The “Relative Approach” for Direct Measurement of Noise Patterns

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A/B listening comparisons and acoustic and psychoacoustic measures are frequently used to evaluate sounds. Their accuracy is compromised if time or tonal structure, recognized by listeners as ‘patterns,’ are present in one or more of the sounds. The “Relative Approach” is a new measurement procedure that can be used to obtain valid results in cases that defy conventional techniques.

Conventional and psychoacoustic measurements and A/B listening comparisons are frequently employed to link subjective impressions of sounds with objective quantifications. The presence of pattern information creates problems in obtaining subjectively-valid results from typical conventional or psychoacoustic measurements. A similar problem arises in performing immediate A/B comparison tests where patterns are present. In an immediate comparison, human hearing can detect small differences between two sound events in terms of loudness or A-weighted sound pressure level. But with a relatively long lapse of time between presentations, the human ear can only determine if the patterns are different.[1]

Listening judgments in “everyday life” occur without A/B comparison. A listener forms a sound quality evaluation within a single sound situation without immediate comparison to other sound situations. If pattern information is present, it draws the attention and dominates the judgment. In such cases immediate A/B comparisons are counterproductive because they bring into play the acoustic short-term memory and draw attention to absolute magnitude differences at the transition between any two sound examples. A quick transition itself is registered as a change, drawing specific attention. The true pattern-related perception, which dominates an isolated presentation, is then disturbed. In experiencing a patterned situation, the absolute level or loudness is almost completely without significance.

As an adaptive receiver, human hearing is highly sensitive to patterns in time and/or tonal structure. It creates for its automatic recognition process a running reference sound “comparison file” or “anchor signal” against which it classifies tonal or temporal pattern information moment-by-moment. It evaluates the difference between the instantaneous pattern in both time and frequency and the ‘smooth’ or less-structured content in similar time and frequency ranges. In the presence of pattern information, the pattern rather than the absolute values dominates the subjective evaluation, even though the magnitude in the temporal, tonal or combined pattern may be much lower than in ‘smooth’ or pseudostationary components of the same situation.

When the magnitude of ‘unpatterned’ energy rises in the same time/frequency region relative to a time or frequency pattern, perceived pattern magnitude decreases. If, for example, a vehicle is driven faster and the higher road and wind noise make a rattle less noticeable, the sensation will be of a lower pattern magnitude and a ‘quieter’ situation, in accordance with the relative perception of the ear/brain system.

Based on these considerations, the Relative Approach was developed to evaluate acoustic quality as a single value, by applying the following equation:[1]

$$Q = f(N,S) + f\left(\sum_{i=1}^{24}\left[\begin{array}{l}\left|F_G(i-1) - F_G(i)\right| \cdot w_1\left(iF_G(i)\right) \\ +\sum_{n=1}^{T}\left|F_G(i,n) - F_G(i,n+1)\right| \cdot w_2\left(i,F_G(i)\right)\end{array}\right]\right)$$

where

Q = acoustic quality.

$F_G(i)$ = a mean value of the critical band level over a period T of 0.4 to 4 seconds.

$F_G(0)$ = $F_G(1)$, $F_G(i,n)$, a mean value of the critical band level over a much shorter period (approximately 2 milliseconds).

n = the current (time-dependent) value.

The weighting factors $w_1(i, F_G(i))$, $w_2(i, F_G(i))$ depend on the critical band level $F_G(i)$. The function f describes an audition factor, dependent on loudness N and sharpness S. As can be seen from this equation, an analysis of temporal behavior occurs within a critical band and is combined with an analysis of frequency response.

The Relative Approach has subsequently been expanded in scope.[2] Various time-dependent spectral analyses can be used as preprocessing for the Relative Approach:

- 1/n octave vs. time filter-bank.
- FFT-based analyses and the subsequent application of a nonlinear transform taking into account the nonlinear relation between sound pressure and subjective perceived loudness according to the hearing model of Sottek.[3] [Due to the nonlinearity in the relationship between sound pressure and perceived loudness, the term “compressed pressure” in compressed Pascals (cPa) is used to describe the result of applying the nonlinear transform.].
- Time-dependent specific loudness patterns.

