Quantifying the variability in stiffness and damping of an automotive vehicle's trim-structure mounts

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Abstract. Small plastic clips are used in large numbers in automotive vehicles to connect interior trims to vehicle structures. The variability in their properties can contribute to the overall variability in noise and vibration response of the vehicle. The variability arises due to their material and manufacturing tolerances and more importantly due to the boundary condition. To measure their stiffness and damping, a simple experimental rig is used where a mass is supported by the clip which is modelled as a single degree of freedom system. The rig is designed in a way that it simulates the boundary condition as those of the real vehicle. The variability in clip and also due to the boundary condition at the structure side is first examined which is 7% for stiffness and 8% for damping. To simulate the connection of the trim side, a mount is built using a 3D printer. Rattling occurs in the response of the clips with loose connections, however by preloading the mount the effective stiffness increases and the rattling is eliminated. The variability due to the boundary condition at the trim side was as large as 40% for stiffness and 52% for damping.

1. Introduction

The level of noise and vibration in automotive vehicles is a major concern for the luxury market where the level should be kept low to ensure the satisfaction of customers. Variability in noise and vibration is common in identical vehicles due to manufacturing tolerances and variations in material properties [1-6], which can result in vehicles with a Frequency Response Function (FRF) that exceeds the threshold set at the design stage. Generating tight manufacturing tolerances can reduce the variability, although this can apply to components which are not significant contributors to the noise and vibration paths. Indeed, while the macroscale components can be designed and manufactured with tight tolerances, the components which join them together can generate variability in noise and vibration frequency response functions.

As an example, the plastic interior trim panels of an automotive vehicle can be attached to the metal door frame using small plastic clips. Ideally, the stiffness and loss factor of these clips would be highly consistent, however this can often contradict with the need for high speed manufacturing and assembly, or ease of assembly. While other authors have noted the importance of panel joints and connectors, few studies have been published on this subject. Further, the accurate knowledge of the connector stiffness and damping is required for implementation in a deterministic prediction program.

In this paper, the variability in stiffness and damping of small clips that are connecting vehicle cabin trims to the vehicle structure are measured and the possibility of reducing the variability is discussed. The variabilities due to the attachment design at the structural side and also at the trim side are measured separately.

Clips usually are modelled by rigid connectors in Finite Element (FE) models of the automotive vehicles (for example RBE2 element in MSC-Nastran) [7]. When they are modelled by spring elements a dynamic pull out simulation is usually implemented in which the stiffness is approximated by the slope of the force-displacement curve for a clip that is removed from its mount [8]. In this paper, the stiffness is obtained through a dynamic test with simulated boundary condition of the clip in the vehicle which can provide a better evaluation of the equivalent stiffness of the clips when they are modelled by spring elements in FE models.

