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Active Vibration Control Applied to Flat Panel Loudspeakers Using the HyVibe Pro

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Abstract: Inertial exciters can be used to transform surfaces into flat panel loudspeakers. Well-known for twenty years in several industries, this technology potentially revolutionizes the car audio industry by drastically reducing weight and volume of sound systems. However, several drawbacks make its implementation very challenging, especially if the used surfaces were not specifically designed for sound diffusion. For example, the eigenmodes of the radiating surfaces and their coupling with the exciter properties significantly affect the perceived sound quality. In this paper, we present the HyVibe Pro, a standalone device designed to enhance flat panel loudspeakers sound quality with embedded audio and active vibration control algorithms. The HyVibe Pro is made of a collocated electrodynamic actuator & accelerometer, and an embedded digital feedback controller. Its main feature is to excite the radiating surface at the full audio frequency range, while controlling the main eigenmodes of the coupled system. Its benefits are presented in terms of frequency and temporal responses on experimental applications.

Keywords: Inertial Exciter, Vibration Control, Flat Panel Loudspeaker

1. Introduction

Audio exciters are compact devices that attach to surfaces and vibrate them. It is a well-known technology that is used in numerous applications in both active vibration control [1] and audio [2]. When an exciter is combined with a panel to generate sound, they are called flat panel loudspeakers. Flat panel loudspeakers present many advantages. As they allow to use surfaces that already exist to generate sound, they are lighter and smaller than traditional sound systems and they can be integrated invisibly. Moreover, they have a more omni-directional response than traditional loudspeakers, especially at high frequencies [3].

Nevertheless, flat panel loudspeakers suffer from well-known issues that affect the sound quality. First of all, their acoustic frequency response highly depends on the surface that is used. More particularly, the eigenmodes of the radiating surface and their coupling with the exciter properties significantly affect the perceived sound quality. In some cases, the excited surface can be carefully designed for sound diffusion. However, when one wants to transform an already existing surface into a loudspeaker, one cannot choose the surface properties.

Another issue with flat panel loudspeakers is that the surface properties can change over time. For example, the Young's modulus of a plastic surface highly changes with temperature [4]. Besides, boundary conditions changes can occur. For instance, some weight can be added to the vibrating surface. These changes will affect the frequency response of the flat panel loudspeakers.

Inertial actuators used to excite surfaces are also a source of issues. One of their main limitations is that their stroke length is finite. When the input voltage is high, the proof-mass can exceed the stroke length and hit the end stops, thereby imparting large impulses to the structure [5], which can damage both the actuator and the structure and generate high audio distortion.

Like loudspeakers, exciters behave differently at small and high amplitude. At high amplitude, they generate signal components that do not exist in the input signal. The most common sources of non-linearity are described by Klippel [6]. Among others, the stiffness of the suspension generates a nonlinear restoring force and the force factor generates a non-linear driving force. These non-linearities can generate audible distortion.

We have presented the main problems that hinder the development of flat panel loudspeakers. In this paper, we propose solutions which combine audio and active vibration control research. A collocated feedback control is used to control the eigen modes of the excited surface and reduce the transducer non-linearities while streaming audio (technology protected by patent [7]). In order to tackle the variations of environment, an adaptive control module is proposed using system identification. Protection mechanisms are presented to avoid stroke saturation. The proposed solutions and additional features are all embedded into a standalone device: the HyVibe Pro.

2. The HyVibe Pro

The HyVibe Pro is presented Figure 1. It is a SISO (Single Input Single Output) module with an ultra-low latency of 22.5 µs. Digital signal processing is done by a microcontroller that contains a Floating-point unit with a clock speed of 400 MHz. The microcontroller embeds all required algorithms. It is connected to a collocated pair of actuator and MEMS accelerometer. It can be used with off-the-shelf actuators and sensors. For instance, Figure 1 shows an exciter from Dayton Audio and an accelerometer from Analog Devices. An audio signal can be sent to the HyVibe Pro via Bluetooth or an analog input. The platform is standalone.

