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# Shunt loudspeaker technique for use as acoustic liner

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## ABSTRACT

In this paper, the underlying concept of acoustic liner is an electroacoustic transducer which acoustic impedance can be changed by electrical means, be it passive or active. 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 takes account of an acoustic equivalent of the electrical load that can take many values within a specified range. Shunt strategies can either be passive, with a resistor, or active, with a negative resistance circuit including at least one operational amplifier, or with more complex impedance control systems. These active strategies allow variable acoustic impedances at the transducer’s voicing face, assuming linearity of the systems.

This presentation aims at giving an overview of the shunt loudspeaker techniques for use as liners in an aircraft engine nacelle, and discuss on possible means of enhancement.

## 1. INTRODUCTION

Despite the continuous efforts in developing engine technologies with low fuel consumption, carbon emission and noise pollution, there still remain numerous challenges to overcome before the European Air Transport industry can reach the ambitious ACARE environmental objectives for 2020[b]. In this frame, the European aeronautics industry has implemented, in the last decades, several ambitious research programs. These programs have allowed achieving “Generation 1” engine noise reduction technologies, demonstrating the capability to achieve the 5dB first-step reduction set for 2010, assuming simultaneous progress in the area of noise abatement operational procedures. In the frame of these projects, research activities were conducted in various fields, among which Active Noise Control Developments[1,2], and leading to successfully assessed prototypes. As a result, many of these assessed technologies are now advanced enough

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[b] http://www.acare4europe.org/docs/Vision%202020.pdf

for further integration work, aimed at addressing some identified trade-offs issues, such as performance improvement and weight reduction.

In the following research projects, the ACARE objective of noise reduction will then be coupled with the necessity to be emissions neutral, and will account potential performance and weight penalties that might be induced by the implementation of novel noise reduction concepts. In this new integrated approach, the active/adaptive technologies developers of the further programs have two main and complementary criteria to fulfill in the achievement of their “Technology Readiness Level”, one on the acoustic performances, the other on the powerplant integration of these technologies (mechanical, aerodynamic and electronics).

In this frame, a novel concept of “shunt loudspeaker” technique has been retained in FP7-OPENAIR, after preliminary validation at laboratory scale[3], within a frequency bandwidth outside the scope of the specific aeronautic industry. This concept sounds appealing for the aircraft industry since it doesn’t need a priori power supply as opposed to usual active noise control techniques, thus leading to a lowering of equipment weight. This concept has also been proven to be effective for reducing modal behavior of closed spaces. The described technique has also a high integration potential, with the help of MEMS-based electrodynamic transducers. This paper will present the underlying concept of shunt loudspeaker, together with simulation and experimental results. The integration potential will be highlighted with the help of a concepts of lightweight flat transducer, namely the isodynamic loudspeaker, that has a high interest in terms of integration.

## 2. THE SHUNT LOUDSPEAKER TECHNIQUE

### A. Description

Let us consider an electroacoustic transducer which, for simplicity, will be assumed to rely on an electrodynamic conversion, such as a moving voice-coil loudspeaker. Even if this represents a particular case of electroacoustic transducer, the following description will not restrict to this kind of loudspeaker, and similar results can also be computed with other types of transducers.

By nature, the electroacoustic transducer’s voicing face (ie. the vibrating part that radiates sound), of surface $S_d$ is a mechanical resonator, be it a rigid mass $m_s$ suspended to the ground by an elastic suspension of mechanical compliance and resistance $C_{ms}$ and $R_{ms}$ (such as cone loudspeakers), or an elastic diaphragm that presents similar mechanical resonator properties, thus modeled with similar mechanical components. Moreover, the vibrating membrane which is coupled to the air, exhibits certain radiation properties depending on the mounting condition (single face or double faces in free field, one face eventually loaded by a cavity of known dimensions, etc…), that can be generally represented by an additional mechanical resistance $R_{mr}$, an additional mass $m_r$, and an additional mechanical compliance $C_{mr}$. In the case of a circular loudspeaker of radius $a$, which rear side is enclosed in a volume $V_r$, that can be seen at its front side as an infinite baffle in free-field conditions, these parameters take the following values[4]:

