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Original Article

Simulation of Harmonics in an Operational Amplifier to Determine the Signal-to-Noise-Ratio

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Abstract *- In this work, the output of a simplified model of an operational amplifier (OA) with noise coupled to the input signal exhibits nonlinearity. Attenuation at the input can reduce harmonic distortion (HD) by some mathematical relation to correct the distorting effect at the output of the amplifier. Assuming an audio speaker produces less than 9 percent distortion at 1 kHz with a 1volt input, this is measured with respect to the fundamental (THD-F). Viewing the effect of the amplifier's nonlinearity, a periodogram of its output when stimulated with a sinusoid set to the maximum allowable voltage of the amplifier 2 Vpk for a duration of 50ms. The methodology includes characterizing a nonlinear OA with memory and an adaptive Digital Pre-Distortion (DPD) feedback system to reduce the output signal distortion level. The initial step in the procedure is to determine the coefficient matrix needed for selecting the Volterra memory polynomial model. This step uses actual measured data for the OA. After deriving the set of coefficients for the OA model, a system-level simulation is performed. This system includes an adaptive DPD algorithm that can be enabled during simulation using the toggle switch and demonstrates how the linearity of the output signal improves DPD correction. Two signals are created a fundamental frequency of* $\frac{\pi}{4}$ *rad/sample with amplitude 1 and the first harmonic of frequency* $\frac{\pi}{2}$ *rad/sample with amplitude 0.025. One of the signals additionally has additive white Gaussian noise with variance* 0.05^2*, setting the random number generator to the default sceneries for reproducible results; the SINAD for the signal without additive noise and comparing the result to the theoretical can be outputted.*

Keywords *- Nonlinear, Algorithm, Harmonic distortion, Digital Pre-Distortion, Periodic solution.*

List of Acronyms Abridge for Use

DE	*Differential Equation*
PS	*Periodic Solution*
DOE	*Department of Energy*
PQ	*Power Quality*
PCB	*Printed Circuit Board*
NAE	*National Academy of Engineering*
APF	*Active Power Filter*
RSS	*Receiving Signal Strength*
HS	*Harmonic System*
SM	*Square Matrix*
LDSs	*Lightly Damped Systems*
HC	*Harmonic Component*
HS	*Harmonic System*
HD	*Harmonic Distortion*
HP	*Harmonic Peaks*
ODFT	*Odd Discrete Fourier Transform*
F_0	*Fundamental Frequency*
DPD	*Digital Pre-Distortion*
OA	*Operational Amplifier*
LV	*Low Voltage*

1. Introduction

Computer-aided design of nonlinear amplifiers can be used to determine the steady-state study of lightly damped nonlinear amplifiers, such as harmonic multipliers and oscillators. In these LDSs, even a new stiff DE algorithm may need larger computing time since the transient frequency response may be a hundred cycles or more; this gives rise to large and inaccurate results. It is important to note that harmonic balance techniques in which assumptions have been made that the response contains a fundamental frequency with several other harmonic frequencies is addressed. This assumption is put into according to (Barbosa et al., 2012; Eyenubo and Oshevire, 2017), DE and an optimization algorithm used to vary the amplitude and the phase of the harmonics such that a mean-square function is minimized:

- The assumed solution can result in an error with respect to the physical situation, e.g., this could be unstable due to some harmonics, subharmonics, or interharmonics components that may have been neglected. The error function will probably not indicate these difficulties.

- Optimization procedures tend to converge, which may be excessive, particularly in higher-order systems. If the fundamental frequency, second, and third harmonics dominate, this will increase to six unknowns (amplitude and phase of each harmonic) for each state variable. If SE contains five state variables, we have thirty variables that must be optimized.
- The harmonic balance algorithm is useful for SS analysis. The portion of the transient response used for the prediction can be determined. Computational time is considerably reduced with the algorithm if the portion of the TR can be resolved in line with the SS reaction.

The commonest ways to denote HD and THD with noise; are determined by applying spectral sinewave to the operational amplifier of the well-defined circuit arrangement and examining the output spectrum (Eyenubo and Ubeku, 2014). The measure of distortion extant in the produce is generally a result of various factors: the smaller and large-signal nonlinearity of the amplifier being investigated, the maximum absolute value and frequency of the input process, the load used in the output of the amp, the circuit's power source voltage, PCB layout, earthing, power supply decoupling, etc.