Figure 1: A picture of the HyVibe Pro

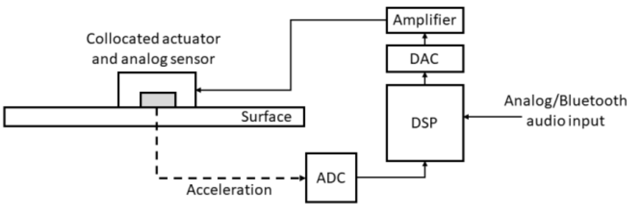

Figure 2: Diagram of the HyVibe Pro

The HyVibe Pro is described in Figure 2. The acceleration is measured by the accelerometer placed on the surface or a fixed frame part of the actuator. The analog acceleration signal is converted to the digital domain by a high-performance ADC. The digital acceleration signal is combined with the audio input and manipulated before being converted to an analog signal by a high-performance DAC. Then, the signal is amplified and sent as a power signal to the actuator. The HyVibe Pro parameters can be configured via Bluetooth Low Energy (BLE) or a user interface including a display.

3. Solutions to flat panel loudspeakers common issues with embedded algorithms

Several algorithms were implemented in order to face the common problems that were presented in the introduction.

3.1 Damping structural modes with collocated feedback control

Low audio frequencies of lightly damped surfaces are characterized by well-separated resonances. This results in a long impulse response time. A way to solve this problem is to add virtual damping to the vibration modes. One method is to perform modal control with a state-space model (for example [8]). Another method is to control the vibration of the surface with a feedback loop with a collocated pair of actuator and sensor. It can be achieved without any model of the structure. What's more, the collocation of a perfect dual pair of actuator and sensor guarantees stability [1]. In the HyVibe Pro, we use an inertial actuator and an accelerometer. As shown in Figure 3, a sensor signal and an audio signal are compared and a control signal is provided by the controller to the exciter.

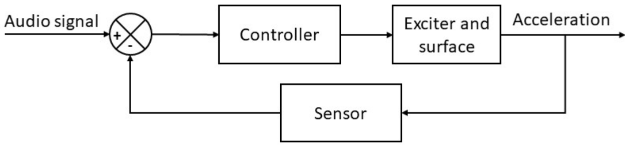

Figure 3: Feedback controller block diagram

Tuning a controller manually while guaranteeing efficiency and robustness can be a hard procedure. Therefore, we developed an automatic calibration procedure using an optimization with a genetic algorithm. The objective function is computed from the output sensitivity, which can be seen as the effect of the controller on the transfer function between the audio signal and the acceleration measurement [9]. Our procedure guarantees the maximum tradeoff between the performance of the active damping and the stability of the feedback loop.

The HyVibe Pro can be used to add virtual damping to any type of surface, such as wood, plastic, steel… In this section, we use a thin aluminum plate (Figure 4) to assess the performance of the control. Vibration and acoustic measurements were conducted in an anechoic chamber.

Figure 4: A collocated pair of actuator and sensor mounted on a thin clamped aluminum plate in an anechoic chamber. Dimensions: 28.5 cm * 43 cm * 1.5 mm

The effect of the controller can be described in both frequency and time domains. Figure 5 presents the transfer function from voltage to surface velocity with and without feedback. The effect of the feedback on the transfer function is represented by the output sensitivity function in Figure 6. First, we can study the damping from a qualitative point of view. Without feedback, we can see that the modes are lightly damped. Indeed, the amplitude peaks are narrow and the phase slope at the peaks frequencies is steep. When feedback is applied, the width of the resonance peaks increases and the phase slope at the peaks frequencies decreases, which means that the feedback loop adds virtual damping to the structure. The controller was designed to add more damping to the most important modes.

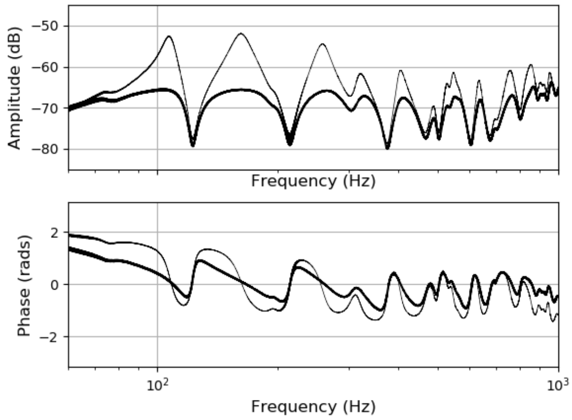

Figure 5: Experimental transfer function from voltage to surface velocity without feedback (thin line) and with feedback (solid line) on the aluminum plate