$$\begin{cases} R_{mr} \approx \dfrac{\rho c S_d}{2}(ka)^2 \\ m_r \approx \dfrac{8}{3}\rho a^3 \\ C_{mr} = \dfrac{V_r}{\rho c^2 (\pi a^2)^2} \end{cases} \Rightarrow \begin{cases} R_{ms} \to R'_{ms} = R_{ms} + R_{mr} \\ m_s \to m'_s = m_s + m_r \\ C_{ms} \to C'_{ms} = \dfrac{C_{ms}.C_{mr}}{C_{ms} + C_{mr}} \end{cases} \qquad (1)$$

where $\rho$ and $c$ are the density of air and the sound celerity in the air, $k$ being the wave number.

From Newton's law of motion, the mechanical dynamics of the loudspeaker assuming piston-like vibrations, can be modeled by a second-order differential equation, given as

$$\left(m'_{\mathrm{s}}\right)\ddot{x}(t)+\frac{1}{C'_{\mathrm{ms}}}x(t)+\left(R'_{ms}\right)\dot{x}(t)=\left(Bl\right)i(t)-S_d\,p(t) \tag{2}$$

where $\left(Bl\right)$ is the force factor, $x(t)$ the diaphragm position, $i(t)$ the driving current, and $p(t)$ the exogenous pressure disturbance acting on the loudspeaker diaphragm. The electrical dynamics can also be modeled by a first order differential equation after meshes law, given as

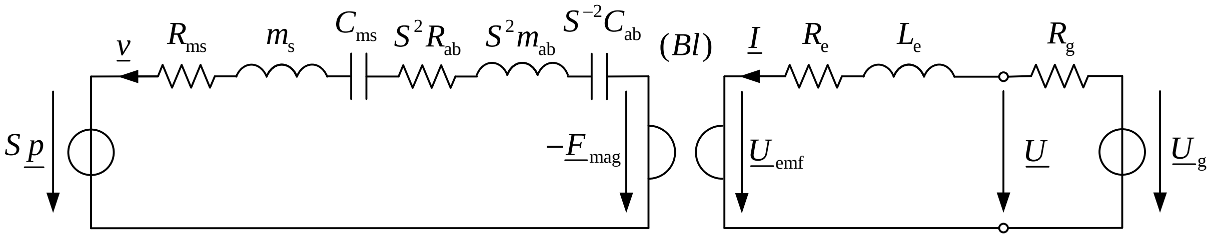
$$u(t)=R_{\mathrm{e}}i(t)+L_{\mathrm{e}}\frac{di(t)}{dt}+\left(Bl\right)\dot{x}(t) \tag{3}$$

where $u(t)$ is the applied voltage, $R_{\mathrm{e}}$ and $L_{\mathrm{e}}$ the DC resistance and the inductance of the voice coil, and $\left(Bl\right)\dot{x}(t)$ the back electromotive force induced by the motion of the voice coil within the magnetic field. Equations (2) and (3) form a coupled set of differential equations describing the electrodynamic loudspeaker system. Expressing the preceding relationships with complex quantities yields the characteristic equations of the generalized electrodynamic loudspeaker, given as

$$\begin{cases} S_d\,\underline{p}=\left(j\omega m'_{\mathrm{s}}+R'_{\mathrm{ms}}+1/j\omega C'_{\mathrm{ms}}\right)\underline{v}-\left(Bl\right)\underline{I}=\underline{Z}'_{ms}\,\underline{v}-\left(Bl\right)\underline{I} \\ \underline{U}=\left(R_{\mathrm{e}}+j\omega L_{\mathrm{e}}\right)\underline{I}+\left(Bl\right)\underline{v}=\underline{Z}_e\underline{I}+\left(Bl\right)\underline{v} \end{cases} \tag{4}$$

where $v=\dot{x}$ is the diaphragm velocity (in piston mode).