Automotive trims are connected to the body-in-white with few bolts and a number of clips. The door of a Jaguar XJ is shown in Figure 1(a) and the associated trim in Figure 1(b). Eleven plastic clips are used to connect the trim to the door whose locations are marked with arrows in the figure. The clip is pushed through a hole in the door structure which keeps them firmly in place and ensures a tight connection at the door side, see Figure 1(c). The clip slides in a slot at the trim side as shown in Figure 1(d), ensuring easy assembly and also to compensate any misalignment that may arise during the assembly. However, such flexibility in the mounting position causes variation in the boundary condition resulting in variation of the dynamic response. In this paper, the variation in stiffness and damping of the mounts are measured using an experimental rig. The boundary conditions are simulated to have those of the real vehicle and the effect of tolerances in trim side connection on equivalent stiffness and damping of the mount are quantified.
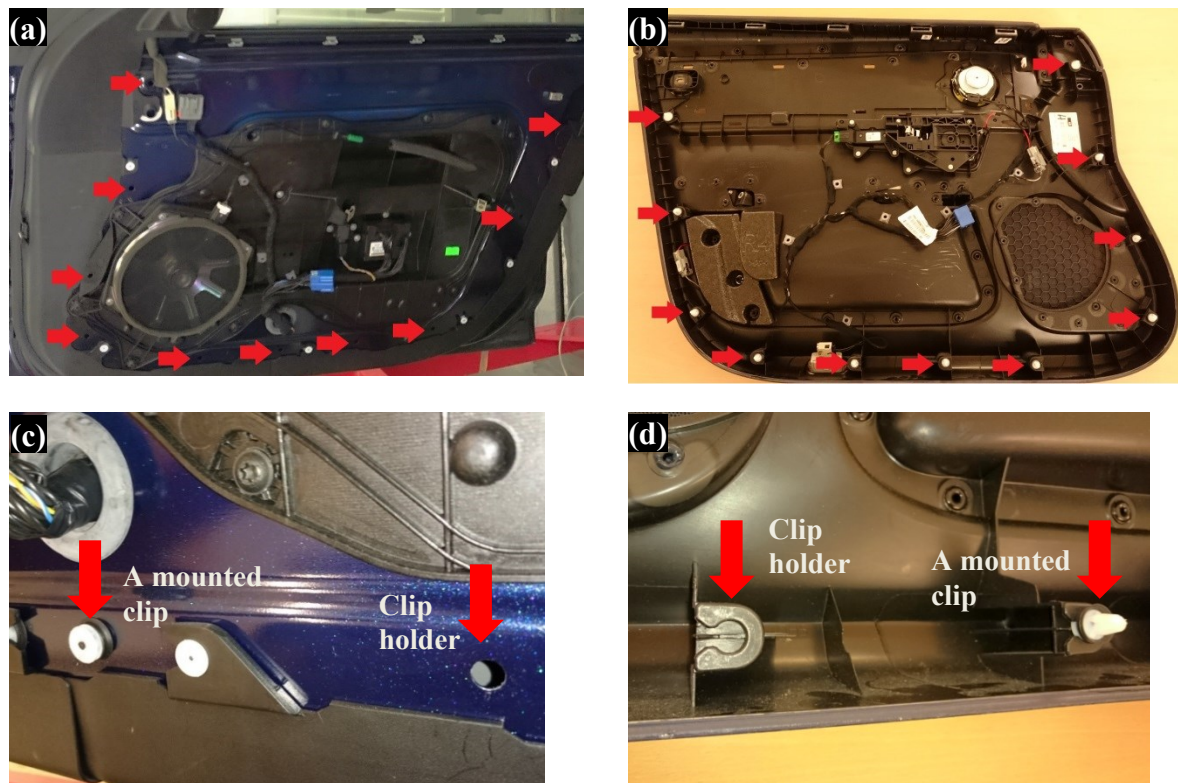

Figure 1. The vehicle door and the trim. a) The door when trim is removed. Clip mounting points are marked by arrows. b) Door trim. Clip mounting points are marked by arrows. c) The close-up view of the mounting point of the clip in the door. d) The close-up view of the slot in the trim which allows compensation in positioning of the trim during assembly.

The test methodology is described in the following section. The measurements on the rig that models only the door side connection are presented in section 3. The results obtained from measurements on rigs that model both boundary conditions are given in section 4.

2. Test methodology

The stiffness and damping of the clip can be estimated by measuring the dynamic response of a mass that is supported by the clip provided internal resonances are high enough to allow it to be represented as a Single Degree Of Freedom (SDOF) system. The resonance frequency is used to obtain the stiffness of the mount and the half power method is used to obtain the damping ratio of the clip. The boundary condition of the clip to the mass and the clip to the shaker are designed in a way that they simulate the real boundary condition of the clips in vehicles which allows to assess their effect on the variability.

The clip is shown in Figure 2 (a). Pushing the clip into the hole of the metal door frame applies a force to the rubber bush on the base of the clip. While the free rubber bush has a low stiffness when not assembled in the door, as soon as it is mounted in the door structure, the pre-loaded rubber ring forms a relatively stiff connection (replicated in the experiment). A series of measurements of clip stiffness with similar boundary condition to that on the door side connection can be used to obtain the variability in mount properties.

To simulate the door structure, a profile with the same thickness as the door structure is used. The hole in the profile has the same diameter as those on the door structure while the closed box shape of the profile ensures high enough internal resonances to consider it as a rigid mass in the frequency range of interest. The profile has been modelled in NASTRAN and it is found that the lowest natural frequency was above 4 kHz. The clip mounted on the bracket is shown in Figure 2(b) and the arrangement is shown in Figure 2(c) where the transmissibility ($T = \ddot{x}_2/\ddot{x}_1$) is measured to estimate the stiffness and the damping of the clip.
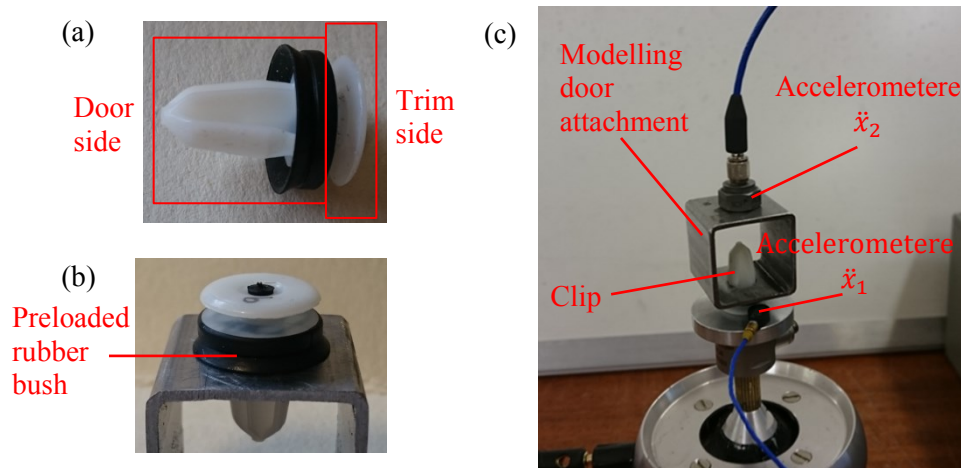