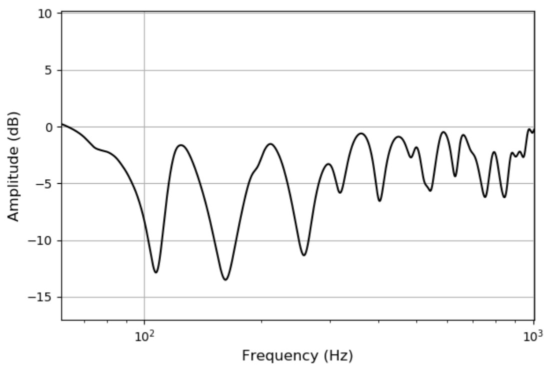

Figure 6: Output sensitivity

The addition of damping can also be studied from a quantitative point of view. We measured the damping ratios on the well separated modes at low frequencies with the half power bandwidth method [10]. The results are presented in Table 1. The control loop multiplies the damping ratio of the first five modes by a factor between 1.7 and 4.8.

The effect of the control can be studied in the time domain too. Figure 7 shows the surface velocity impulse response on the 0 Hz – 1 kHz bandwidth. We can see that the control reduces the decay time of the impulse response.

Frequency (Hz)	107	162	258	321	405
ζ_{OL} (%)	3.7	5.3	4.2	3.7	2.5
ζ_{CL} (%)	17.6	16.5	10.7	6.1	5.1
ζ_{CL} / ζ_{OL}	4.8	3.1	2.5	1.7	2.0

Table 1: ζ_{OL} represents the Open-Loop damping ratios, ζ_{CL} represents the Closed-Loop damping ratios, and ζ_{CL} / ζ_{OL} the multiplying effect of the control loop on the damping ratio**.**

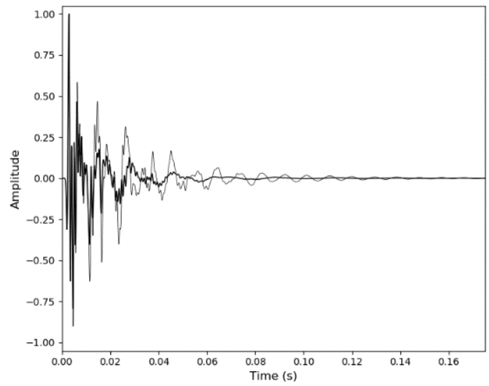

Figure 7: Experimental surface velocity impulse response on the 0 Hz – 1kHz bandwidth without feedback (thin line) and with feedback (solid line) on the aluminum plate

3.2 Facing environment variations with adaptive control

In the previous section, we have added virtual damping to a surface with constant properties. However, in real situations, the surface and exciter properties can evolve with time, making the controller less efficient. If the controller is not robust enough, it can even lead to instabilities. System variations can be faced while maintaining a high-performance level using adaptive control [9]. The HyVibe Pro provides an adaptive feedback module, which consists in an identification block and a controller whose parameters are updated depending on the identified system (Figure 8). The system identification is performed in real-time recursively by processing pairs of input-output measurements sequentially. Well-known identification models can be used such as OE, ARX, ARMAX, NARMAX [11].

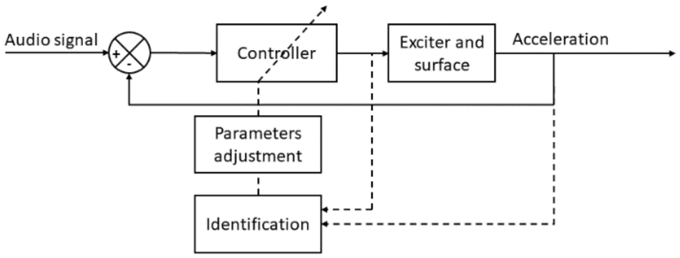

Figure 8: Adaptive feedback block diagram

We used the adaptive control module on a thin plastic plate while heating it. Before heating the plastic, in Figure 9, we can see that the real-time identified frequency response is almost identical to the initial measurement and that the control adds virtual damping to the structure. After that the plastic temperature has risen, we can see Figure 10 that the real-time identified frequency response is different from the initial measurement. The Young's modulus has decreased, therefore the modes frequencies have shifted to lower frequencies. The identification of the system changes allows to update the controller and keep the closed-loop system stable and efficient.

