Investigation of PNCAR mountings for vibration isolation

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Investigation of PNCAR mountings for vibration isolation

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Abstract: The Panel Noise Contribution Analysis Referenced (PNCAR) is a methodology for assessing airborne Transfer Path Analysis (TPA) in vehicle interiors. The technique is based on applying the acoustic reciprocity principle using Microflown particle velocity sensors along with pressure microphones for estimating local pressure contributions.

The measurement procedure is cost effective, robust and it can be done in one working day. A complete cabin interior characterization is performed in two steps. Firstly, the acoustic transfer paths are measured in several sessions by attaching a set of probes to the different surface areas of the vehicle and exciting the sound field using a monopole sound source at the reference spot. Next, pressure and particle velocity are measured under stationary operational conditions. This procedure is repeated till covering the complete cabin interior. Experiences shows that a typical car interior can be sufficiently subdivided into 10 to 12 measurement sessions leading to have between 110 and 130 total measurement positions, covering a frequency region from 60 Hz to 1.5 kHz.

This methodology directly implies that the Microflown probe must be attached to the surface of the car interior. The distance probe-surface had been fixed in about 0.02 m. As the particle velocity sensor must be isolated from surface vibrations, the probe is fixed with a special mounting structure which decouples the acoustic sensors from the surface vibrations.

In this paper several types of mountings are tested and compared with a completely isolated reference probe. Results show the effect of vibrations transmitted through the frame of the mounting, and other different phenomena related to the mass-spring system.

Keywords: particle velocity, Microflown sensor, PNCAR, vibration isolation

1. Introduction

The PNCAR [1] method is performed by using a scattered PU probe array. The advantage of the array is in its flexibility since it is not limited by a specific geometry. In practice that means that the array can be adapted to complicated geometrical shapes such as car dashboard for instance. Such surfaces can be effectively covered in a moderate time. However, the scattered array is set by attaching the probes directly on the surface which directly implies undesirable coupling between the vibrating surface and probe frequency response.

PNCAR relies on particle velocity measurements close to the vibrating structure. According to the so called *very near field theory* the particle velocity very close to the surface is proportional to the surface displacement. This property allows to measure structural vibrations via particle velocity with a non-contact procedure.

The main aim of the investigation was to design a mounting for decoupling P-U probes from the structural vibrations. Such mounting should not only have great performance in terms of vibration isolation but it should also meet some practical requirements such as small weight and small size.

The paper is organized as following. Section 2 outlines the *very near field theory*. The following section describes the design approach from a vibrational point of view as well as from practical limitations which were imposed on the design. In section 4 the prototypes under assessment are presented. In section 5 the measurements set-up for verifying the design and the obtained results are outlined along with a discussion focused on assessing the data presented, followed by the conclusions sections 6.

2. Very near field theory

By following [2, 3] let's start by defining the Helmholtz wave equation in terms of velocity potential $\boldsymbol{\Phi}(\boldsymbol{r})$, i.e.

$$\nabla^2\Phi + k^2\Phi = 0 \qquad (1)$$

where ∇^2 is equivalent to the Laplace operator and $\boldsymbol{k}$ is the wave number $(2\pi f/c_0)$. To describe the sound field of a vibrating surface Equation (1) should be solved with the following boundary conditions:

$$\begin{cases} u_n = \partial\Phi/\partial_n & \text{if } r = 0 \\ \Phi \propto e^{jkr}/r & \text{if } r \to \infty \end{cases} \tag{2}$$

where **r** is the distance to the vibrating surface; ∂/∂_n is the normal partial derivative and u_n is the normal component of the particle velocity. The observable acoustic values, sound pressure p and particle velocity u, are connected with the velocity potential as following

$$u = \nabla\Phi, \qquad p = -j\omega\rho_0\Phi \tag{3}$$

where ∇ represents gradient operator and ρ_0 is the density of the medium (air). According to [2] it is possible to establish a region between the vibrating surface and the beginning of the so called *Near Field* where the Equation (1) is reduced to the Laplace equation for incompressible fluids. In order to derive this expression it is necessary to perform a Taylor series expansion of the velocity potential term $\Phi(r)$ in the neighborhoods of the surface and then consider only sound waves of wavelength (λ) much greater than the spatial wavelength which defines the vibrating surface (L). In summary, it is shown that the sound field at a normal distance **r** from a vibrating surface is called the very near field if the following two conditions are met:

$$\begin{cases} r \ll L/2\pi & \textbf{condition I} \\ \lambda \gg L & \textbf{condition II} \end{cases} \tag{4}$$

In the very near field the normal component of the particle velocity coincides with the structural velocity of the vibrating surface with the neglectable error. Previous measurements have shown that condition (I) of Equation (4) is not very strict since the surface velocity profile can still be determined at a distance of $L/2$.