Figure 2. The experimental setup to measure the variability in stiffness and damping, door side boundary condition reproduced. a) A clip. b) A clip mounted in the profile that resembles the door side boundary condition. c) The experimental setup.

To estimate the measurement error, a series of measurements are conducted where the accelerometers were removed and mounted again (performed in order to separate out measurement errors from the natural variability of the clip properties). The amplitude of transmissibility is shown in Figure 3(a). There is a dominant peak at about 1000 Hz which make it possible to model the rig as a SDOF system. The transmissibility phase is shown in Figure 3(b) where a 180 degree shift in phase is visible for the main peak. The coherence was generally over 0.9 for measurements of this paper. There

is a local maximum before the main peak at about 500 Hz which is due to a coupling of the rotational degree of freedom and is ignored for the purpose of this study. The normalized standard deviation of the measurement is less than 1% for the stiffness of the mount and is about 4% for the damping of the mount.
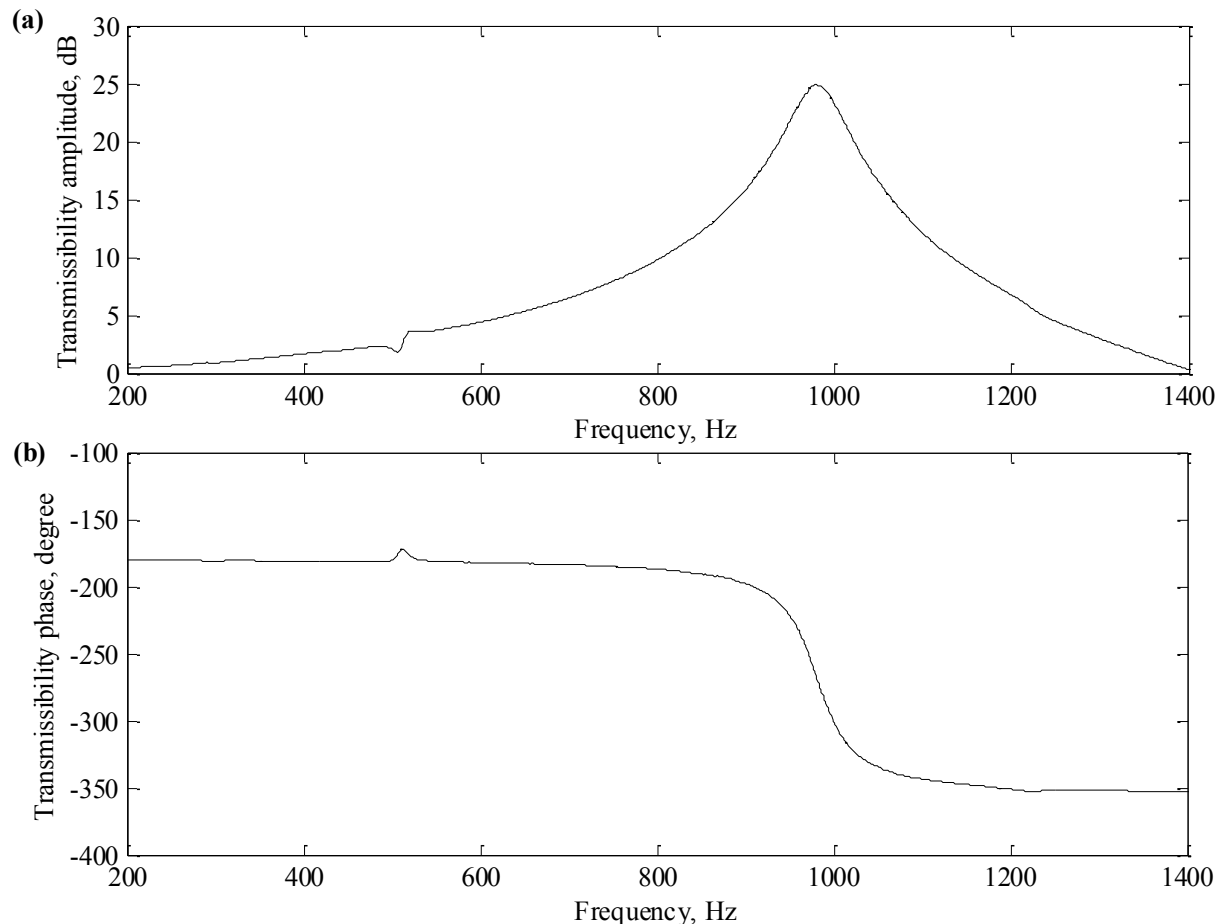