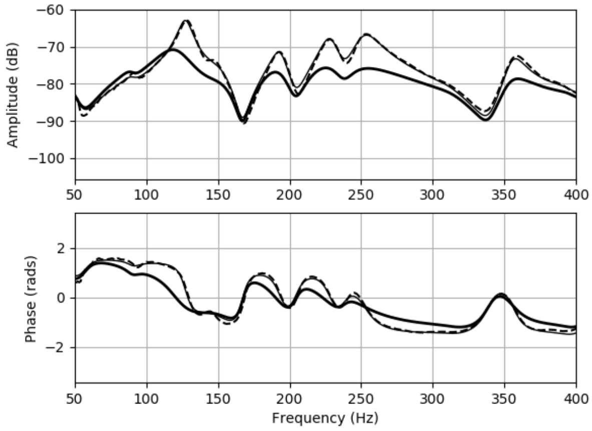

Figure 9: Experimental transfer functions from voltage to surface velocity: initial measurement (dashed line), online identification of the open loop (thin line), closed loop with adaptive control (solid line). The surface is a thin clamped plastic plate at room temperature. Size: 28.5 cm * 43 cm * 3 mm

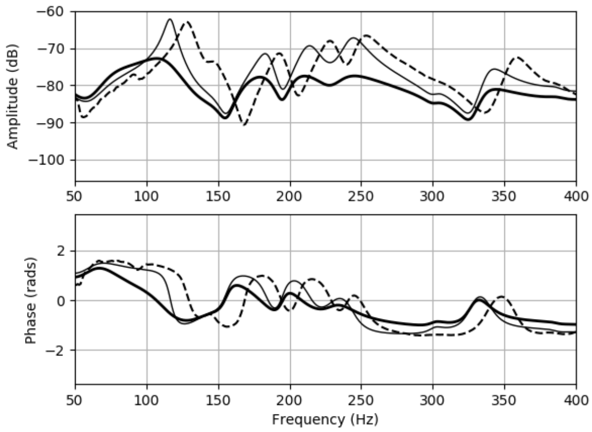

Figure 10: Experimental transfer functions from voltage to surface velocity: initial measurement at room temperature (dashed line), online identification of the open loop when the surface is heated (thin line), closed loop with adaptive control when the surface is heated (solid line).

3.3 Solutions to stroke saturation

Stroke saturation generates distortion and can damage flat panel loudspeakers. One approach to prevent this issue is to use a detection scheme [5]. In another approach, Klippel [12] presents a mechanical overload protection that can be used for loudspeakers but also for inertial exciters. The HyVibe Pro provides two solutions inspired by this approach to avoid stroke saturation. In both algorithms, the audio signal is sent to an excursion model that predicts when the excursion would exceed an excursion limit. The first module is a feedforward solution. As shown Figure 11, the parameters of an adaptive filter are updated in real-time depending on the predicted excursion. For example, the adaptive filter can be a high-pass filter with a varying cut-off frequency or a notch filter with a varying gain.

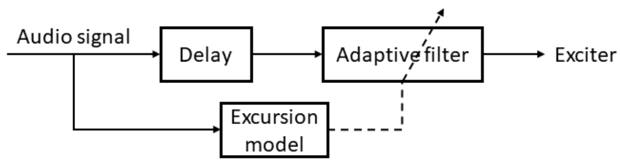

Figure 11: Feedforward protection mechanism block diagram

A simulation of the effect of an adaptive high-pass filter is presented in Figure 12.

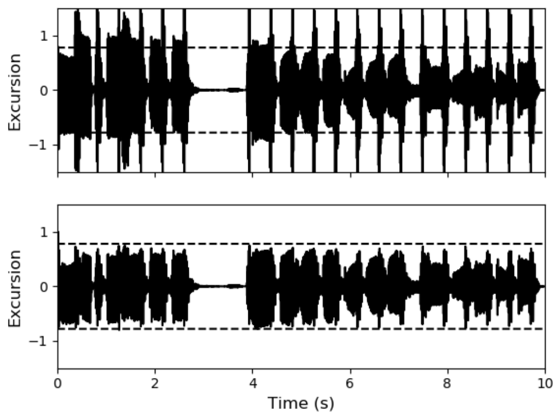

Figure 12: Predicted actuator excursion without (top) and with (bottom) the feedforward protection mechanism. The excursion limit is represented by the dashed line.