Under driving operation, $S_d\,\underline{p}=0$ and no external force is applied to the mechanical system; under generating operation $\underline{U}=0$: there is no voltage source at the electric terminals of the loudspeaker. For simulating the dynamics of a loudspeaker, in the case where the wavelength is greater than the transducer's dimensions, it is common to use electroacoustic analogies[4]. By taking account of the radiation impedance, we obtain the analytical description of the loudspeaker system, be it mechanical or acoustical, in the form of a synthetic circuit illustrated on the figure below.



$$\underline{F}_{\mathrm{mag}}=(Bl)\underline{I}$$
$$\underline{U}_{\mathrm{emf}}=(Bl)\underline{v}$$

**Figure 1**: Circuit representation of generalized closed-box loudspeaker system

where $\underline{U}_{\mathrm{g}}$ and $R_{\mathrm{g}}$ are the voltage source and internal resistance of the audio amplifier, representing the electrical source of the loudspeaker.

Starting from this circuit representation, if we remove the electrical source and replace it by certain shunt impedance $\underline{Z}_{\mathrm{sh}}$, the driving current in the coil, when an electromotive force voltage exists, becomes equal to $\underline{I}=-\underline{U}_{\mathrm{emf}}/\left(\underline{Z}_{\mathrm{e}}+\underline{Z}_{\mathrm{sh}}\right)$ where $\underline{Z}_{\mathrm{e}}$ is the blocked electrical impedance of the coil ($\underline{v}=0$).

If an external acoustic pressure (excitation) impinges on the loudspeaker diaphragm, then an electromotive force voltage $\underline{U}_{emf}$ is created at the loudspeaker diaphragm, and consecutively an electrical current appears in the coil due to the shunt, creating a reaction force that varies the vibratory reaction of the loudspeaker diaphragm. Stating that, it is obvious that the shunt induces specific acoustic impedance, thus absorption. The following aims at quantifying that effect.

After the preceding description, and solving the equation system (4), the loudspeaker diaphragm exhibits certain equivalent acoustic impedance, accounting the mechanical impedance, the radiation impedance, and the electrical shunt, after the following:

$$\underline{Z}_{sl} = \frac{\underline{p}}{\underline{v}} = \underbrace{\frac{\underline{Z}'_{ms}}{S_d}}_{\substack{\text{natural}\\ \text{acoustic impedance}}} + \underbrace{\frac{(Bl)^2}{S_d\left(\underline{Z}_e + \underline{Z}_{sh}\right)}}_{\substack{\text{shunt}\\ \text{acoustic impedance}}} \tag{5}$$

For simplicity, the shunt will be considered as purely resistive: $\underline{Z}_{sh}=R_{sh}$, and the transducer's electrical impedance will be assumed as purely resistive $\underline{Z}_e=R_e$ on the frequency range of interest and especially around the resonance frequency $f_s$ of the mechanical resonator. Then the preceding result can be expressed in terms of normalized acoustic admittance, exhibiting the resonant behavior of the shunt loudspeaker, and especially the quality factor $Q$ of the acoustical absorber at resonance frequency $f_s$:

$$\underline{y} = \frac{\rho c}{\underline{Z}_s} = \frac{\rho c S_d}{\underline{Z}'_{ms} + \dfrac{(Bl)^2}{\left(R_e + R_{sh}\right)}} = \frac{y_0}{Q} . \frac{\left(j\omega/\omega_s\right)}{\left(j\omega/\omega_s\right)^2 + Q^{-1}\left(j\omega/\omega_s\right) + 1}$$

$$\text{where } \begin{cases} y_0 = \dfrac{\rho c S_d}{R'_{ms} + \dfrac{(Bl)^2}{R_e + R_{sh}}} \\ \omega_s = 2\pi f_s = \left(m'_s C'_{ms}\right)^{-1/2} \\ Q = \dfrac{\omega_s m'_s}{R'_{ms} + \dfrac{(Bl)^2}{R_e + R_{sh}}} \end{cases} \tag{6}$$

The values of impedance that the loudspeaker diaphragm exhibits to the acoustic field can then take different values in a specific range, depending on the mechanical impedance of the loudspeaker, the force factor, and the DC resistance of the coil. At the diaphragm's resonance, the value is $y_0$. One target value can then be $y$=1 at resonance frequency, then the shunt resistance should be chosen such as:

$$R_{sh} = \frac{(Bl)^2}{\rho c S_d - R'_{ms}} - R_e \tag{7}$$

## B. Numerical simulations

The figures below illustrate the effect of shunting the loudspeaker in the case of the closed-box loudspeaker (continuous line curves). The chosen transducer is a Monacor SPH-300TC bass loudspeaker[c], in a 50 dm$^3$ closed-box, in free field conditions. The results are expressed in terms of acoustic impedance (left chart), and absorption coefficient (right chart). These results give the evidence of the performances of the shunt loudspeaker technique for use as locally reacting noise absorbers around its resonance frequency, for example in the scope of damping low-frequency modal behavior in a room (typically below 100 Hz).

