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DESIGN OF SWITCHING AMPLIFIER USED IN NEGATIVE IMPEDANCE DISPOSAL FOR THE ACTIVE CONTROL OF TRANSDUCER'S ACOUSTIC IMPEDANCE

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We present a concept of "active material" with variable acoustic properties, being constituted of an electroacoustic transducer which acoustic impedance can be changed by an active mean. Among the different ways to obtain variable acoustic properties on an electroacoustic transducer's voicing face is the shunting of the transducer's electrical input. With such shunt devices, the acoustic impedance that the transducer's membrane presents to the acoustic field comprises an acoustic equivalent of the electrical load that can take many values within a specified range. The shunt strategy can either be a passive, with a simple resistor for instance, or active, by way of a negative resistance circuit including at least one operational amplifier. The advantage of the active mean is that it should theoretically allow obtaining very high values of acoustic impedances, in other words to even obtain perfect isolating acoustic material. Though, the use of the operational amplifier presents many drawbacks such as operational instability, high sensitivity to adjustments, and inefficient electrical energy transfer in the electronic circuit. Moreover, when it comes to absorbing/reflecting very high sound pressure levels, these devices are pushed towards their functional limits. In order to counteract the aforementioned problems, a switching amplifier has been designed for the negative impedance disposal. The present work will describe the design of such a switching amplifier for enhanced stability and performances of the active material concept. Theoretical considerations will be compared to experimental (acoustical and electrical) assessments of a prototype, highlighting the main advantages and drawbacks of such disposals, and leading to concluding remarks on general behaviour and possible means of enhancements.

1. Introduction

An active material with variable acoustic properties is a loudspeaker system whose acoustic impedance can be modified by the simple addition of a variable electric load at its terminals, be it passive (simple resistance) or active (negative resistance for example). It is proven that an electric resistance of positive value can modify the value of acoustic impedance such as the loudspeaker system becomes an excellent absorber around its resonance frequency[1,2]. However, in order to allow a greater variability of the acoustic properties of the "material", it is essential to be able to impose "negative" values of impedance, and consequently to specify a device with suitable operational amplifiers. Some preliminary developments have been performed on electrodynamic loudspeakers loaded with negative resistance disposals based on linear operational amplifiers circuits, with interesting results in terms of acoustic impedance control[3]. Though, one of the main drawback that has been experienced with such loads is the fact that those electrical devices are known to be poorly efficient, and the requested electrical power to perform the control is prejudicial to the stability of the active material, and induced non desirable effects such as high non-linear distortion due to the high gains applied, heating of the electrical device and subsequent variation of the load impedance, especially in case of high sound pressure levels, etc. Moreover, linear amplifiers are known to be very sensitive to the variations of the electrical load, and this is the case of electroacoustic transducers for which electrical impedance is highly frequency-dependant. In order to ensure an efficient electrical control that does not affect much the acoustic impedance control, one have to design specific power amplifier, under the above-mentioned specifications.

Among the many possibilities of design, the Class-D amplifier presents certain advantages, particularly a great effectiveness in power, and a less sensitivity to the variations of the electric parameters of the loudspeaker system[3]. So, we were interested in investigating a Class-D amplifier for an active noise control application. This paper aims at presenting an experimental proof of concept which has been performed with an impedance tube assessment after ISO 10534-2 standard[4]. A comprehensive presentation of the technique will be provided, together with numerical simulation of the acoustic behaviour in standard configurations (impedance tube), and experimental assessments to highlight its performances.The acoustical and electrical performances of the prototype are presented hereafter so as to show the efficiency of the concept in laboratory conditions with broad band noise excitation.

2. Design considerations

2.1 Class-D amplifier as active shunt device

Physical realization of an active shunt utilises some kind of controlled energy source. In vast majority of the cases the controlled energy source is an electronic amplifier with specific control circuits. In the specific case of the negative impedance converter, it is the combination of power operational amplifier (either specialized one or combination of standalone operational and power-amplifier) and network of passive components representing the desired impedance. Commonly used power-amplifiers have their output stage biased in class-A or class-AB. Let us call them linear amplifiers to distinguish them from switching amplifiers. Linear amplifiers ensure very good linearity, minimum distortion and simplistic integration into the shunting system.

The main drawback of the linear amplifier is a poor efficiency except the special case of absolutely matched load, which is unusual in generic systems. This legitimates the use of a switching amplifier, namely the class-D. Due to inherently linear transfer function of its power stage, properly designed switching amplifier exhibits the same level of linearity and distortion as its linear counterpart. Although the integration of switching amplifier into the shunting system is not an easy task, it offers two great benefits over linear amplifier – energy efficiency and bidirectional energy flow.