Figure 3. Transmissibility of the experimental setup used to measure stiffness and damping of the clip. (a) Amplitude of transmissibility. b) Phase of transmissibility.

The second series of experiments is conducted with the clip held at a position on the trim by an edge in the mounting point that is shown in Figure 4(a). To accurately replicate the attachment of the plastic clips in the plastic trim holders, a 3D printer was used to manufacture controlled samples with known tolerances. The design of the clip mount which is manufactured by a 3D printer is shown in Figure 4(b) and the experimental setup is shown in Figure 4(c). The clearance between the edge and the mounting surface forms different fits in practice. The equivalent distance on the mounting block is shown in Figure 4(d) and is marked with h. Measurements on an existing door trim showed that the distance h varies between 3.2 mm to 3.6 mm for different mounting points on the door trim. For those with a wider opening, the fit is loose which results in a reduced effective stiffness and the clip may rattle at extreme cases (although is easier and quicker to assemble in a factory). A series of these mounts with different tolerances are produced to model different boundary condition of the clips. Tolerances are checked manually and a block with a tighter fit ($h = 3.05$ mm) is also produced to measure the stiffness of a modified design where a tight fit is used to reduce the variability. The measurements on trim side are presented in section 4.
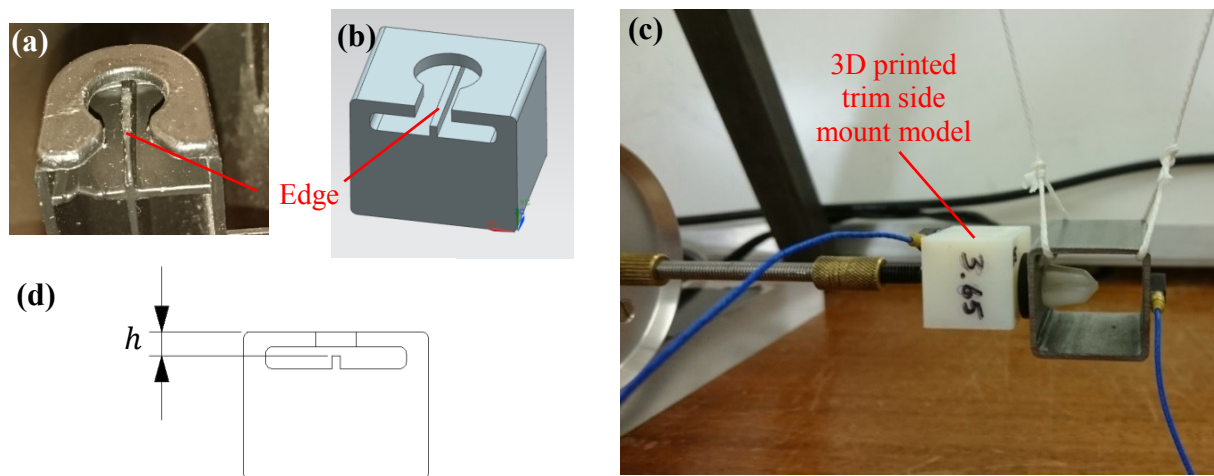
Figure 4. The experimental setup to measure the variability in stiffness and damping, both boundary conditions resembled. (a) Mounting boundary condition of the clip on trim. (b) Experimental mount model of trim side connection. (c) Experimental setup to measure the variability due to both boundary conditions. (d) Front view of the mount.

