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ABSTRACT

Compressors driven by inverters will produce high frequency noise, which will have adverse influence on total noise level. An existing compact inverter rotary compressor is studied in this paper and the effect of inverter carrier waves with Space Vector Pulse Width Modulation(SVPWM) technique on motor vibration and noise is analyzed and summarized. From order analysis and motor modal analysis, the results show that the high order harmonic current induced by inverter carrier wave will produce high frequency electromagnetic force, which will excite the stator into resonance, and finally leads to high frequency noise. The high frequency noise level is reduced by more than 5dBA after structural optimization of the motor.

1. INTRODUCTION

Inverter rotary compressors are popular in modern home air conditionings due to their advantages as high energy efficiency and improved performance for comfort, which makes noise level one of the main feature while evaluating a AC system. Common noise sources include mechanical noise, air flow and electromagnetic noise, among them the electromagnetic noise comes from the interaction between air gap magnetic field and electromagnetic force of the motor. In a motor, electromagnetic force could be dispersed into tangential and radial directions, while the tangential component produces torque to support the rotation and the radial component will force the rotor into deformation then produces vibration and noise. An inverter rotary compressor is powered by inverters with non-sinusoidal wave electricity and a large amount of high frequency harmonics will be caused due to the inverted output of three phase AC power. As a matter of fact, high order harmonic current and phase voltage inside of the stator will cause rapid changing electromagnetic force and finally produce high frequency noise, it is worth noticing that when the frequency of radial electromagnetic force matches the natural frequencies of the motor, the noise will increase enormously.

The figure below shows the noise distribution of a compact inverter rotary compressor prototype, it could be seen that the peak in noise frequency rests in 4k~5k Hz, leads to a pretty sharp noise.

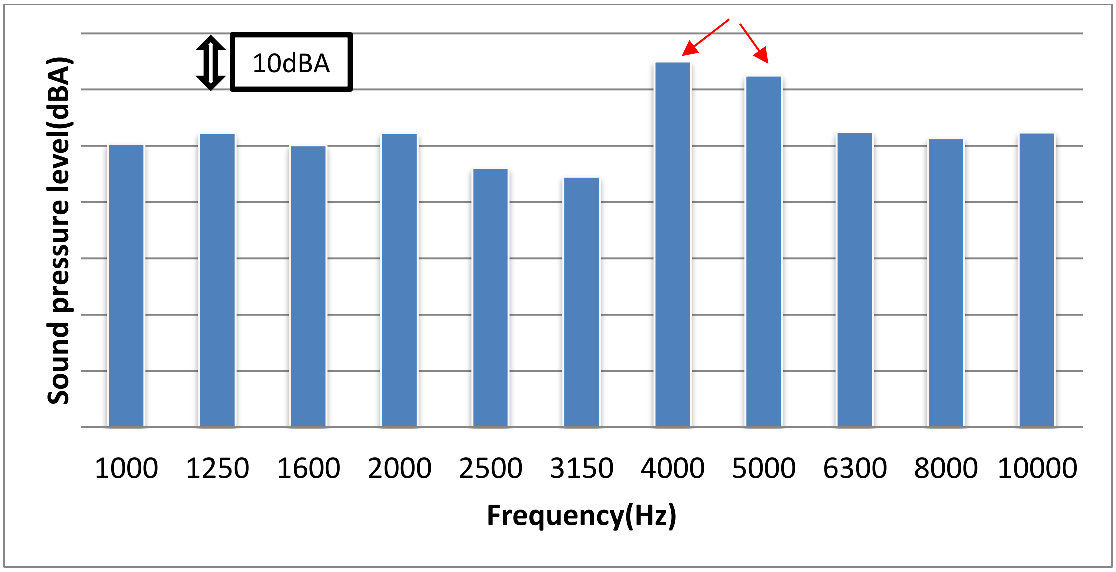

Figure 1: Noise spectrum of an inverter rotary compressor

2. LOCATING AND ANALYSIS OF NOISE SOURCE

2.1 Locating

Sound source localization is the task of locating a sound source given measurements of the sound field. The sound field can be described using physical quantities like sound pressure and particle velocity. By measuring these properties it is possible to obtain a source direction. Figure 2 shows a noise scan of a compressor via Microflow Scan&Paint sound source localization system in a semi anechoic room, the deeper the red color, the higher the sound amplitude. The sound pressure diagram indicates that the 4k~5k Hz peak arises near the motor, which could conclude the noise is radiated and diffused into ambient environment from the motor.