Thus, any distortion requirement is somewhat trivial, except careful test provisions are stated. HD is computed by observing the visible output frequencies on the spectrum instrument and viewing the 2nd, 3rd, 4th, etc., with respect to the measure of the first frequency generally stated as the ratio in %, ppm, and dB. For example, 0.0015% distortion is equivalent to 15ppm. The unit "dBc" means decibels relative to the carrier of harmonic's quantity in dB of the "carrier" of fundamental frequency (Thomas and Biradar, 2013).

Distortion of harmonic is explicit for each module (normally only the 2nd and 3rd are stated), or they may combine in RSS form to give THD. The distortion constituent which produces THD is typically determined by choosing the root sum of squares of the first five or six fundamental harmonics. In sundry pragmatic conditions, there is a trivial error if only the 2nd and 3rd harmonics are incorporated. Thus, the RSS method initiates the higher-order terms of insignificant consequence on the THD if they are 3 to 5 times lesser than the main harmonic (Ahmed et al., 2019).

This work establishes a precise approach to evaluating SNR from sustained vowels on the harmonic configuration model. Fundamentally, the projected algorithm builds an exact HS where each harmonic is parameterized by frequency, magnitude and phase. The harmonic configuration is integrated as a module of the dialogue signal. The noise factor can be approximated by deducting HC from the speech signal. The planned procedure contrasted with SNR abstraction algorithms centered on spectral and time domain systems and exploiting distinct functioning procedures (Eyenubo and Ubeku, 2014).

2. Related Works

In recent years, PQ issues have become a vital concern for both the utility and end-users. This results from the widespread use of modern power electronics devices in various domestic appliances such as electrical motor drives, power supplies, induction heating, electronic lighting, etc. These electronic and solid-state-based devices generate current harmonics, which are injected into the distribution network and cause voltage disturbances at different points of the network; industrial converters, motorized loads, and light bulbs in electrical distribution networks have an effect on the PQ operation of electric networks. These days, the swelled harmonic pollution from electric companies is considered a critical issue that should be deeply studied to strengthen the PQ performance of electric networks (Bajaj et al., 2020; Eyenubo, 2016).

The NAE ascertained that electrification was the highest attainment of the 20th century (Martynov, 2011). Developed by Tesla and executed by Westinghouse, the electrical power grid stimulated the second industrial revolution in which factories were run by electrical motors and the night was lit up by incandescent lamps. In a later period, loads changed and society's enthusiasm for electric energy with consumers needing both improved quantity and quality. Unceasing quality power is critical for the post-industrial digital economy that is progressively built. Economy-based businesses and power outages are unsatisfactorily luxurious (Šinik et al., 2020; Martynov, 2011). The DOE assessed power/hour for a brokerage business as $8.7 million, whereas the CC business costs $4.3 million. In Europe, the prediction of PQ problems cost industry and commerce 11.5 billion euro per annum, which is only 5% of the cost (Teansri et al., 2012).

It is essential to forestall the stated outcomes of harmonics in PS on both connection points and other loads. The PS operatives also correct their operational plans founded by IEEE Std 519 or IEC Std 61000 Stds (Barbosa de Silva, Roberto Perillo, 2021; Wang et al., 2019). As a standard, THD is set at 5% in the LV system agreeing with IEEE Std 519-2014, as CD boundaries associated with TDD should match limits shown in Table 1. Several applications for mitigating harmonics exist amongst line reactors, phase-shifting transformers, K-Factor transformers, and low-pass active, passive and hybrid filters (Gong et al., 2021; Khan et al., 2017).

The clean SW of currents/voltages are of great concern in PS; since the PS equipment is planned to function with fundamental power frequency. There are odd/even harmonics in PS due to nonlinear loads from power electronic components, static VAR compensators, converters and arc furnaces. The HD caused nonlinear loads in the power grid, leading to an unfavourable nuisance for PS and consumers. Regarding the PS, reducing PQ might result in the overloading of transformers, rotating equipment (Nawzad Rashid, 2011), neutral conductors and failed capacitor banks might affect the reliability method. As for the consumers, lower PQ might further increase economic losses (Eyenubo and Ubeku, 2014). The clean SW of currents/voltages are of great concern in PS; since the PS equipment is planned to function with fundamental power frequency. There are odd/even harmonics in PS due to nonlinear loads from power electronic components, static VAR compensators, converters and arc furnaces. The power converter is operated as APF, such that the HD is compensated amongst satisfactory limits (Eyenubo and Ubeku, 2014; Rouabah et al., 2020; Sahli et al., 2020; Choudhary et al., 2016; Eyenubo and Oshevire, 2017). This converter comprises a dc-dc buck-boost converter of a simple polarity switch inverter. The key advantages of such network topologies are low inverter swapping occurrence. Thus, losses are insignificant. Swopping losses are limited to those of the buck-boost converter, which operates utilizing various methods.