Energy efficiency of the switching amplifier is given by operating in an “on/off” regime instead of throttling the energy flow from the power supply to the load. Efficiency of switching amplifier is almost two times higher than that of the linear one as it can be seen in Figure 1. It shows the dependence of the amplifier efficiency on the output level with nominal, purely resistive load. Nominal load means such a value impedance to which an amplifier is able to provide maximum power (with maximum amplifier’s output voltage the load consumes maximum allowed output current). The pure resistive load was selected for the clarity of the presentation. With reactive loads, linear amplifiers have even smaller efficiency than switching ones.

It is not usually emphasized but a possibility of bidirectional energy flow between load and a power supply within switching amplifier is a very important feature. Every time an output terminal of amplifier sees a negative power, the power is instantly transferred through supply rails to the smoothing capacitor. This feature is not useful only in systems where power is produced by load i.e.

power harvesting systems, but in all systems with reactive loads (capacitors, inductors, electromechanical systems with inertial masses etc.) where the energy is periodically stored and extracted from the load.

The following intends to summarize the differences between switching and linear amplifier (as for shunt device):

- higher efficiency. Power losses in amplifier are caused only by small voltage drop on full opened transistor working as switches and on parasitic resistivities in the trace of the output current. In most cases, the efficiency is more than twice the linear case, and the dissipated energy is less than one fifth the linear case,
- low dissipated heat and much smaller dimensions for high power systems,
- bidirectional energy flow between the load and the amplifier's supply. Linear amplifier does not allow energy flow from the load to the supply and converts it to heat,
- zero or very low crossover distortion without excessive quiescent input power. To achieve the low crossover distortion a class-AB linear amplifier must be biased with significant quiescent power,
- considerably cheaper for high power systems,
- possible Electromagnetic Compatibility and Electromagnetic Interference problems due to production of high frequency, high power waveform on its output.

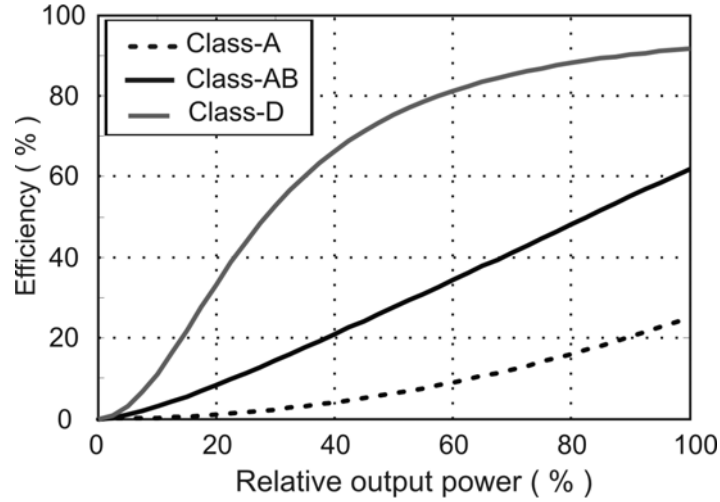

Figure 1: Typical energy-efficiency characteristics of different amplifier topologies with purely resistive load

2.2 Negative impedance shunt with Class-D amplifier

The realization of the negative impedance shunt $Z_0(\omega)$ using Voltage Negative Impedance Converter (VNIC) shown in Figure 2 with power operational amplifier is straightforward. Although the frequency characteristics of the reference (inverted) impedance $Z_R(\omega)$ combined with dynamic properties of operational amplifier $A_O(\omega)$ can lead to instabilities and difficulties with tuning of desired negative impedance, it is possible to quickly analyse effect of all components in the circuit. Impedance seen by the connected load $Z_L(\omega)$, in our case the speaker electrical impedance, can be expressed as follows:

$$Z_O(\omega) = -\frac{R_2}{R_1} Z_R(\omega), \text{ where } Z_R(\omega) = R_3 + j\omega L . \quad (1)$$