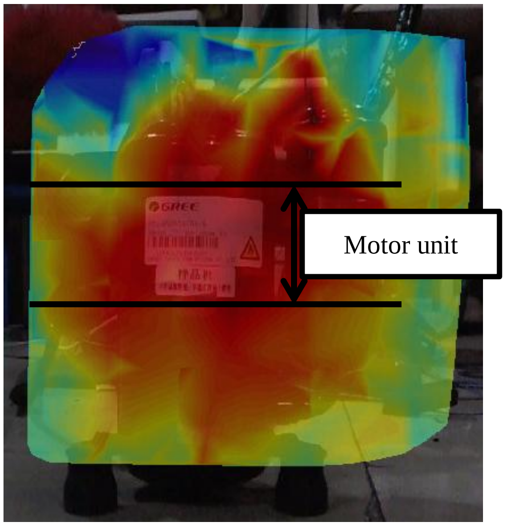

Figure 2: Sound pressure diagram of 4k~5k of the compresser

2.2 Analysis of electromagnetic force

As mentioned above, noise is cause by the electromagnetic force and the force contains into tangential and radial components. When analyzing noise the radial component has a greater effect, from the Maxwell equations, eq.1 shows the radial electromagnetic force:

$$p_n(\theta,t) = \frac{b^2(\theta,t)}{2\mu_0} = \sum p_m \cos(m\theta - \omega_m t - \varphi_{m0}) \quad (1)$$

where
μ_0 $=4\pi \times 10^{-7}$;
m mode order;
ω_m angular frequency;
p_m, φ_{m0} amplitude and phase angle of the force wave, respectively.
As an approximation, $b(\theta, t)$ may be deduced from the product of the airgap MMF, $F(\theta, t)$, and the air~gap permeance, $\lambda(\theta, t)$, i.e.,

$$b(\theta, t) = F(\theta, t)\lambda(\theta, t) \tag{2}$$

As a matter of fact, switch frequency of the inverter will interact with the high order harmonics to produce large amplitude vibrational force, shown in eq.3:

$$f = \mathrm{m}f_{sw} \pm nf_o \tag{3}$$

where
f frequency of high vibrational force；
m，n =1，2，3…；
f_{sw} switching frequency；
f_o operating frequency of the compressor
As a result, inverter powered compressors will produce high frequency vibrational force and then high frequency noise.

2.3 Order analysis of the motor

From previous sections it could be conclude that the motor is the noise source, so in the following part the motor is isolated and investigated in a vibration testing system to analyze its response to high frequency vibrations. The layout of the testing system is shown in fig 3, it could exclude the effect of other components of the compressor. The stator is mounted on the bracket and the rotor is connected to an adjustable break by a coupling. The break could apply different torque on the rotor to simulate different load, acceleration sensor will monitor the vibration of the motor. A frequency sweep, which is shown in fig 4, shows the motor undergo structural resonant vibration near 4k~5k Hz, along with large amplitudes.