Table 1. CD limits for rated voltages of 120 V - 69, 000 V in harmony with the IEEE Std 519

I_{SC}/I_L	TDD (%)
< 20	5.0
20 < 50	8.0
50 < 100	12.0
100 < 1000	15.0
> 1000	20.0

I_{SC} = highest short-circuit current of PCC
I_L = maximum load current (only fundamental frequency components)

2.1. The Significance of Inadequate PQ on PS Appliances

Deficient electric PQ has several negative drawbacks on PS devices and end users; this prodigy is precarious because its outcomes are frequently unknown until failure occurs. Therefore, considering how disruptions are engendered relate within a PS and how they touch constituents is imperative for averting collapses. Even if failures do not arise, poor PQ and harmonics losses can initiate diminution in PS lifetime modules and end-user gadgets. Some of the major damaging outcomes of inadequate PQ involve the undermentioned Eyenubo and Ubeku (2018):

1. Harmonics increase root mean square and peak waveform; this suggests the kit could get a destructive high peak voltage vulnerable to breakdown. Excessive voltage may also constrain PS elements into saturation regions features, producing supplementary harmonics and intrusions. The waveform deformation after-effects are reliant on the harmonic-phase angles.
2. There are undesirable outcomes from heaters, noise, and abridged life on capacitors, surge suppressors, rotating machines, transformers, fuses, and customer paraphernalia varying from trivial clocks to big industrialized loads.
3. Utility establishments are generally involved in distribution transformers that may require duration to prevent early failure due to heat caused by harmonics.
4. Further shortfalls of transmission lines, cables, generators, AC motors, and transformers may ensue due to harmonics, e.g., interharmonic and subharmonics (Levacic et al., 2018).
5. Breakdown of PS apparatuses and client loads may arise due to unexpected disconnections such as voltage and/or current upsurge due to similar resonance and ferroresonance.
6. Breakdowns of protecting gadgets such as fuses and relays are probable.
7. Interharmonics might arise, disturbing undulate control signals and causing sparks at subharmonic echelons.
8. Harmonic unsteadiness may be triggered by large and unforeseen harmonic bases such as arc furnaces.

Handbooks are organized for PQ and abridged by varied functioning groupings; a suggested procedure is typically upgrading the instructions-endorsed procedure. The primary purposes for establishing regulations, recommendations, and guidelines in PS with nonsinusoidal voltages or currents are to save interruptions to user apparatus within acceptable boundaries and to stipulate matching terminology and test techniques for PQ nuisances, then offer a conventional proposal on which a wide array of engineering is referenced (Khosrojerdi et al., 2014).

3. Methodology of Current SNR Removal Procedures

Three procedures based on period, spectral and cepstral methods are examined sequentially to liken the operation of the scheduled algorithm to the prevailing SNR systems. Each process is a symbolic illustration of special methods for evaluating the vital quality stricture of the voice wave. Numerous procedures were achieved, such as voice model-based algorithms and adaptive practices. As a sample of a time-based scheme, Boersma's algorithm is established on the second most regularized autocorrelation utility recognition, which is utilized in equation (1).

$$SNR = 10\log\left(\frac{r(\gamma)}{1-r(\gamma)}\right) \tag{1}$$

Where $r(\gamma)$is the second local maximum of the normalized autocorrelation and γ is computed by a pitch detector. The spectral procedure considers harmonic module data focused on wavelength peaks and noise. The technique divides the spectrum of voice signal against two expanses (signal of harmonic and noise regions); the algorithm illustrates a frequency-based scheme. The cepstral methodology studies on harmonic knowledge are focused on the fundamental HP and the noise knowledge centered on low frequencies. Generally, cepstral processes perform subdivision with short-pass or detangle lifts cautiously dimensioned. Thus, these approaches produce an estimate of baseline noise from where the SNR value can be calculated.