These considerations are the basis of vibration measurements for Microflown P-U probes. An important issue is related to the estimation of the *very near field* size along the normal direction to the surface. In order for this condition to be verified, r has to be at least two orders of magnitude smaller than $L/2\pi$. Nevertheless, it must be highlighted that the effective wavelength associated with the vibrating surface will change with the frequency according to the mode index. For a simple geometry, such as a rectangular panel of dimensions L_x and L_y, L can be defined as

$$L = \sqrt{\left(\frac{L_x}{n_x}\right)^2 + \left(\frac{L_y}{n_y}\right)^2} \tag{5}$$

where n_x and n_y are the mode indices for the *x* and *y* axis respectively. This means that as we go up in frequency the measurement distance range that allow us to measure direct structural vibrations using a P-U probe is reduced according to the panel size and the mode index.

3. Mounting design

Firstly the design approach is considered from the very basic theoretical point of view in Section 3.1 and then from practical requirements in Section 3.2.

3.1 Vibration control

The problem of decoupling surface vibrations from the probe movement can be represented by a simple mass-spring system where the excitation comes from the base motion, as shown in Figure 1 [4].

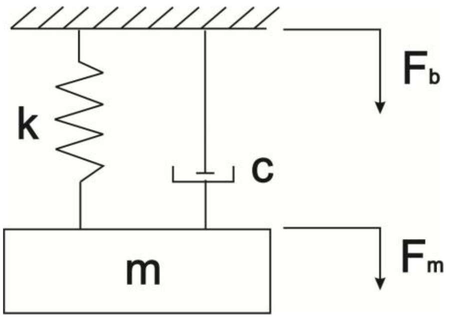

Figure 1: Damped system with base excitation. The F_b indicates base excitation force and F_m a response force of a mass-spring system.

Amplification of the transmitted force F_m occurs at the natural resonance frequency of a mass-spring whose amplitude is strongly dependent on the damping (*C*). In general, the best isolation (reduction of transmitted force) is achieved for higher frequencies than the resonance, more efficiently if the damping system is low. Therefore, the transmittance above the natural resonance frequency is very low hence the system can be defined as “dynamically decoupled” in certain frequency range.

At low frequencies, that is below natural frequency, the single mass shows a much higher velocity response than the spring, the velocity of the assembled mass spring system will therefore be limited by the latter. Above the natural frequency, in the frequency region where isolation occurs, the mobility of the spring exceeds the one of the mass and continues to grow while the mobility falls off. In the frequency range above the rigid body resonance the vibratory velocity response is therefore completely governed by the mass, which will limit the vibration displacement. Since the dynamic force transmitted by the spring is proportional to the vibration displacement the transmitted force will be limited as well. It must be emphasised that the mounting does not damp the vibrations but rather create an impedance mismatch between source and structure causing reflection of energy due to the impedance mismatch. This is the cornerstone of passive vibration isolation.

The mounting could have movement restrictors to limit the static displacements in case of (quasi-)static overload due to for instance discontinuities in the road surface.

This solution is not practically possible because a movement restrictor would generate interference and unwanted peaks in the output signals, in case of collision with the probe. This displacement limitation is otherwise achieved with more damping on the spring system, finding a compromise between displacements allowed of the probe and vibration isolation effect.

The Microflown probe is sensitive to DC flow so a high displacement during the measurement will turn into overloads and higher noise floor.

3.2 Practical considerations

The desirable mounting for decoupling should be small in size and have small weight. Small size allows more flexible positioning due to the smaller surface areas. In order to decrease the probe influence on the vibrations the mass of it should be as small as possible.