3. Variability due to door side connection

The first series of tests conducted to measure the variability of the clips in the door side connection which was assumed to have less variability due to its connection design. When clips are mounted and dismounted on the profile, the wear can cause a change in effective stiffness. In the first series of the tests a single slightly worn clip is mounted and dismounted to simulate the effect of the wear and ageing. Each time the transmissibility measured for three times where the profile was rotated slightly each time. The amplitudes of the transmissibility are shown in Figure 5. The resonance frequency of the system occurs at a range between 750 Hz to 850 Hz. The estimated average stiffness is 724 kN/m with a normalised standard deviation of 8%. The estimated damping ratio is 0.04 with a normalised standard deviation of 15%. Although this stiffness is relatively high, it is not as rigid as the metal structure and thus modelling in finite element programs should be undertaken using spring elements and not rigid connectors.
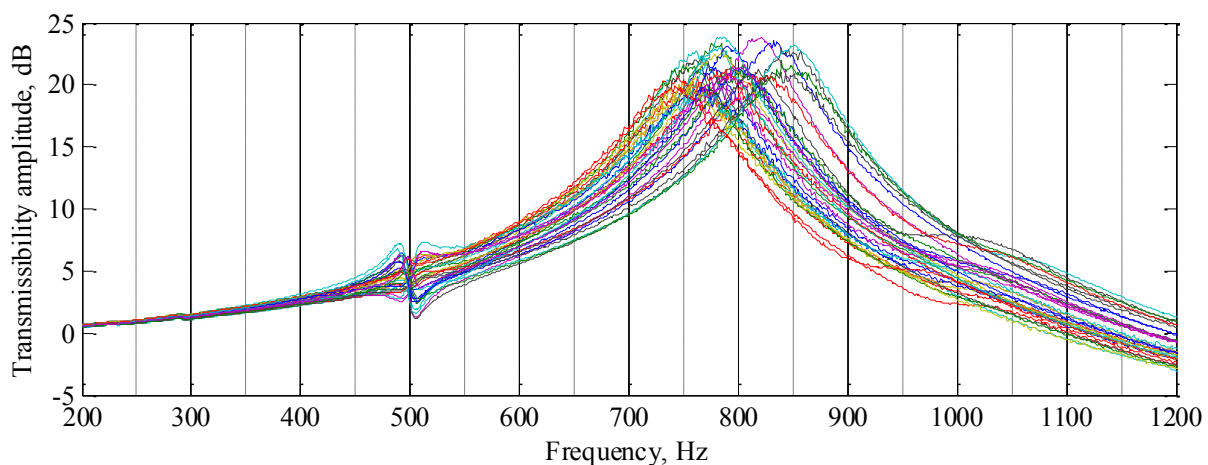

Figure 5. Amplitudes of transmissibility for a worn mount for a series of measurements where mounted and dismounted when measurement conducted three times, each time with a small rotation in the supporting profile.

The second series of measurements are conducted on new clips with no or slight sign of wear. This was to simulate the variability in stiffness of the mounts of a new vehicle. Five measurements on each clip were conducted where the supporting profile were rotated between each measurement. The measurements are shown in Figure 6 where the resonances cover a frequency span mainly between 1000 Hz and 1080 Hz which is higher than the resonance frequency of the worn clip shown in Figure 5 which suggest a reduction in stiffness due to usage for a worn clip. This can be due to a decrease in preload as the mounting becomes looser by usage. The average estimated stiffness is 1250 kN/m with a normalised standard deviation of 7% which is lower than that of the worn clip. The estimated damping ratio is 0.03 with a normalised variation of 8%.
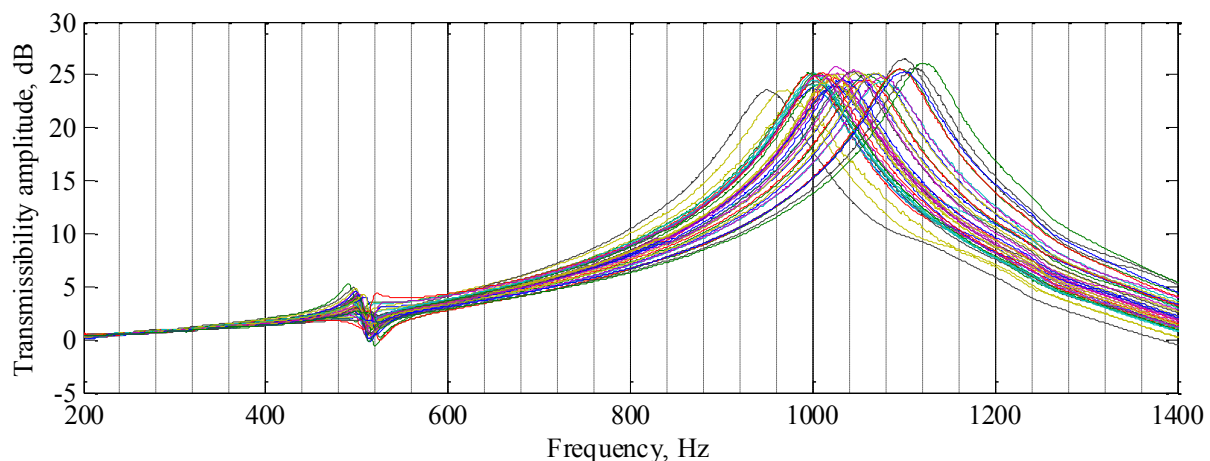

Figure 6. Amplitudes of transmissibility for ten different clips, each one measured five time with the supported profile rotated between measurements.

