analyser allowing both samples preload and excitation above 1000Hz. The upper limit of frequency characterisation is set by the first normal mode interfering with the measurement. This limit is about 3000Hz. Moreover the shearing of samples is pure whereas the classical Oberst's beam method induces a bending excitation of materials.

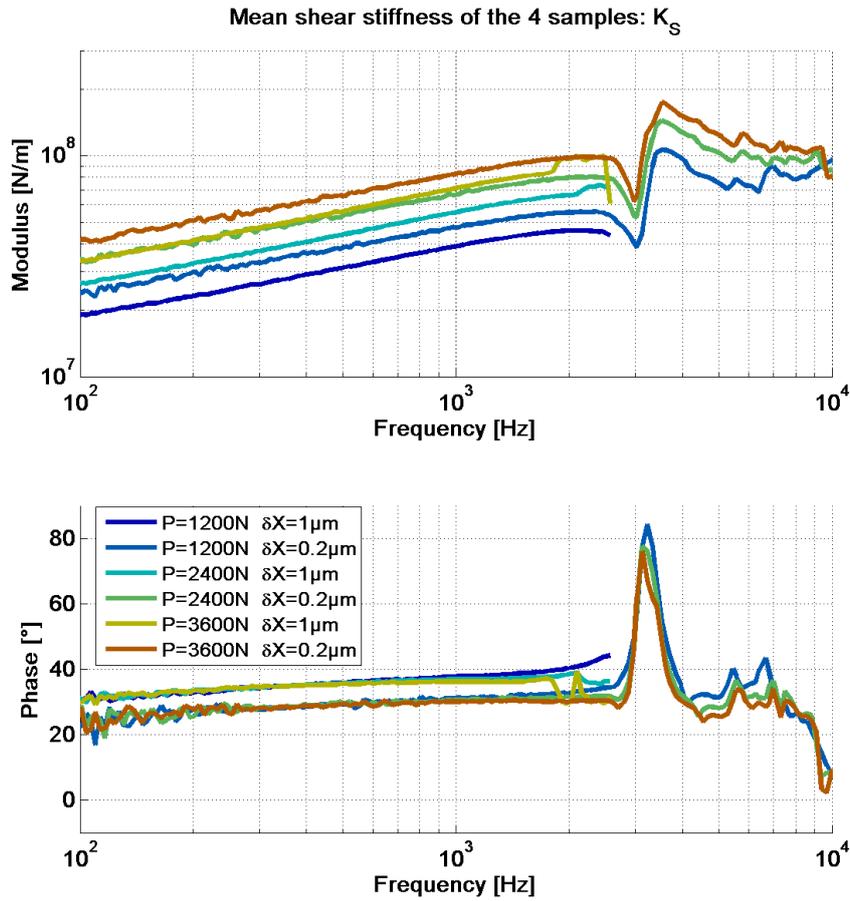


Figure 14: Mean shear stiffness of MSC5048 samples without adhesive

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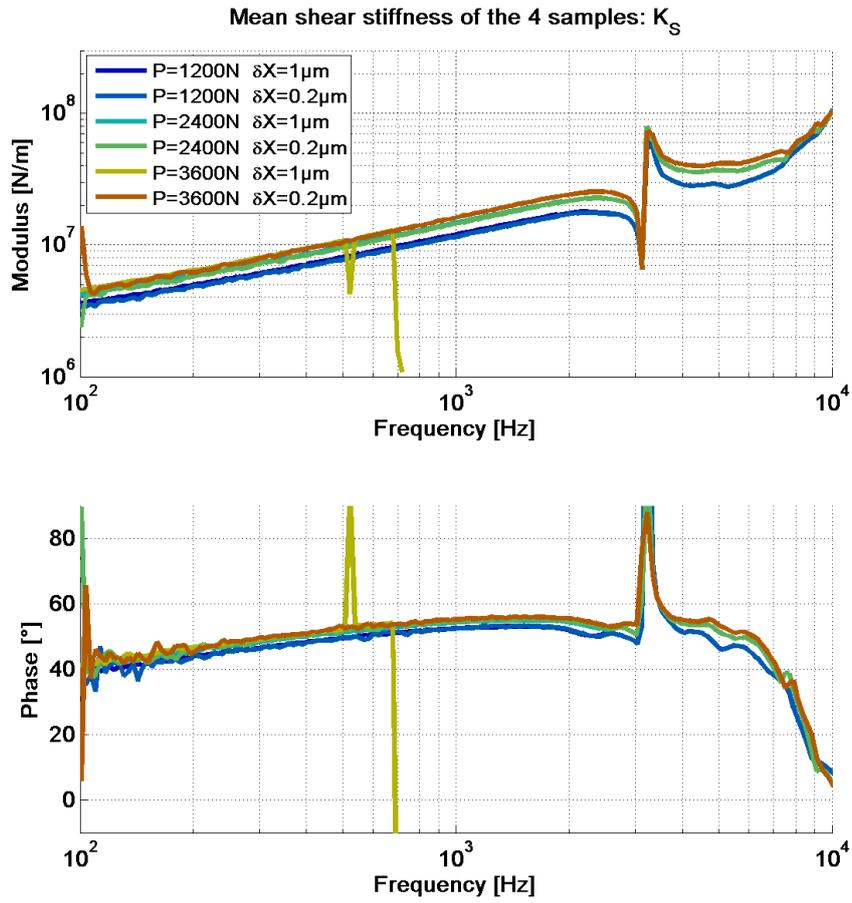


Figure 15: Mean shear stiffness of MSC5048 samples with adhesive

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