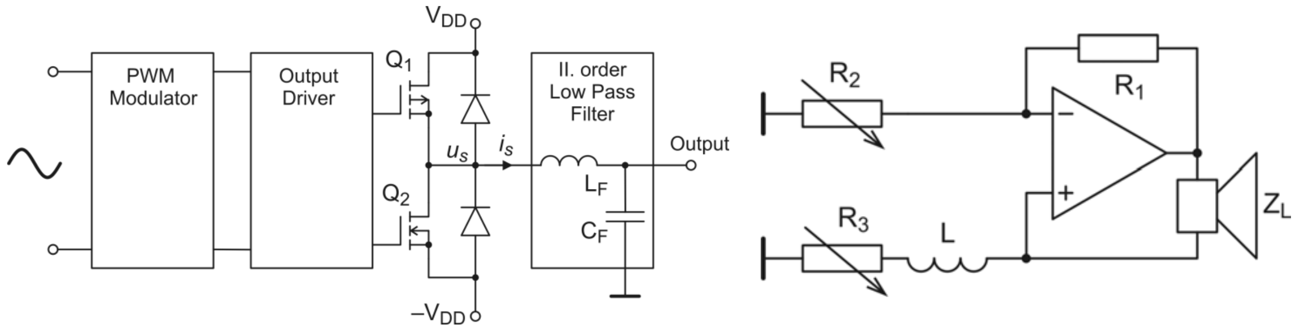

Figure 2: left: Class-D power amplifier scheme; right: Voltage Negative Impedance Converter scheme[5]

Our main objective, namely reaching the state of the maximum acoustic absorption or reflection, is achieved by adjusting the frequency dependence of the impedance $Z_O(\omega)$, which is controlled by the components of the circuit. For example: if the circuit is adjusted according to the condition $Z_O(\omega) = -Z_L(\omega)$, the speaker behaves almost like a infinitely rigid wall and is an ideal acoustic reflector. In reality, it is possible to achieve such a condition only in a narrow frequency range, as the electrical impedance $Z_L(\omega)$ of the speaker is a quite complicated function of frequency and it is not easy to achieve its matching with the impedance $Z_R(\omega)$. In the circuit, the inductance L is of a constant value, the resistance R_3 is used to mach the L/R ratio of the loudspeaker and the resistance R_2 controls the absolute value of the negative impedance.

Incorporating a switching amplifier into the VNIC circuit is not as easy as with a linear amplifier. The first problem is that there hardly exists class-D amplifiers behaving like an operational amplifier with inverting and non-inverting inputs. So the class-D amplifier works only as a power output of another OA. The second problem is that the PWM modulator stage inserts transport delays. Third problem is caused by the high amplitude of the switching signal component on the amplifier output. It can be reduced by the use of proper filter.

It was decided to realize the negative impedance shunt with class-D power stage, since it has a great advantage in universality. Schematic diagram of class-D OA integrated in a VNIC is displayed in Figure 3. Class-D amplifier from Figure 2 with output filter at 10 kHz is preceded by a differential amplifier. The gain of the differential amplifier was set very high to achieve the operational behavior. Subsequently, low pass filters were connected to the differential amplifier inputs.

The achieved effective impedance of the VNIC circuit with the class-D output stage (see Figure 3) can be expressed as:

$$Z_O = \frac{\left[A_U.P_1.P_3(1-D_1)-10\right]Z_L Z_R}{Z_L + Z_R + A_U.D_1.P_1.P_3.Z_L + A_U.P_1(D_1-1).Z_R.P_3}, \qquad (2)$$

where $D_1 = R_2/(R_1+R_2)$ is the constant of voltage divider, $P_k = 1/\left(1 + j2\zeta_k\omega/\omega_k - \omega^2/\omega_k^2\right)$ the 2nd order low pass filter transfer functions of the filters.

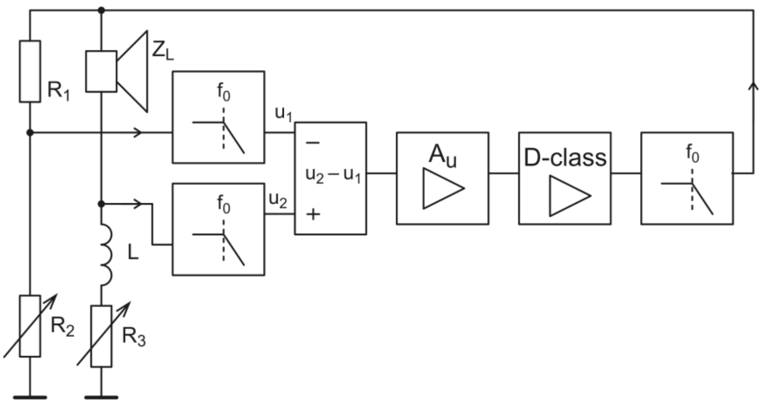

Figure 3: Negative shunt circuit used Class-D amplifier

3. Experimental assessments

3.1 Sound absorption coefficient

In order to assess the acoustic performances of the loudspeaker connected to the negative impedance circuit (VNIC), the experimental setup depicted in the Figure 4 has been used. The measurements were performed by using the two-microphone method according to the ISO 1534-2 standard. Due to the home-made impedance tube dimension and the microphones placement, the following experimental assessments will only address the [40 Hz-250 Hz] frequency bandwidth.