4.   Variability due to connections on two sides

The design of the mounting on the trim side makes the position of the clip uncertain in practice. Furthermore, there is a large variability in the size of the gap, marked by h in Figure 4, in manufactured door's trims. Three set of measurements were conducted in order to examine the effect of the gap h on the effective stiffness and damping of the clips. First, measurements were conducted on the tightest fit of the mounting block ($h = 3.05$ mm) which was slightly tighter than the real fits on the existing door trim and is referred hereafter as *"extra tight fit"*. This set is used as guidance to what is achievable in practice for a modified design, even if it would prove more difficult to fit on a production line within tight timeframes. Second the measurements on a fit that is equivalent to the tightest fit on the existing trim are presented and finally the effect of loose fits on the response are shown.

The amplitudes of transmissibility for five measurements for a tight fit at the trim side are presented in Figure 7. The clip was moved slightly for each measurement inside the mounting block of the trim side connection. It can be seen that there is another small peak at a frequency of about 940 Hz which is due to rotating degree of freedom and is more visible in this graph comparing to the previous cases as the mounting block is not symmetric and the clip is not placed exactly at the centre of the mounting block. However, there is still a dominant peak which can be modelled as a SDOF system and the stiffness of the mount and the damping can be estimated from it with the same method as used before.

The average estimated stiffness is 760 kN/m with a normalised standard deviation of about 4%. The stiffness is nevertheless lower than the average stiffness obtained when only door side connection is considered which is due to the flexibility of the trim side mount. As the fit is tighter than what was measured on the existing door, the assembly of the clip in the door mount was not as easy as it was on

the vehicle trim, however it is still an achievable fit in practice that allows assembling the clips on the door trim without requirement for any tool.
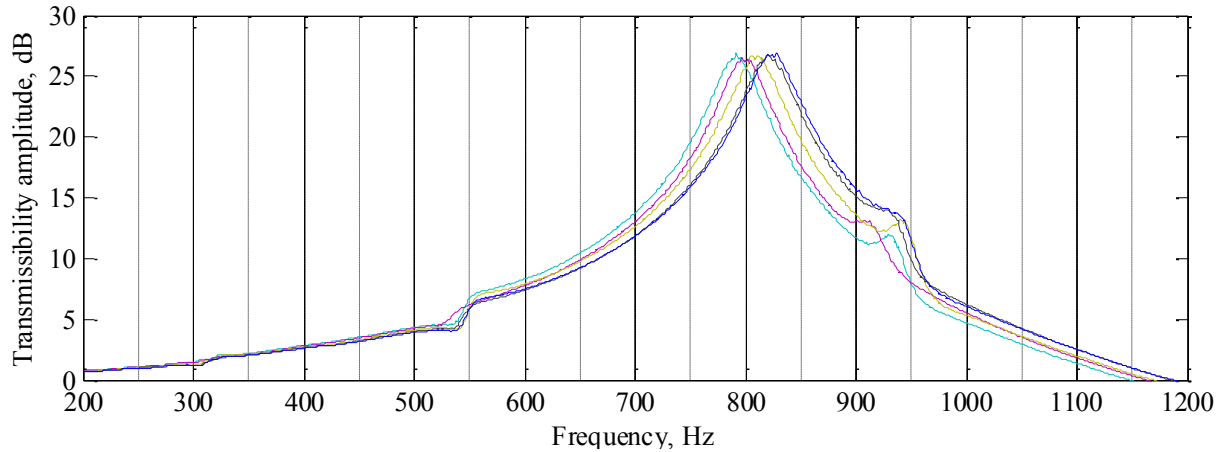

Figure 7. Amplitudes of transmissibility for the *extra tight fit* ($h = 3.05$ mm) for five different position of the clip in the trim side mount.