The second solution is a feedback control loop using a current sensor, which is illustrated in Figure 13. It is a virtual sensing approach that allows to monitor mechanical variables without a physical sensor. The current measurement combined with the voltage prediction allows to measure the back-EMF signal and use it to add virtual damping to the actuator itself. The amount of damping added to the actuator is computed from the excursion prediction. Adding virtual damping to the actuator allows to decrease the excursion when the actuator is excited near its resonance frequency. In Figure 14, virtual damping is added to an actuator on a car window. The excursion peak is reduced by 5.5 dB. It means that when an equal amplitude swept-sine is used as the input signal, the stroke saturation will occur for an input amplitude 5.5 dB greater with active damping than without active damping. Although this technique needs a calibration phase, there is no need to know the Thiele-Small parameters.

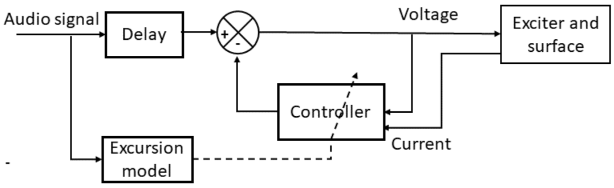

Figure 13: Feedback protection mechanism block diagram

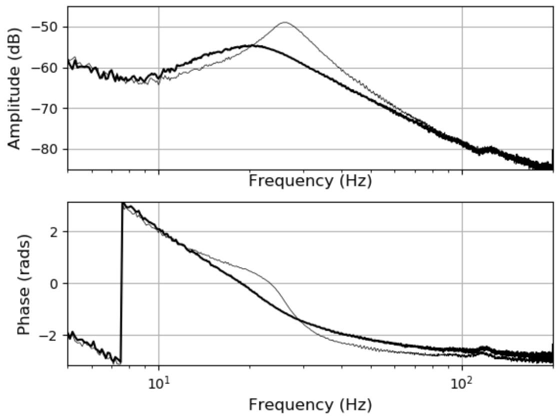

Figure 14: Transfer function from voltage to excursion without (thin line) and with (solid line) active damping of the actuator. The actuator is fixed on a car window.

In the case in which the exciter is highly coupled with the surface, the excursion frequency response can present several modes. Virtual damping will be added to each excursion mode.

3.4 Distortion reduction by feedback

Preventing stroke saturation from occurring removes a great source of distortion. However, many other sources can cause audio distortion. One way to reduce the detrimental effects of the non-linear behavior of the transducers is to use a state-space representation of the system and use a non-linear control law [13]. Another solution is to use motional feedback. It was first proposed by Philips [14] to reduce non-linear distortion in bass speakers. When an undesired harmonic is generated by the transducer, it is seen and rejected as a perturbation by the control loop. For example, Figure 15 presents a temporal simulation of a simple mass-spring non-linear system response to a sinusoidal input without and with motional feedback.

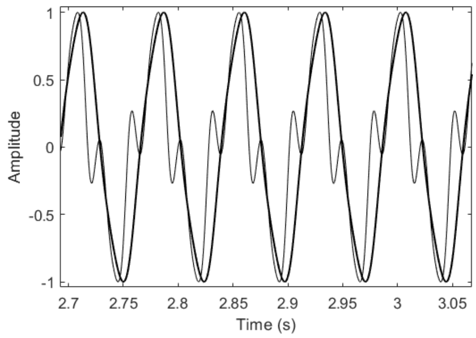

Figure 15: Response of a non-linear mass-spring system to a sinusoidal without (thin line) and with (solid line) feedback control

To be more specific, the effect of the control loop on the distortion can be predicted with the output sensitivity. With a sinusoidal excitation at 80 Hz, non-linearities will cause a second harmonic at 160 Hz. If the output sensitivity magnitude is -10 dB at 160 Hz, then the second harmonic magnitude will be reduced by 10 dB. The effect of the motional feedback has been assessed with acoustic measurements. Figure 16 presents the acoustic measurement of the Total Harmonic Distortion (THD) done in an anechoic chamber with the thin aluminum plate presented paragraph 3.1. The open loop system and the closed loop system were both equalized to the same target curve in order to remove the effect of the frequency response amplitude on the THD. The measurements show that the control loop reduces by 10% the THD from 70 Hz to 100 Hz and 3% the THD between 250 Hz and 300 Hz.