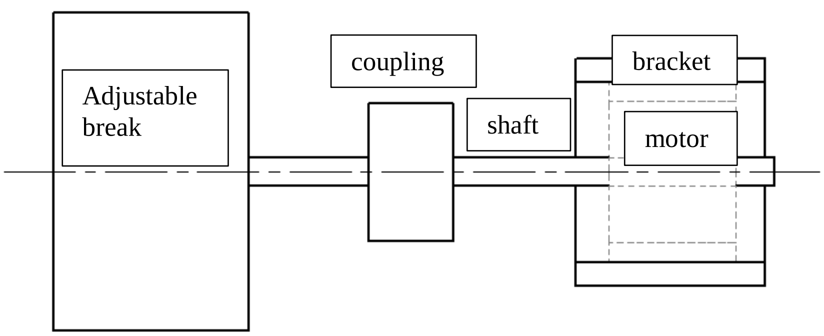

Figure 3: motor vibration testing system

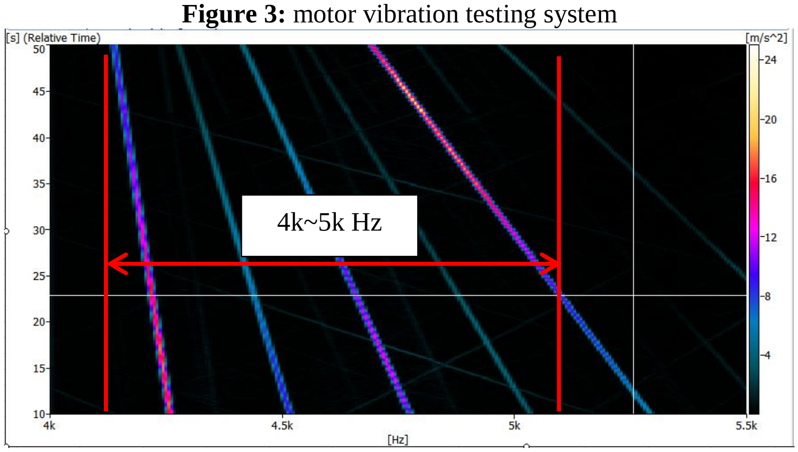

Figure 4: order analysis of the rotor

3 MODAL ANALYSIS OF THE MOTOR

For vibrational and noise analysis, the main vibrational modals that worth investigating are modals with 0 axial mode, and low order radial mode. The figure below shows the 2nd, 3rd and 4th vibrational modal of the motor, they are similar to a ellipse, triangle and quadrilateral, respectively.

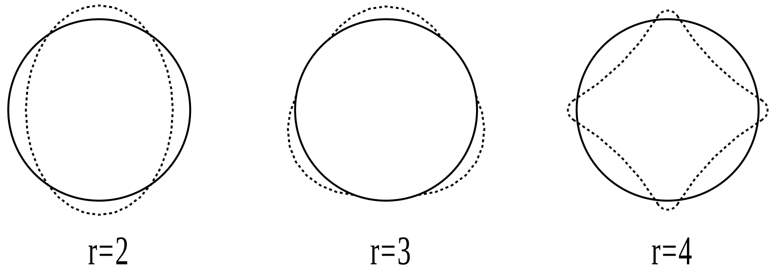

Figure 5: radial modal of the motor

3.1 FEM of the stator core

The stator modal shape is determined by stator core. Simulation model of the stator core is shown in fig 6, and the FEM modal analysis results are shown in fig 7, corresponding to 2nd, 3nd and 4nd vibrational modal shape. The FEM results are in good agreement with the theoretical results discussed above.

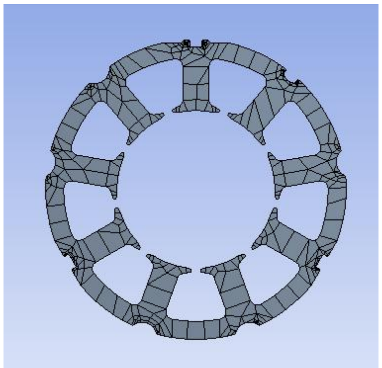
Figure 6: FEM model of the stator core

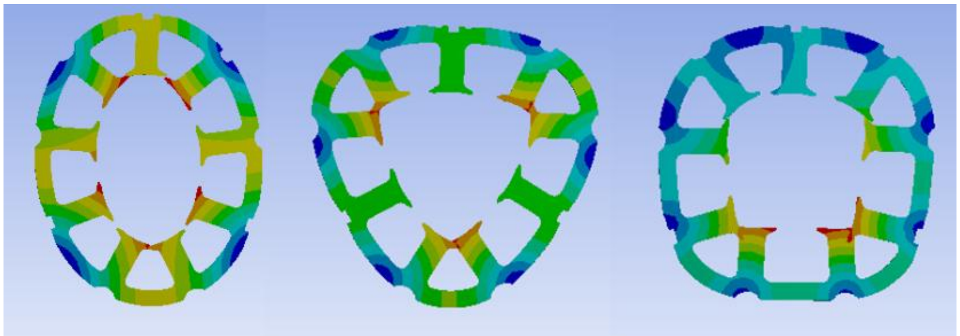
Figure 7: FEM results of the stator core

Fig 8 shows the frequency response of the stator core from the impact test. Due to the stator core is structural symmetric, two frequencies that are very close will be recorded for each vibrational modal, so in table 1 only one of them will be shown for convenience. The error between FEM and experiments are all within 1%, which means the simulation is very convincing.