The measurement on the tightest fit that was measured on the existing door is presented in Figure 8. The FRF are measured for positioning the clip in the trim side mounting block at five different positions. The spread of the fundamental resonance frequency is wider in this case. There is additional peak at about 850 Hz for two sets of measurements which is due to rotational degree of freedom which is more significant for the mounts that is positioned further away from the centre of the trim side mounting block. The main peak can still be distinguished through its amplitude which is higher than other peaks. Also, the phase angle is changing almost 180 degree for this peak which does not happen for other peaks. The main peak can still be modelled by a SDOF system. The estimated average stiffness of the clip is 670 kN/m with a normalised standard deviation of 12%. The estimated average damping ratio is 0.025 with a variation of 21%.
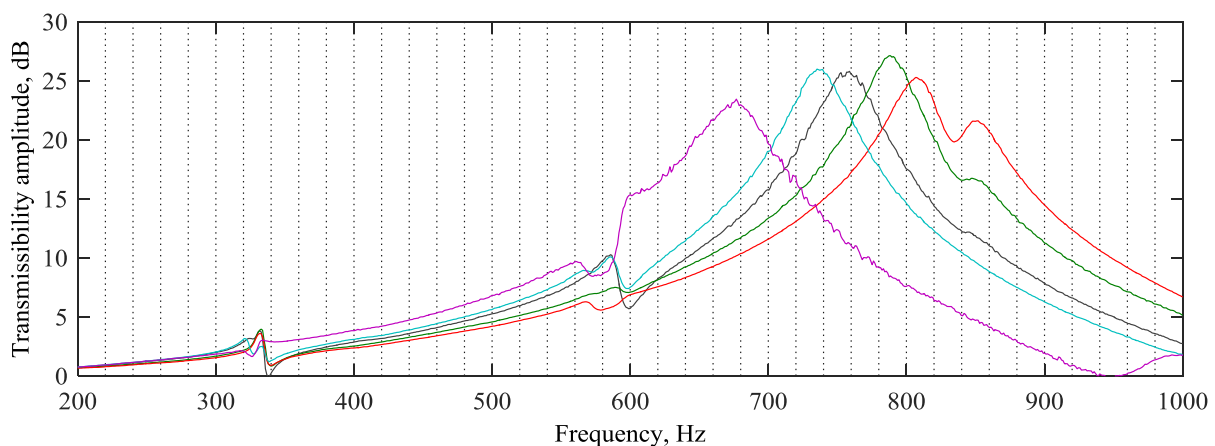

Figure 8. Amplitudes of transmissibility for the tight trim side fit ($h = 3.24$ mm) for five different position of the clip in the trim side mount.

The amplitudes of transmissibility for the loosest fit ($h = 3.65$ mm) of the door trim are shown in Figure 9. The clip rattles as a result of the loose fit for which the transmissibility is shown in Figure 9 (a) for two different position of the clip in the mounting bock. However, the clips are loaded by the trim weight in the vehicle which can cause a more stiff connection and eliminate the rattling. In the

current experiment the clips are loaded by tensioning the thread that the profile was suspended on. The measurements for three different positions of the clip in the trim side mount are shown in Figure 9 (b) where the rattling is eliminated completely. The clip will move from the centre of the mounting block as a result of the preload. In this arrangement, the rotational degree of freedoms of the system are excited and, thus, a single degree of freedom FRF cannot exactly model the system. However, the transmissibility peak at the shaker loading direction is clearly distinguishable which allows the estimation of the stiffness to be 271 kN/m. The estimate of the damping is not given as it is affected by close peaks.