3.1. SNR Withdrawal Process

The prearranged SNR system includes harmonic and noise component assessment. Firstly, the signal is segmented into structures and a sine display with equation (2).

$$h(n) = sin\left[\frac{\pi}{2}\left(n+\frac{1}{2}\right)\right], 0 \le n \le N-1 \quad (2)$$

Ferreira (1998) was of the view that the harmonic module is valued from the ODFT signal by separating the frequency, magnitude and phase of both harmonics. In the ODFT domain, the considerations of harmonic arrangement are considered and are not changed by noise. These strictures are employed to produce the harmonic configuration in the ODFT region. The harmonic factor is taken from the overall signal, giving way to the constituent noise evaluation. Ultimately, the SNR quantity of each plan is analyzed from these two mechanisms using equation (3).

$$SNR = 10\log\frac{\sum_{k=1}^{N/2}|H(k)|^2}{\sum_{k=1}^{N/2}|R(k)|^2} \quad (3)$$

3.2. Removal of Harmonic Spectral Limitations

Every harmonic is displayed (Ferreira, 2001) by a sinusoid corresponding to equation (4):

$$x(n) = A\sin\left[\frac{2\pi}{N}(l-\Delta 1)n+\varphi\right] \quad (4)$$

Where A is the sinusoid measure, N is the window dimension and $l-\Delta l$ are integer part of the DFT, similar to the sine frequency. The fractional bin section characterizes the measure amongst the l and the actual frequency estimate. The procedure calculates the ODFT of the voice signal, and local maxima are obtained by a peak algorithm. The highest bins are the initial values that agree to the integer part of the exact frequency bin. The harmonic limits are calculated using the equations below (Khosrojerdi et al., 2014).

$$\Delta l = \frac{3}{arctan}\left[\frac{\sqrt{3}}{1+2\left[\frac{X_0(l-1)}{X_0(l+1)}\right]^{1/G}}\right] \quad (5)$$

$$\varphi = < X_0(l) + \pi\left(1-\frac{1}{2\pi}\right) - \pi\Delta l\left(1+\frac{1}{N}\right) \quad (6)$$

$$A = \frac{4|X_0(l)|}{N}\left[\frac{\sqrt{3}}{2cos\left[\frac{\pi}{6}(2\Delta l-1)\right]}\right] \quad (7)$$

Where X_0 is the ODFT, G, and F are measurement parameters attuned by simulation.

3.3. Harmonic Module Combination

The harmonic arrangement is predictable by operating a mixture of each sinusoid consideration taken out from the ODFT illustration of each signal frame in view of the windowing influence. In order to calculate the sinusoid frequencies, the response of sine processes without variation inferences (frequency alteration) was evaluated as revealed in the equations for phase (8) and magnitude (9).

$$< H(\omega) = \frac{-\omega(1-N)}{2} \quad (8)$$

$$|H(\omega)| = A\frac{\left|cos\frac{N\omega}{2}\right|\left|sin\frac{\pi}{2N}\right|}{2}\left|\frac{1}{sin\frac{1}{2}\left(\frac{\pi}{N}-\omega\right)} + \frac{1}{sin\frac{1}{2}\left(\frac{\pi}{N}+\omega\right)}\right| \quad (9)$$

4. Result and Discussion

Figure A: shows an abridged replica of an operational amplifier with noise in the input demonstrating nonlinearity; attenuation at input reduces harmonic distortion with the determined permissible voltage of 2 Vpk for an interval of 50ms.

Periodogram effect when simulated with sinusoidal waveform set to the maximum voltage of 2 Vpk. It is observed as various frequencies 4, 6, 8, to 10 of fundamental 2 kHz are found due to nonlinearity with a flat range of noise of amplifier as illustrated in Figure 1.

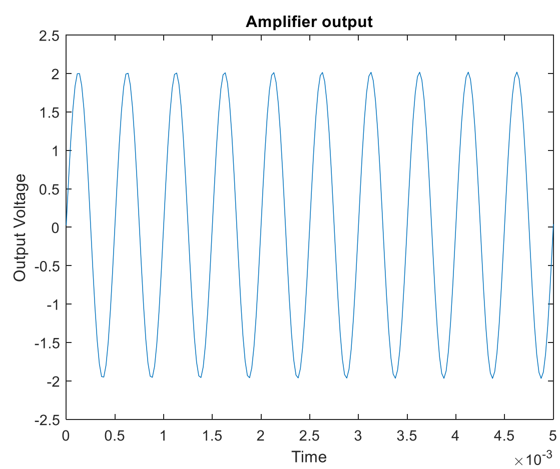

Fig. 1 The outcome of nonlinearity appliance sinusoid frequency 2.5 kHz tried at 50 kHz where the signal-to-noise ratio is 80 dB