The concept behind the Relative Approach is to determine an estimated value for the current signal from the signal history known to the present time, and to subtract this estimate from the actual current signal. The estimated value can initially be regarded as a mean value for former signal values. The difference between the current signal value and the estimated value is a measure of signal change [only values above a threshold (hearing model of Sottek[3]) are considered]. In a simplified view, the Relative Approach may be considered a subtraction of a running average from a running instantaneous analysis centered in it – the end result could be considered “the opposite of averaging.” There are two different mechanisms for the described signal estimation based on variation analysis. The first time-sensitive method is optimized for temporal patterns: smoothing over the frequency axis for each time interval; regression over the time axis for each frequency interval. The second frequency-sensitive method is optimized for tonal components, with regression over the time axis for each frequency interval and smoothing over the frequency axis for each time interval.

Sensitivity to different temporal pattern durations or spacings is obtained by selection of the time weighting (0.1 to 50 milliseconds for a filterbank base calculation), or of the block size for a Fourier base calculation. Frequency sensitivity is determined by the octave subdivision in either the filterbank or Fourier base calculations, or by both the block size and the critical band subdivision in the loudness calculation.

The same Relative Approach tool with different settings can resolve different patterns occurring in the same situation with a great degree of independence. It thus affords a kind of ‘orthogonality’ allowing largely-independent quantifications to be made of different co-existing tonal and temporal patterns such as occur in information technology (IT) equipment noises, or the ‘thumps’ and tones of windshield-wiper mechanisms.

Recent extension of the method adds a choice of combining

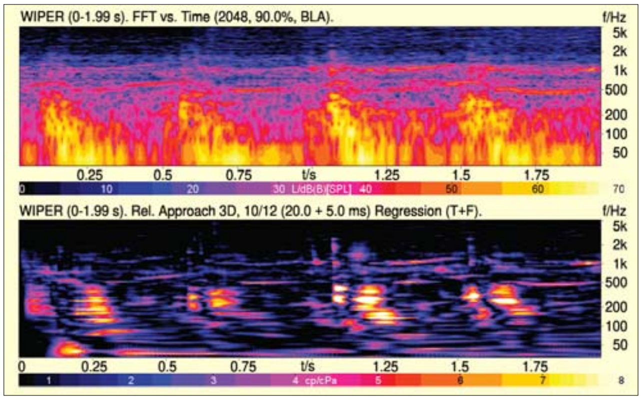

Figure 1. Windshield wiper, two cycles. Upper graph – conventional FFT spectrum vs. time with best choice of block size for resolving both tonal and 'thump' patterns. Lower graph – Relative Approach, with variation analysis optimized for sensitivity to both temporal and tonal patterns. Time scale is horizontal, frequency vertical; color indicates magnitude.

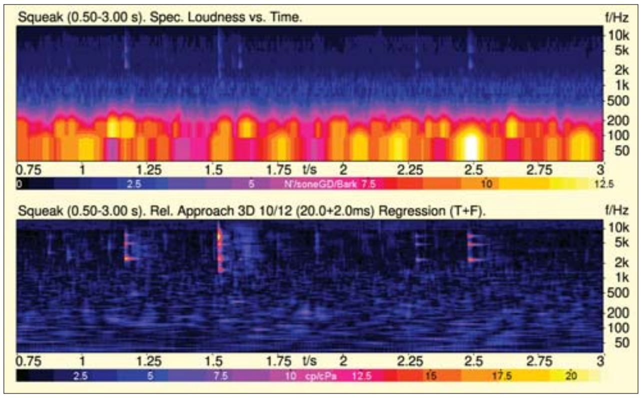

Figure 2. Squeak quantification – the upper graph is a specific loudness vs. time measurement (ISO 532B filter method) of a squeak situation in a car driven at highway speed. The lower graph is a Relative Approach measurement.

time-sensitive and frequency-sensitive regression procedures, with adjustable priority weighting between the two and independent settings choices for each. In this way both time and frequency patterns in a sound situation may be displayed in the same measurement result. Although developed to model the pattern-sensitive evaluation of human hearing, the method has wider engineering applicability in quantifying patterns in noise and potentially also patterns in vibration.

The Relative Approach algorithm objectivizes pattern(s) in accordance with perception by resolving, or extracting, them while largely rejecting pseudostationary energy. At the same time, it considers the context of the relative difference of the 'patterned' and 'non-patterned' magnitudes.

Due to measurement of relative instead of absolute magnitudes, Relative Approach results are largely insensitive to the absolute magnitude of the entire signal. If the relationship of a detected pattern to the surrounding average remains unchanged, the analysis output (the relative signal) will also remain unchanged over a wide range of overall magnitudes. A pattern that has the same relationship to its surrounding continuum may be detected and judged as essentially the same over a wide range of overall objective magnitudes. Similarly, lowering the level of a complete signal without altering the pattern relationship is likely to result in the same subjective evaluation as before. If a time-data file exhibits no temporal or spectral pattern(s), a Relative Approach measurement will yield a null output. The adaptation of the Relative Approach is similar to that of hearing. Relativity-sensitive analysis suggests application to hitherto-intractable situations.[4]

In addition to providing aurally-accurate objective results, the Relative Approach offers a realistic answer for unattended screening of products and processes whose operation creates or may create time- and/or frequency-patterns. The method has already been applied to automated brake-squeal detection and several other end-of-line tests.