The mounting should also minimize the distance between the probe and the surface and thus increase the frequency range and accuracy.

The damping must control the maximum displacement of the probe but at the same it should not be too high for achieving good isolation above the resonance of the mass-spring system.

4. Mounting prototypes

First design incorporated a simple block of dense foam with the probe placed on top of it, as it is shown in Figure 2. Although the design is very simple, it is a poor isolator for low frequencies.

In theory the decoupling of the probe –surface can be improved by increasing the thickness of the foam but this would also have undesirable effect on sensor performance due to the increased distance between the vibrating surface and PU probe.

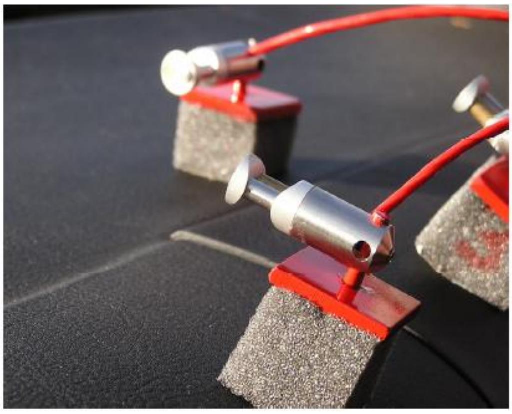

Figure 2: Early mounting design based on dense foam.

The next damping system was based on the basis of a simple harmonic oscillator (mass-spring). The mounting supporting structure is made out of aluminium and has a shape of a triangular as it can be seen in Figure 3 below.

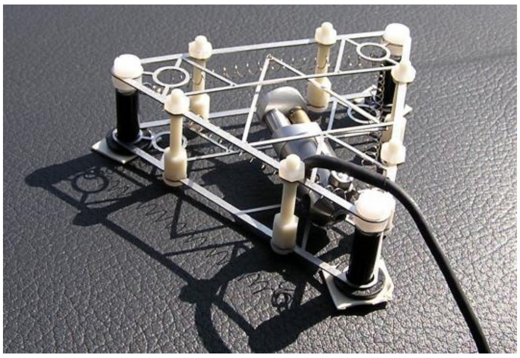

Figure 3: Aluminium triangular mounting.

The probe is suspended on three springs which are in parallel with the triangular sides. The P-U probe is suspended approx. 20 mm above the surface.

This design is better from the previous one in terms of vibration isolation but on the other side it has other down sides such as big size and rather complicated and delicate frame structure

The latest design is based on trapezoidal mounting shape and 4 springs system to which a probe is attached as it can be seen in Figure 4. Additionally, a second prototype version of this trapezoid structure was built using a double layer rubber band in the union between springs and frame in order to increase the damping of the system.

Figure 4: Trapezoidal mounting.

In comparison to the triangular design the trapezoidal one is simpler and thus more robust. Although the latest design of the probe has an additional frame and a connector attached to the sensor element, the total force generated by this mass is neglectable under dynamic conditions above the resonance frequency due to high isolation from structural vibrations (almost static mass). Furthermore, using the same springs but adding mass, the new prototype should have a lower natural frequency compared with the triangular probe.

5. Design verification

Three mounting designs were tested: triangular, trapezoidal and trapezoidal with high damping. Highly damped trapezoid mounting is a modification of the trapezoidal where the springs had a double layer of rubber in the union with the frame.

4.2 Measurement set-up

The measurement set-up consisted of a hard-membrane loudspeaker acting as a shaker attached to a metal plate where the probes where mounted. The signal used for exciting the system was random noise filtered below 500 Hz. The whole set-up can be seen in Figure 5 below.

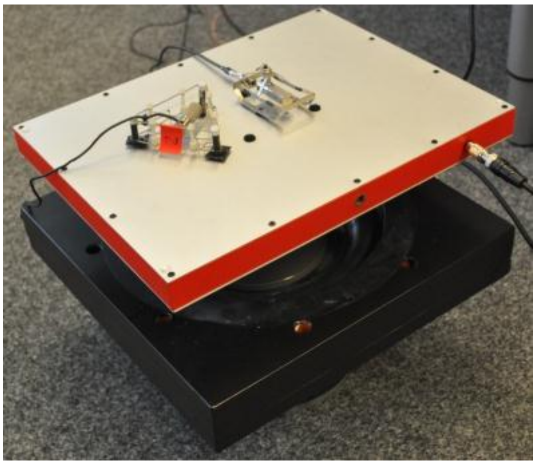

Figure 5: Measurement set-up with the P-U probes.