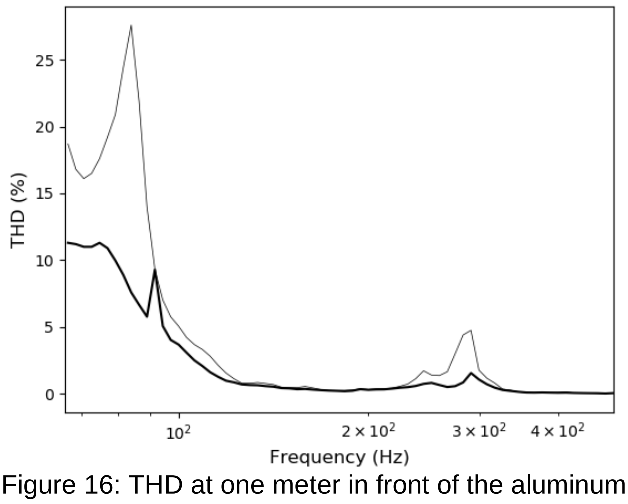

Figure 16: THD at one meter in front of the aluminum plate without (thin line) and with (bold line) feedback control

4. Additional modules

4.1 Speaker and Room Equalization

Adding virtual damping to surfaces enhances flat panel speaker vibrational behavior by flattening the vibration modes for audio applications. However, the perceived sound quality also depends on the radiation of the surface, the room influence, the listening point, and the listener preferences. For this reason, an equalization module is embedded in the HyVibe Pro.

Linear filtering can be applied in order to match a target frequency response. There are two main types of linear filters: Finite Impulse Response filters (FIR) and Infinite Impulse Response (IIR) filters. FIR filters are always stable and allow to correct the phase but they are computationally expensive especially if they are used to equalize low frequencies. What's more, they introduce latency. IIR filters are more computationally efficient but they can be numerically unstable [15]. The HyVibe Pro allows to use both IIR and FIR filters. Filters can be designed with numerous methods [16]. Depending on the use cases we use IIR parametric filters designed with a method inspired from [17] or FIR filters designed with the frequency sampling method [18].

The equalization is directly applied to the audio input signal. Figure 17 shows several examples of equalization performed on the acoustic frequency response of the aluminum plate (presented paragraph 3.1). We used different numbers of IIR peak filters to match a flat target response. For instance, with 30 peak filters, the standard deviation of amplitude is reduced from 5.7 dB to 0.4 dB. The equalization works best combined with active surface damping. Indeed, it is easier to obtain a flat response once the main surface modes have been flattened.

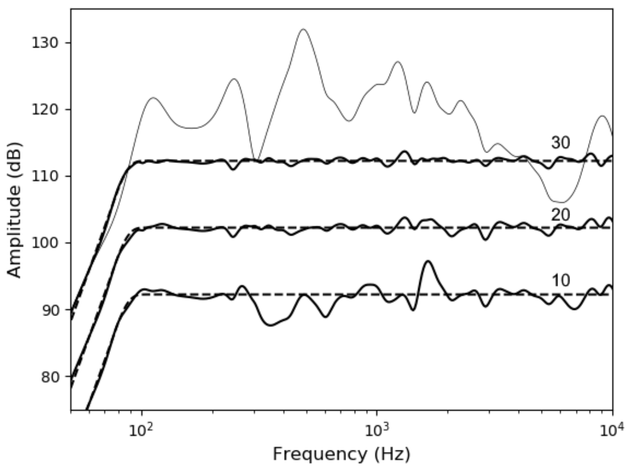

Figure 17: Acoustic frequency response (1/6 octave smoothing) of the aluminum plate without EQ (thin line), with EQ with 10, 20 or 30 peak filters (solid lines), target response (dashed lines). The responses are scaled by 10 dB to improve legibility.

4.2 Active Vibration Control

The HyVibe Pro can be used for active vibration control purposes. It is possible to implement any SISO active vibration algorithm using a pair of actuator and sensor. Classical feedback methods can be implemented, such as Integral Force Feedback (IFF), Positive Position Feedback (PPF) or Direct Velocity Feedback (DVF) [1]. Model based algorithms such as Linear Quadratic Control, H2 and H-infinite models can also be implemented.

4.3 Mobility measurement

The HyVibe Pro can be used to measure the mobility characteristics of a mechanical structure. This method presents several advantages compared to the use of an impact hammer. Indeed, the small size of the actuators allows to perform measurements on hard-to-access mechanical structures. Moreover, a single exciter can be used to perform measurements over the full frequency range, whereas several hammers and heads are usually necessary to obtain a full range spectrum. Figure 18 presents a comparison of a measurement done with an impact hammer and the HyVibe Pro. We can see that the surface mobility measurements are identical with the two methods.