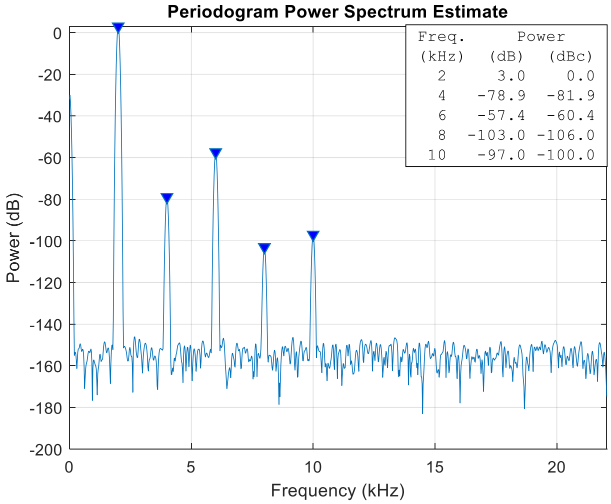

Fig. 2 Periodogram power range of the fluctuated input sine curve from 2 – 10 kHz

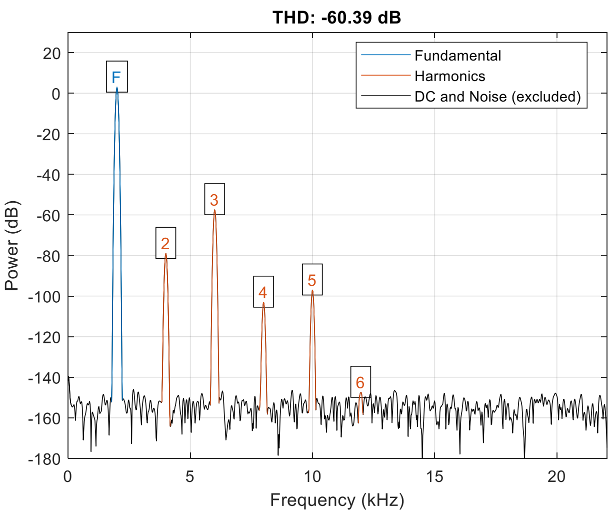

Fig. 3 Measuring nonlinear alteration of lowest frequency and subharmonics waves

Examining some general distortion systems of measurement for evaluation uses the periodogram to indicate distinct harmonics of fundamental indication. Thus, the input wave's THD reverts the power harmonic substance percentage to the original signal. It will be observed that the 3rdand leading harmonic is 60 dB from the fundamental warp occurring mainly, as depicted in Figure 3.

Estimating the overall noise displayed can be evaluated; thus, SNR sends the proportion of fundamental frequency to all nonharmonic matter.

An additional noise plot is widened about the range; attenuation fixing of the 2nd and 3rd harmonic is, however, less. If a function that utilizes a lesser bandwidth is accessible, this will broaden ever-increasing the diminution of the harmonic matter, as seen in Figure 4

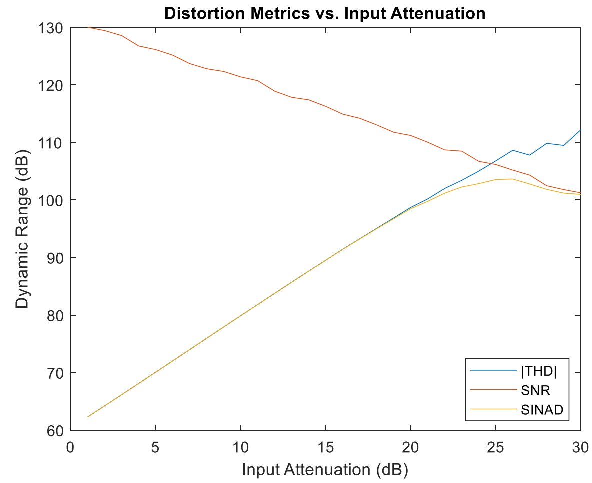

Fig. 4 Processing of distortion remove of SNR THD and SINAD as the utility of input diminishes

The THD dimension corresponds to variability of harmonics, SNR that allows the operational target; SINAD equal total active range free of misrepresentation. Figure H indicates valid dynamical scope conforming to metric. The size of THD matches the series of harmonics. Correspondingly, SNR agrees with active gamut not touched. SINAD matches the total active variety free distortion. SNR decays as mitigation rises; since the signal is reduced noise of the operational amplifier remains unaffected.