An accelerometer was attached to the top of the metal plate for measuring a reference signal of the surface vibrations, as indicated in below in Figure 6**.**

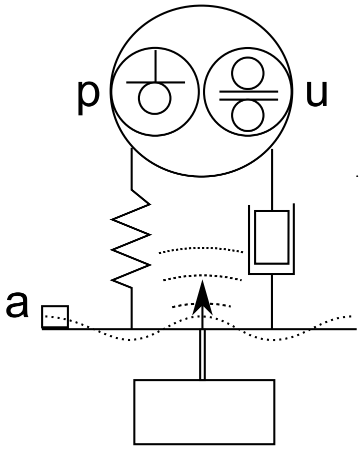

Figure 6: Schematic presentation of the measurement set-up.

The following aspects of mounting performance were addressed:

- Accuracy of the particle velocity spectral estimation measured by the mounted probes
- Spectrum of the freely oscillating system

The measurement was done under 7 different excitation loads as shown in Figure 7 below. Excitation levels were obtained by calculating the root mean square value of the reference signal measured by the reference accelerometer.

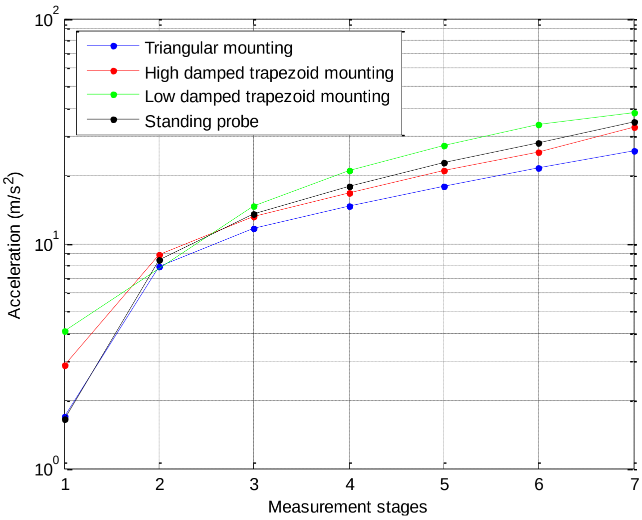

Figure 7: 7 Measurement runs; excitation loads.

4.3 Results

4.3.1 Comparison of particle velocity frequency responses

The frequency responses are presented alongside the reference velocity sensor and show substantial agreement as it can be seen in Figure 8. As expected, the major differences occur at very low frequency end due to the mountings natural frequency.

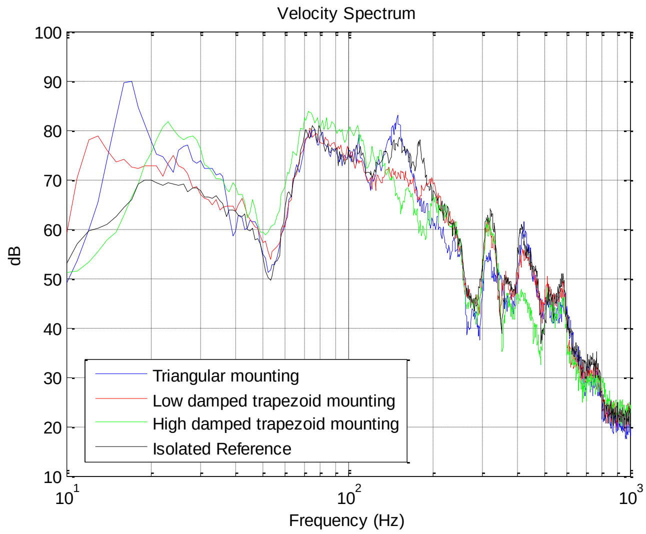

Figure 8: Particle velocity frequency responses comparison.

The next Figure 9 shows the difference between reference frequency response and frequency response of different mountings in third octave bands.