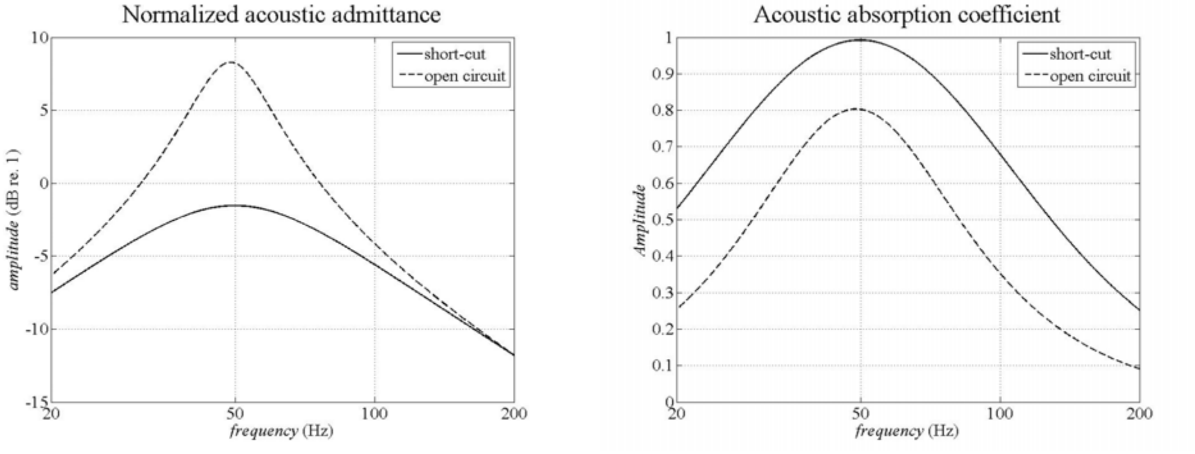


**Figure 2:** computed normalized acoustic impedance (left) and absorption coefficient (right) of the shunt loudspeaker system, for two different settings (no load and shortcut)

## C. Experimental assessement

The preceding results have been assessed experimentally with the following setup: the abovementioned loudspeaker, considered as an absorptive material, has been put at the end of a custom-made impedance tube of diameter 300 mm, and the normal incidence acoustic impedance has been measured with a two-microphone techniques after ISO 10534-2 standard. Figure 3 illustrates the results of the electroacoustic absorber behavior under normal incidence, obtained with the Monacor SPH300-TC, in terms of normalized acoustic admittance and acoustic absorption factor, for the two electrical loads that have been considered in the preceding section (open circuit and shortcut).