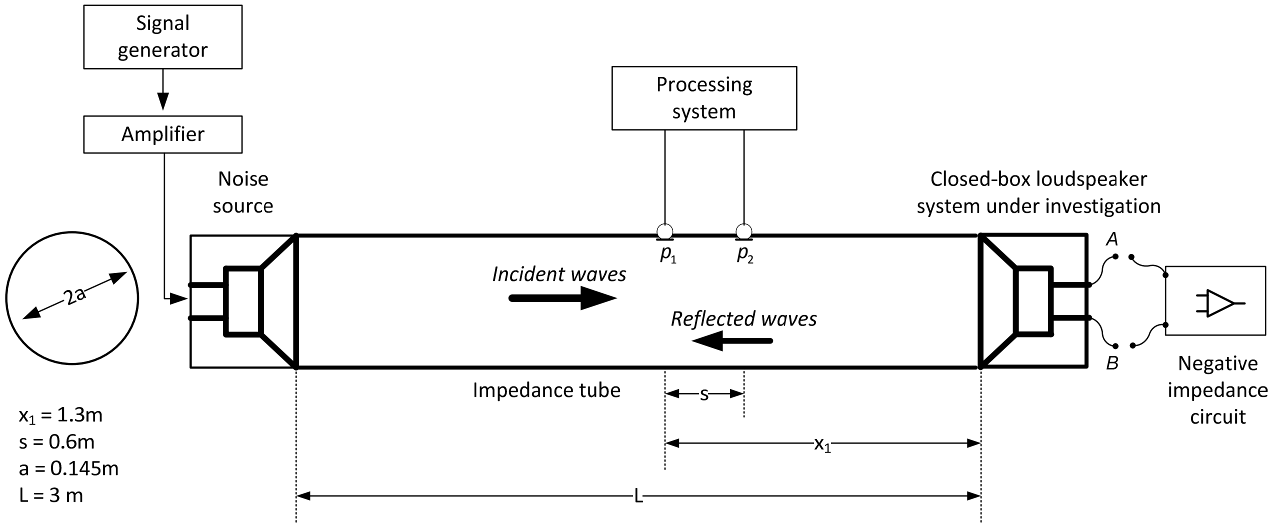

Figure 4: Sound absorption factor determination setup

The details of the experimental setup depicted in Figure 4 are listed hereafter:

- the source is a home-made closed-box loudspeaker system (Kenwood KFC-WPS1200F in a 35 dm3 closed-box), designed to provide the requested acoustic power in the requested frequency bandwidth,
- the excitation signal is a logarithm swept sine from 30 Hz to 300 Hz during 30 seconds,
- the active material under investigation is a closed-box loudspeaker (Monacor SPH-300 in a 50 dm3 closed-box),
- two Bruel & Kjaer Type 4165 electret microphone (sensitivity 50 mV/Pa) sense the acoustic pressure at the placement detailed in Figure 4,
- the home-made impedance tube measures 3m length with a 0.29 m diameter allowing acoustic assessments under plane wave assumption from 30Hz up to 700Hz.

3.2 Experimental results

By finely adjusting the components within the negative impedance circuit, some various stable operating points have been identified. We can then explore the effect on the transducer's acoustic impedance with the help of the setup depicted in Figure 4. The experimental results obtained with two different negative impedances are given in Figure 6, and compared to the same measurement with the loudspeaker in open circuit (Figure 5).

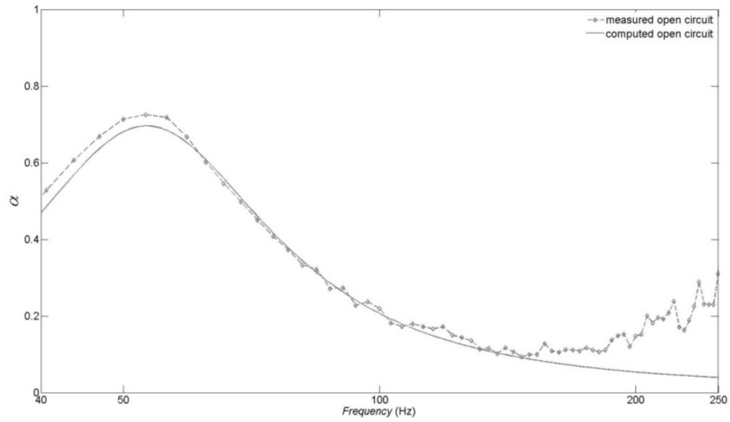

Figure 5: Measured and computed absorption coefficient of the closed-box loudspeaker in open circuit