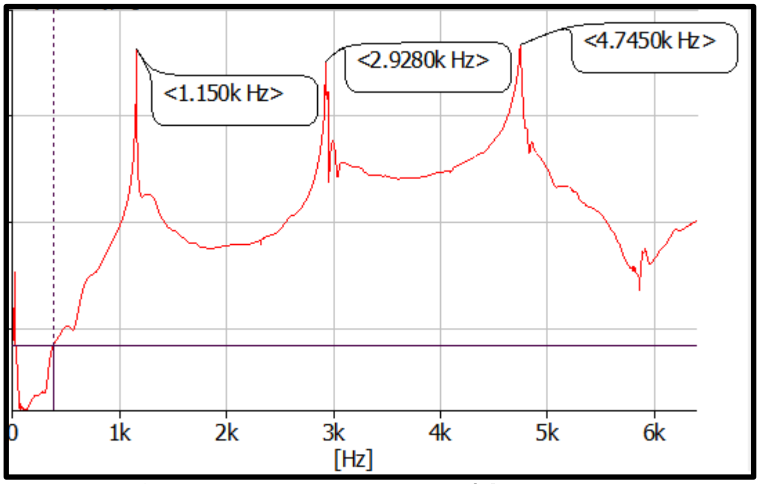

Figure 8: Frequency response of the stator core

Table 1: Results from simulation and experiments of the stator core

Modal order	Second	Third	Fourth
Simulation	1152 Hz	2919 Hz	4743 Hz
Experiment	1150 Hz	2928 Hz	4745 Hz
Error	0.17%	~0.31%	~0.04%

3.2 Modal analysis of the Stator

Stator consist of stator core and windings. The modal frequencies will be changed since total mass is influenced by the mass of windings. As above, the same procedure is applied to the stator, the modal shapes are shown in fig 9 and the resonant frequencies are listed in table 2. The error is smaller than 2%. Compare table 2 with table 1, it can be seen that the modal frequencies of stator are lower than stator core, but modal shapes are the same.

Table 2: Results from simulation and experiments of the stator

Modal order	Second	Third	Fourth
Simulation	913 Hz	2163 Hz	3560 Hz
Experiment	910 Hz	2181 Hz	3521 Hz
Error	0.33%	~0.83%	1.11%

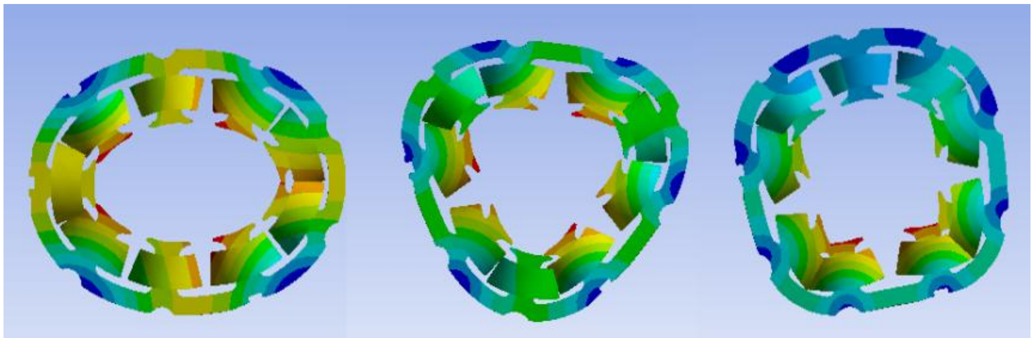

Figure 9: FEM results of the stator

3.3 Modal analysis of the stator with shell

In practical motor unit, the stator will be heat assembled to the shell, then modal frequencies of stator will be changed because of the stiffness of shell. In this section only the bulk shell which is in contact with the stator is analyzed in order to simplify the study. The FEM model and actual model are shown in fig 10 and modal shapes are shown in fig 11 along with the frequencies listed in table 3, all the errors are below 2%. The results also show that modal frequencies of stator with shell are different from stator core and stator, but modal shapes are the same.