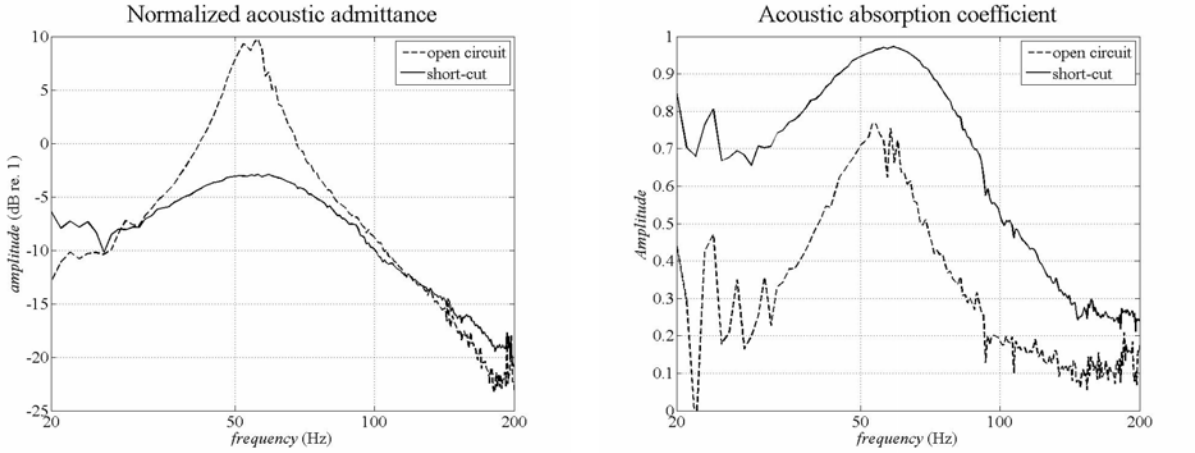


**Figure 3:** measured normalized acoustic impedance (left) and absorption coefficient (right) of the shunt loudspeaker system, for two different settings (no load and shortcut)

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[c] http://www.hautparleur.fr/_audax/ht210f0b.jpg

### D. General observations on shunt loudspeakers

A basic analytical description of the loudspeaker in the frequency domain is sufficient to model its dynamics, and hence to predict acoustic performance. By conducting a short sensitivity analysis on the loudspeaker parameters it is shown that it is possible to tune the resonance toward a desired value. Then, by connecting suitable shunt impedance, the quality factor can be enhanced to provide an improved absorption[5]. The frequency band of interest is obviously centered on the "natural" resonance frequency of the loudspeaker system, and the bandwidth is determined by the quality factor obtained by shunting. The electrical shunt directly impacts the performances in terms of frequency bandwidth, as well as the targeted acoustic impedance thus acoustic absorption value.

Experimental assessments shows high accuracy of the numerical model, and then further developments aiming at lowering the size and/or augmenting the center frequency and the frequency bandwidth of the shunt loudspeaker are proven to be obviously predictable by simple scaling of the electroacoustic parameters of the loudspeaker.

## 3. IMPROVEMENTS REQUIRED FOR ACTIVE LINER APPLICATIONS

### A. General specifications for active liners

As mentioned earlier, the weight constraint for the implementation of active/adaptive control concept for the aircraft industry is a driving one for further active concept developments in this area. This involves the developments of, at least, integrated electroacoustic transducers, thus inducing trade-offs on the performance side. This also make semi-active techniques, such as shunt loudspeakers, extremely interesting since it does not imply any heavy on-board electronics, or high power amplifiers required by any active noise control concept.

Though, the shunt loudspeaker technique has been exclusively assessed in the frame of very low-frequency noises, for instance modal acoustics in rooms, typically below 100 Hz. But, since the frequency band specifications for shunt loudspeakers (based on electrodynamic transduction), are linked to the diaphragm's resonance frequency, it is necessary to design the loudspeaker such as its resonance occurs in a higher frequency range. This has been proven to be a quite simple task to perform by using thin stretched polyimide diaphragms, of quite low mass density (around 1000 kg/m$^3$), which can be tuned in the high frequency range by applying specific tension. The following aims at legitimating the developments of a MEMS-based isodynamic loudspeaker, which should allow reaching the specifications of integrated shunt loudspeakers for use as engine liner.

### B. The integrated shunt loudspeaker concept

In order to attain the targeted frequency bandwidth, along the same underlying principle of shunt loudspeaker, it has been proven that isodynamic transducers can provide an effective alternative to the conventional cone speaker[6]. These devices use electrodynamic transduction and offer the advantage of low moving mass (because the membrane is a flexible thin film). This type of transducer is shown in Figure 4.