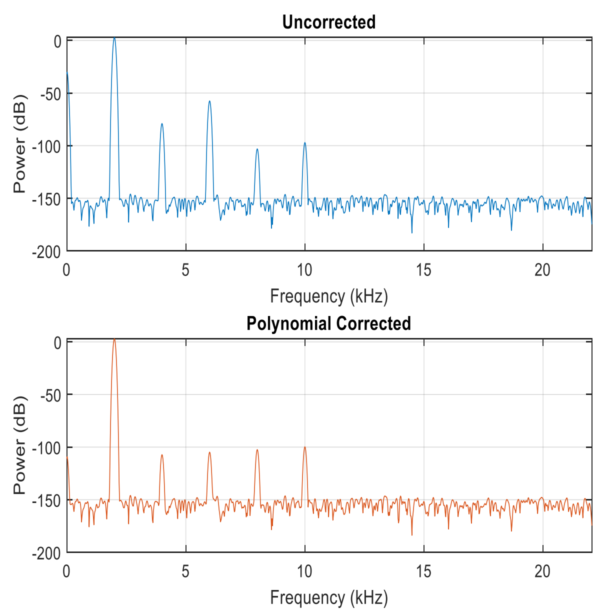

Fig. 5 Post-processing to eliminate the distortion by a stimulus with linear ramp fitting a 3rd-order polynomial

It should be noted that the enormity of THD progresses gradually till it traverses SNR curl, as measurement turns out to be erratic. This occurs when harmonics have "faded" underneath the amplifier's noise. A pragmatic selection of amplifier diminution is 26 dB (generating a SINAD 103 dB), a realistic compromise amongst harmonic/noise warp.

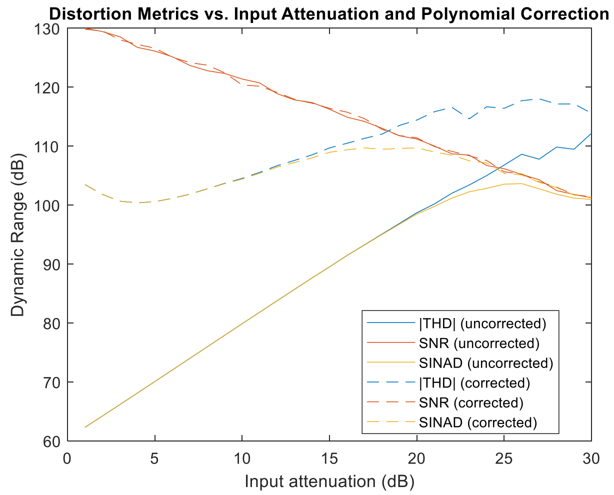

Fig. 6 Arrangement of reduction with polynomial valuation

Model functioning voltage reduces general SINAD in the scheme; as seen in the figure, THD is enhanced significantly, while SNR was unchanged by polynomial improvement. Three metrics are plotted as seen in Figure 6; THD has progressed substantially, while signal-to-noise-ratio was not touched; this is anticipated since the multinomial improvement only influences distortion of harmonic without noise.

5. Conclusion

From the simulated results, it can be inferred that the intended algorithm presents a reasonable level of precision. The algorithm does not have a significant tendency to underestimate or overestimate. This feature means there is no need to calibrate or compensate for the estimated SNR value. In some cases, calibration may not be effective due to the acoustic diversity of human voices. In spite of presenting the second-best values regarding the variation of the errors according to F_0(fundamental frequency) with theoretical SNR, it can be resolved that measures carried out by the suggested algorithm are not significantly touched by the F_0 and the noise intensity. This indicates that the procedure determines several levels with approximated precision.

The suggested procedure presented comprehensible SNR values analogous to the HNR estimates of other algorithms. The harmonic plus noise ideal adopts good calculation of the harmonic and noise modules. Furthermore, the outcomes are similar among investigations related to harmonic and noise components in each signal depiction.

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