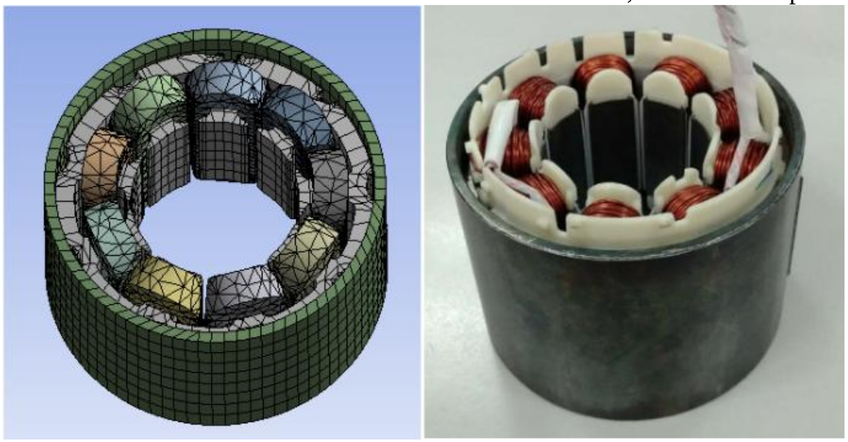

Figure 10: FEM and actual model of the stator with shell

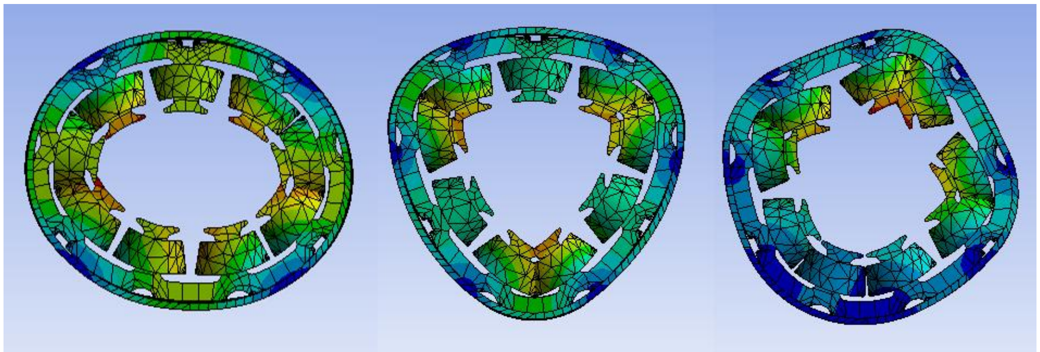

Figure 11: FEM results of stator with shell

Table 3: Results from simulation and experiments of the stator with shell

Modal order	Second	Third	Fourth
Simulation	1419 Hz	2830 Hz	4219 Hz
Experiment	1448 Hz	2870 Hz	4258 Hz
Error	~2.00%	~1.39%	~0.92%

From table 3 it could be summarized that the fourth order resonant frequency is 4219 Hz, which matches the results from the pervious section that the noise is mainly ranging in 4k~5k Hz. This shows the interaction between the switching frequency and the high order harmonics will excite the fourth harmonic resonance of the motor. What's more, the results above have been proved eligible for optimization with their <2% error.

4. OPTIMIZATION AND VERIFICATION

Eq. 4 is derived from the mechanical dynamics to solve for natural frequencies, it shows the modal could be modified by altering the stiffness or mass. The main sensitivity range for human ears are 0.5k~5kHz, so if the natural frequencies of the motor is turned above 5kHz, the noise performance could be much improved.

$$f_n = \frac{1}{2\pi}\sqrt{\frac{k}{m}} \tag{4}$$

4.1 FEM results

Radial stiffness of the motor is mainly affected by the tooth and yoke of the punching plate of stator core, so in order to change the radial resonant frequency, the width of yoke and tooth could be increased, as shown in fig 11. Resonant frequencies after this processing is listed in table 4, the fourth order modal frequency become 6125Hz, avoids being excited to resonant to increase the high frequency noise enormously by the high frequency vibrational excitation generated by the interaction between the switching frequency and the high order harmonics.