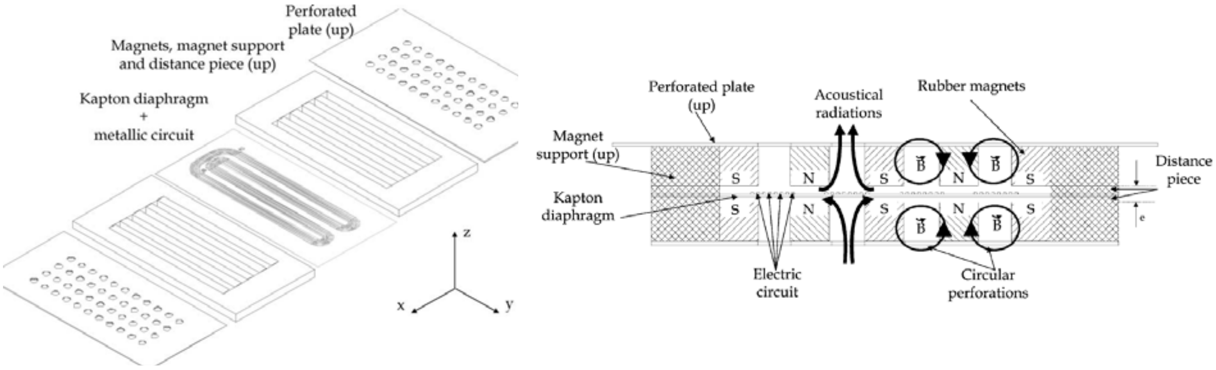

**Figure 4:** isodynamic transducer principle (left: split view: right: transversal cut-view)

Another advantage of the isodynamic transducer is that its topology is well suited for low cost manufacturing using rubber magnets, and has a high integration potential, even within curved surface. With such magnets, inductions in the order of 0.3 T can be achieved along the electrical conductors. The stressed membrane can be made of kapton film, with deposited aluminium or copper tracks. The overall thickness of such transducers only depend on the magnet dimensions, namely a few centimeters. This is another argument in favour of such transducer for overcoming integration issues.

**Figure 5** presents some simulation results obtained on an isodynamic transducer (dimension 17,5cm x 8,5cm), which parameters have been formerly computed and experimentally assessed in a former publication[6].

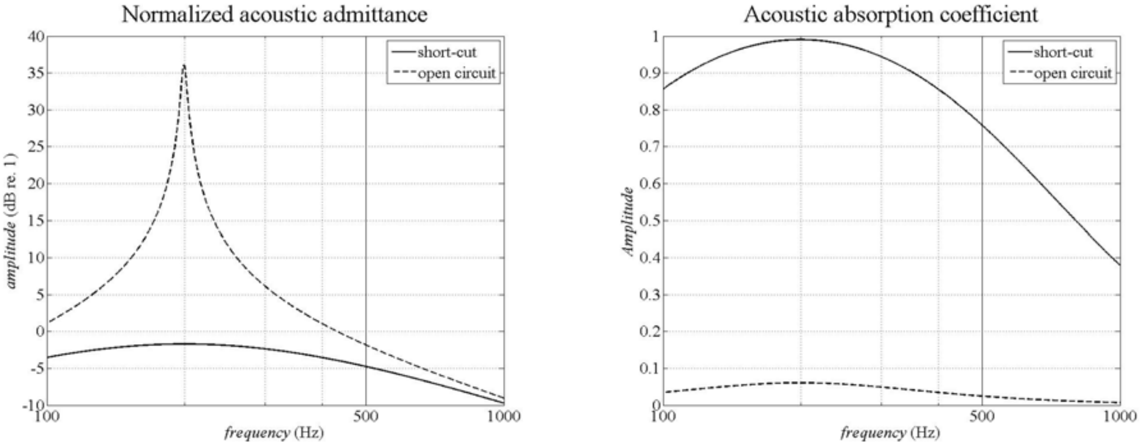

**Figure 5:** computed normalized acoustic impedance (left) and absorption coefficient (right) of the shunt isodynamic loudspeaker system, for different settings

This preliminary result shows that an isodynamic loudspeaker of relatively wide dimensions exhibits interesting results in terms of acoustic impedance control, and that some improvement can be achieved by reducing its size. Up to now, the miniaturization of such concept has not been achieved. This development work is actually ongoing and first simulation results are expected very soon.

## 4. CONCLUSIONS: FURTHER DEVELOPMENTS

The above-mentioned results indicate that the isodynamic transducer principle complies with the shunt loudspeaker technique specifications, especially in the frame of integrated wall-mounted acoustic liners for aircraft nacelles. Though it is still important to reduce the size in order to ensure higher frequency tuning of the membrane resonance, thus allowing the setting of the acoustic impedance within the targeted bandwidth. Work is actually ongoing to give a formal proof of concept of the MEMS-based isodynamic shunt loudspeaker, and to have a better insight of the corresponding limitations and ways of improvement.

## ACKNOWLEDGMENTS

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