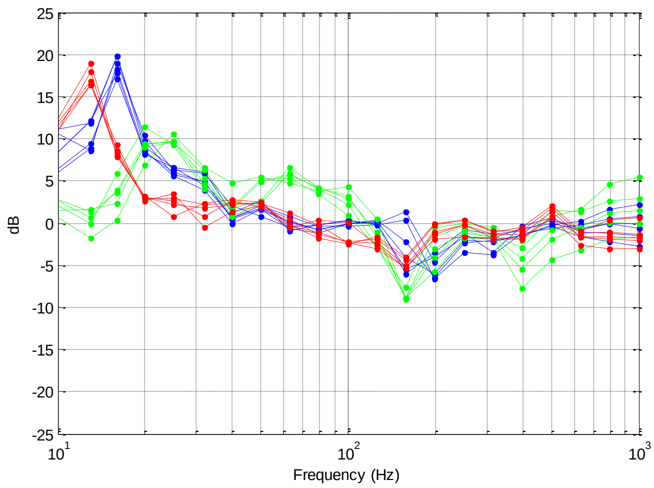

Figure 9: Difference between reference frequency response and different mountings frequency responses in dB.

As it can be seen the error is best minimized by low damped trapezoid mounting (red colour). The error after reaching its maximum around 13 Hz decays rapidly and approaches to zero around 30 Hz. The triangular mounting (blue colour) error peak is shifted up in frequency (in comparison to the trapezoidal mounting) therefore it decays down to zero at higher frequency. Consequently, triangular mounting has more constrained frequency range. However, the worst performance is showed by the highly damped trapezoid mounting (green colour) where although there is no a single high error peak in low frequency, it on the other hand can be seen that error varies drastically throughout the frequency range and does not converges to 0. Although damping does provide huge control over the maximum displacement at the natural resonance, it does however not prevent the energy from surface vibrations transmitting through the system which results in error fluctuation throughout the whole frequency range.

4.3.2 Free oscillation of the mountings

In the following Figure 10 the data obtained from the freely vibrating probes after the excitation signal was switched off is presented. The time data used for calculating the shown auto-spectra corresponds to the signal segment from selected from the excitation was stopped till the RMS value was reduced by 30 dB. Five different measurements of each probe were synchronized. The average length of the time segments addressed was of 1.4 seconds in the case of triangular mounting, 1.9s on the case of the trapezoid with low damping and 0.4s for the highly damped mounting.

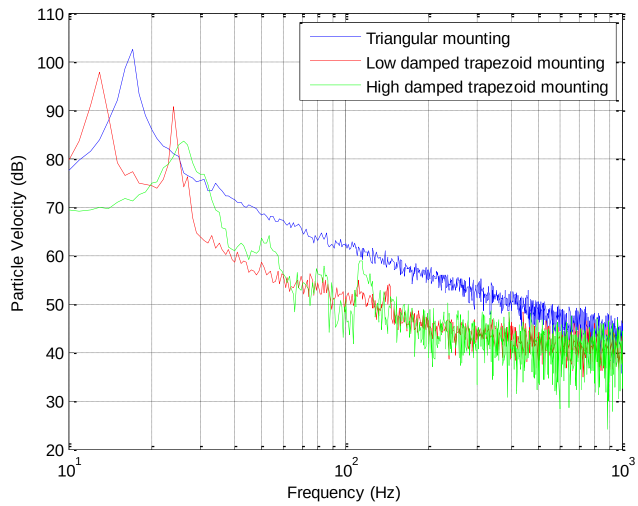

Figure 10: Particle velocity auto-spectras from free-vibration condition.

In summary, the new probe mounting with low damping shows a significant improvement in comparison to the old design in terms of vibration isolation.

6. Conclusions

A new probe mounting has been developed and tested for isolating a P-U probe from surface vibrations. Without modifying the proximity of the probe in previous designs (20 mm) enhancements on accuracy and working frequency range had been achieved using a robust mass-spring system attached to a small trapezoid frame. The effects of adding additional damping to the system have been studying, showing that although controls the vibrations at the resonance, it also decreases the isolation capabilities in the higher frequency range.

As a result, a new prototype of probe mounting had been design successfully, maximizing the accuracy of the particle velocity spectrum measured.

7. References

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