In parallel, a measurement of the negative electric impedance loading the loudspeaker system is performed and the resulting frequency response is added to an analytical model as shunt impedance. Thus, we can compute the absorption coefficient of the shunt loudspeaker with or without VNIC (solid lines in Figure 5 and Figure 6) and compare it to the measured absorption coefficient (dot lines).

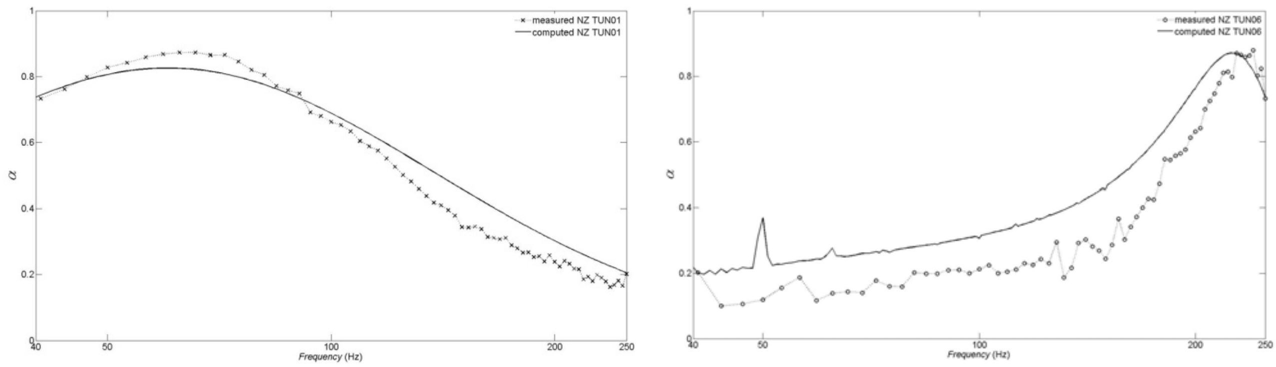

Figure 6: Measured and computed absorption coefficient of the closed-box loudspeaker with various desired negative impedances

3.3 Observations

Compared to the loudspeaker system in open circuit where no VNIC is shunting the loudspeaker system, we observe that the measured absorption factor is enhanced when adding a negative impedance circuit with desired electric impedance value. As long as the absolute value of the shunt negative impedance does not exceed the voice coil electric impedance, the VNIC makes possible to enlarge the frequency bandwidth where the loudspeaker system is efficient to absorb sound energy. When the shunt negative impedance becomes close in absolute value to the voice coil electric impedance, a shift of the efficient area toward a higher frequency band can be observed (Figure 6, left).

4. Conclusions

It has been proven that shunt loudspeakers with a negative impedance circuit based on class-D power amplifier is an efficient technique for providing enhanced acoustic absorption in the low-frequency range, and allowing a rather broad variability. An experimental proof of concept has been performed with an Impedance Tube assessment, after ISO 10534-2 standard. Further experimental validations should be performed to analyze more in-depth the gain margins allowed by this amplifying technique, the criteria of stability, and the issues related to non-linear distortion for example.

REFERENCES

[1] H. Lissek, F. Sandoz, From the electrical shunting of a loudspeaker to active impedance control, *Proc. of Acoustics 08*, 2008, Paris.
[2] A.J. Fleming et al., Control of resonant acoustic sound fields by electrical shunting of a loudspeaker. 2007, *IEEE Transactions on Control Systems Technology*, p. 689-703.
[3] H. Lissek, *Les Matériaux Acoustiques Actifs à Propriétés Acoustiques Variables*, PhD thesis, Université du Maine, Le Mans, 2002.
[4] ISO-10534-2:1998, *Acoustique - Détermination du facteur d'absorption acoustique et de l'impédance des tubes d'impédance - Partie 2: Méthode de la fonction de transfert*, International Organization for Standardization, 1998.
[5] M.S. Ghausi, *Electronic circuits*, Van Nostrad Reinhold Company New York 1971.
[6] Maxim Application Note 3977, *Class D Amplifiers: Fundamentals of Operation and Recent Developments*, http://pdfserv.maxim-ic.com/en/an/AN3977.pdf.