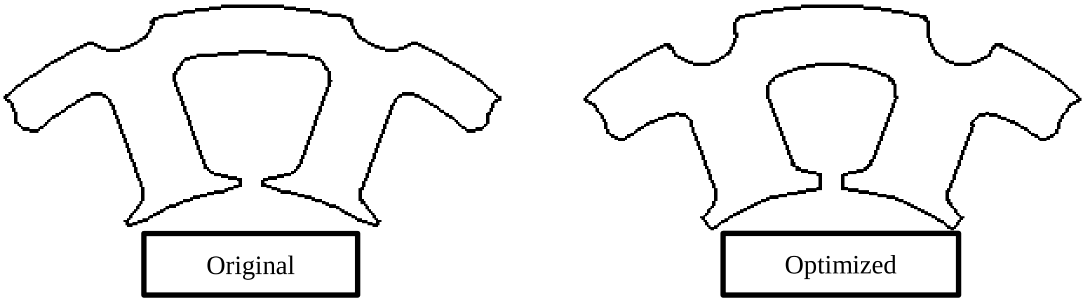

Figure 12: Structural optimization of the motor

Table 4: Frequencies pre and post optimization

	Original	**Optimized**
Stator core	4743 Hz	6650 Hz
Stator	3560 Hz	4882 Hz
Stator with shell	4219 Hz	6125 Hz

4.2 Experimental verification

Compressors pre and post optimization are compared by experiments, the response of 4k Hz and 5k Hz is shown in fig 13, each peak value drops 5.7dBA and 6.3dBA respectively, the results show that this is a good way though optimize the modal frequency of motor to avoid to be excited resonance to decrease the high frequency noise level.

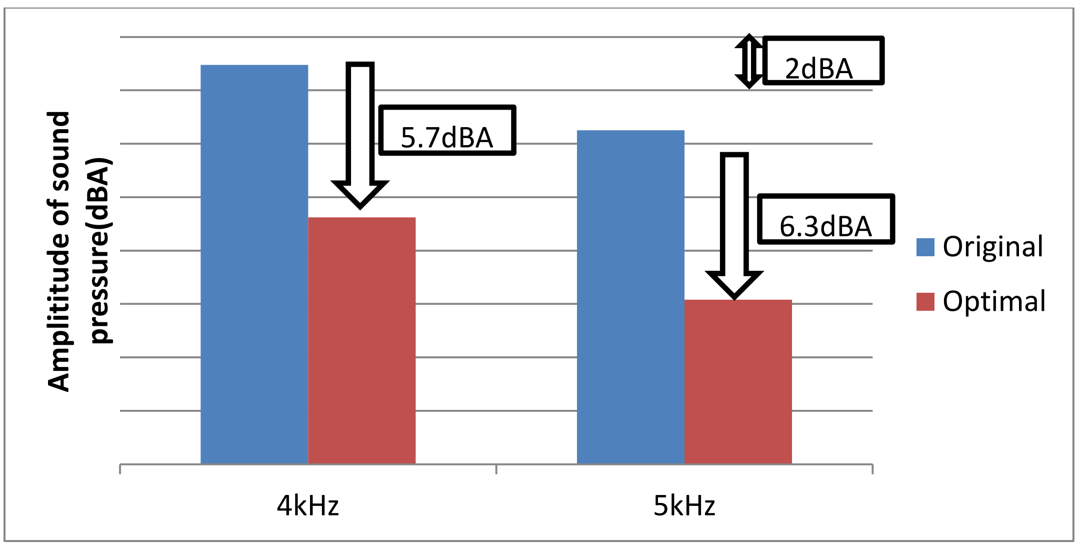

Figure 13: Comparison of sound pressure level

5. CONCLUSION

Noise source locating, electromagnetic force analysis, order analysis, modal analysis and FEM simulations have been done to investigate the 4k~5kHz high frequency noise of the inverter rotary compressor, we conclude as following:

1. The interaction between the switching frequency and the high order harmonics will produce high frequency vibrational excitation and then results in high frequency noise could be convinced from noise source locating, electromagnetic force analysis and order analysis.

2. The fourth vibration modal is excited by the high frequency vibrational excitation and finally causes the enormous increasing of 4k~5k Hz peak is proved by modal analysis and FEM simulations of the stator core, stator and stator with shell.
3. The fourth vibration modal frequency is increased to 6125Hz from 4219Hz by thickening the tooth and yoke of the punching plate to avoid the excitation, the 4k~5k Hz response is lowered by 5.7~6.3dBA.
4. Ideas and references are provided to benefit the upcoming effort on improving inverter compressor's high frequency noise performance in this paper.

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