An estimate of the stiffness and damping ratio of the clip is obtained by conducting a series of measurements on the test rig where both door side and trim side boundary condition are modelled. The rattling in these measurements is eliminated by preloading the threads and different fits are used for the trim side boundary condition. The estimated average stiffness is 520 kN/m with a range between 208 kN/m and 829 kN/m and a normalised variability of 40% although this does not imply a normal distribution. The stiffness is lower than where only the door side boundary condition is considered and the variability is much higher as a result of the effect of variation of fit on the equivalent stiffness. Excluding measurements with two close peaks, the estimated damping ratio is 0.03 with a normalised standard deviation of 36%, with a range between 0.02 and 0.06. The damping ratio is equivalent for the average that has been obtained for the door side but its variation is much higher. The variation in damping ratio is obtained by excluding some measurements and it should be treated carefully.
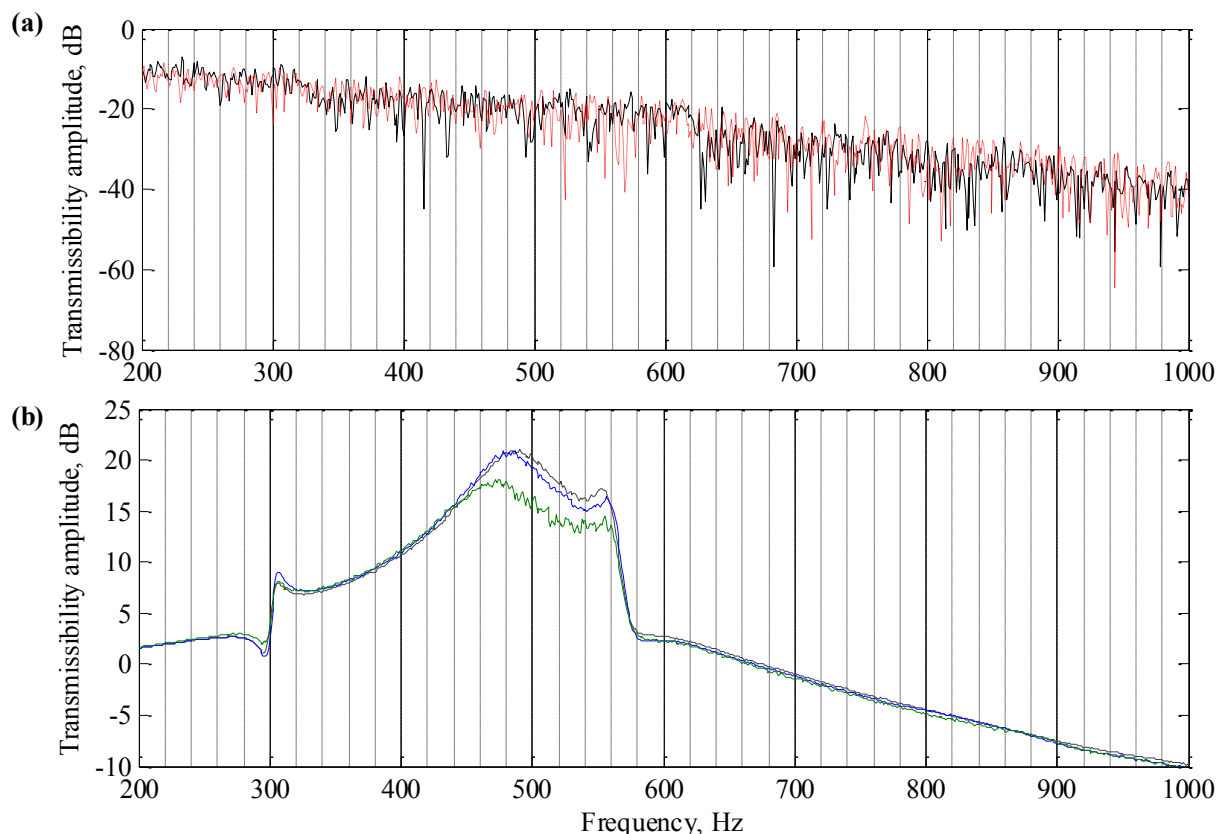

Figure 9. Amplitude of transmissibility for the loosest trim side fit ($h = 3.65$ mm). (a) Two different position of the clip in the trim side mounting block. (b) Applying preload by tensioning the threads holding the profile, three different position of the clip in the trim side mounting block.

Conclusions

The variability in the clip mount stiffness and damping is assessed through a series of tests. The test setup is designed in a way that allows modelling it as a SDOF system in the frequency range of interest. The measurement variability of the test setup is less than 1% for the estimated stiffness and about 4% for the estimated damping. The stiffness and damping of the clip is estimated by measuring transmissibility which allows modelling the clips as spring and damper element in Finite Element models of automotive vehicle to predict their NVH performance.

The boundary condition that forms within the connection of the clip to the vehicle structure and trim affecting the variability and effective stiffness and damping of the clip. In the first set of measurements the door side boundary condition is represented. The average estimated stiffness was obtained as 1250 kN/m with a normalised standard deviation of 7%. The estimated damping ratio is 0.03 with a normalised variation of 8%. If a clip is worn and used as a result of mounting and dismounting, a decrease in average stiffness to 724 kN/m is observed and the variability increased slightly to 8%.

The mounting point of the clip on the trim provides some degree of adjustment through its design, which can result in uncertainty in the exact position of the clip in its mount. Furthermore, the fit was varying from tight to loose on different mounting points of a vehicle door trim. The boundary conditions were replicated by building a mounting block with a 3D printer with different gaps that allows a variation in the resultant fit. The average estimated stiffness for the clips with both boundary conditions was 520 kN/m with a normalised variability of 40%. The stiffness was considerably lower than the average estimated stiffness when only the door side boundary condition is resembled. A tighter fit is proposed to reduce the variability which resulted in an estimated stiffness of 760 kN/m with a normalised standard deviation of about 4%.

Acknowledgments

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