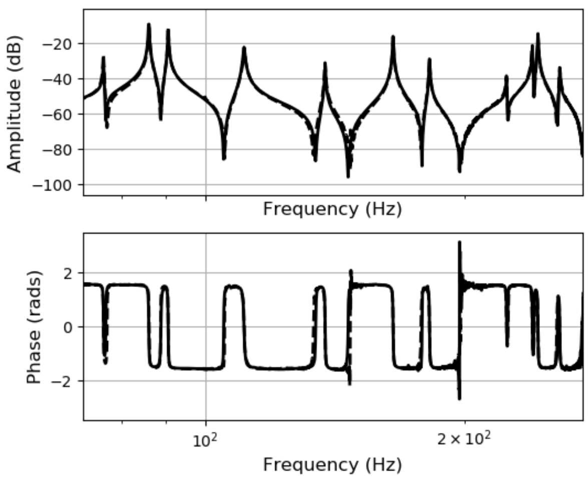

Figure 18: Mobility measurement with an impact hammer (solid line) and with an actuator (dashed line) on a thin glass plate in free boundary conditions. Dimensions: 80 cm * 50 cm * 3.81 mm

4.4 Driving and controlling loudspeakers

The HyVibe Pro can also be used to drive and control loudspeakers. For example, it is possible to put a sensor on the membrane and virtually change the stiffness, damping or mass via a feedback loop. It is also possible to use a current sensor and control a loudspeaker with the back-EMF.

5. Summary

In summary, the HyVibe Pro is a system made of a collocated pair of actuator and sensor and a microcontroller, whose embedded algorithms tackle the most common problems of flat panel loudspeakers. It has a feedback module that allows to damp the vibration modes of surfaces and reduce the audio distortion, an adaptive feedback module to deal with the variations of environment conditions, and protection mechanisms to avoid stroke saturation. Additionally, the HyVibe Pro can be used to drive and control loudspeakers, to perform active vibration control, to compensate the frequency response of a transducer and the listening room, and also to measure a surface mobility. All the features of the HyVibe Pro are summarized in Figure 19.

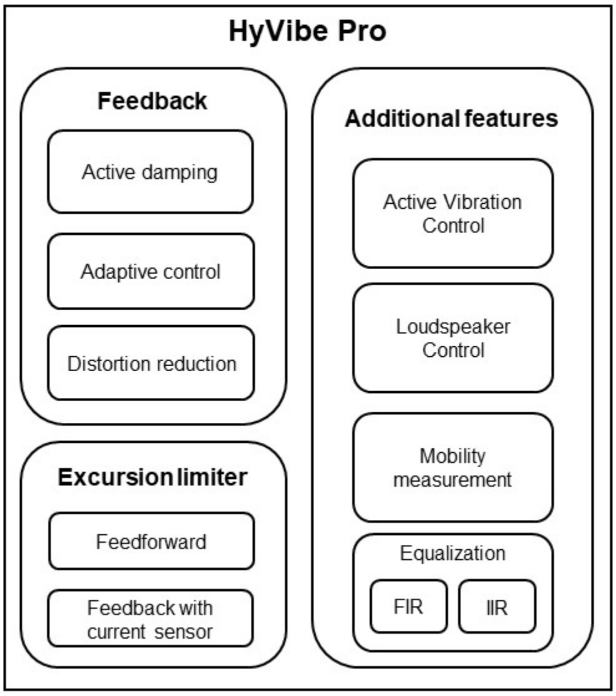

Figure 19: Block diagram summarizing the features of the HyVibe Pro

6. Conclusion

Flat panel loudspeakers present many advantages: they allow to integrate sound invisibly by using already-existing surfaces to diffuse sound, resulting in a gain of weight and space. Besides, they have a more omni-directional response than traditional loudspeakers. Yet, their use remains limited, due to the influence of the surface properties and the exciter limitations. In this paper, we presented the HyVibe Pro, a standalone device which combines active vibration control and audio solutions in order to deal with the most common issues of flat panel loudspeakers.

7. Acknowledgment

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9. Glossary

ADC: Analog to Digital Converter
ANC: Active Noise Control
AVC: Active Vibration Control
DAC: Digital to Analog Converter
DSP: Digital Signal Processor
EMF: ElectroMotive Force
FIR: Finite Impulse Response
IIR: Infinite Impulse Response
SISO: Single Input Single Output
THD: Total Harmonic Distortion