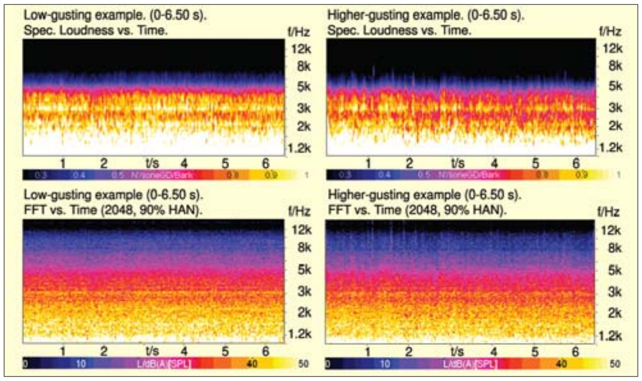

Figure 3. Wind noise gusting, conventional measures. Left graphs – lower-gusting example. Right graphs – higher-gusting example. Signals are unfiltered. Upper graphs – specific loudness vs. time (FFT 2048 points, 1/5-Bark resolution). Lower graphs – FFT vs. time (2048 points, 90% overlap). Though a clue is visible (stronger time structure from about 2 to 8 kHz in the higher-gusting case), the peak spectral levels, level vs. time and overall levels appear to quantify the opposite evaluation to that of human hearing.

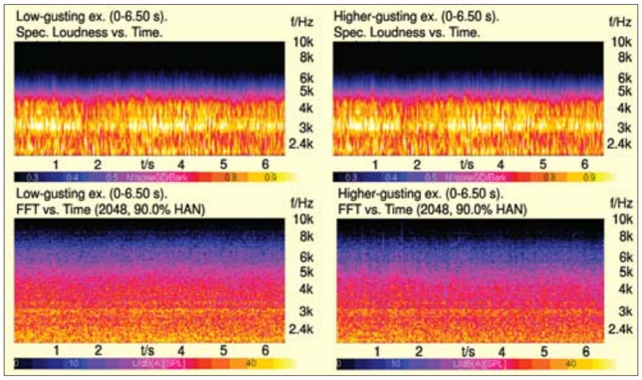

Figure 4. The same examples and measures as Figure 3 (higher-gusting is on the right), bandpass-filtered 2-6.5 kHz. Although the same clue is again visible, a clear 'gusting' quantification agreeing with human hearing is not achieved. The sensation of gusting is a pattern-sensation, independent of whether the objective level and loudness of an example of higher-gusting is greater or less than those of a lower-gusting example.

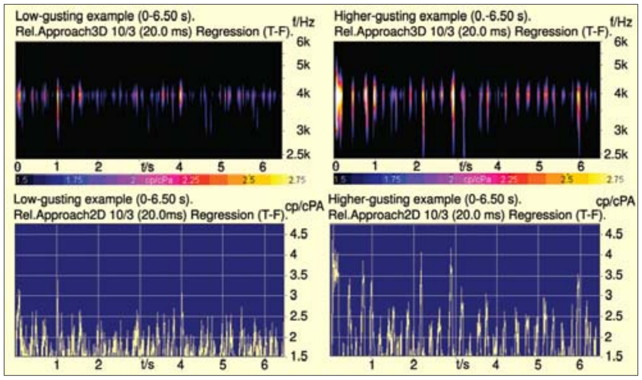

Figure 5. Same wind gusting examples, Relative Approach 3D (upper) and 2D (lower). The Relative Approach 2D curves are achieved by summing the Relative Approach 3D results over frequency; octave-bandpass-filtered at 3.9 kHz coinciding with the spectral region of peak sensitivity to loudness of human hearing. Variation analysis – optimized for tonal pattern. All gusts are individually resolved. Additionally, use of the 10th percentile (value exceeded 10% of the time) from the Relative Approach 2D will provide a reliable single-number measure of the wind-gusting pattern sensation.

Typical Applications

The windshield wiper example shown in Figure 1 compares absolute-value measurements with adaptive relative-value (pattern-sensitive) quantifications. An example of squeak quantification is shown in Figure 2.

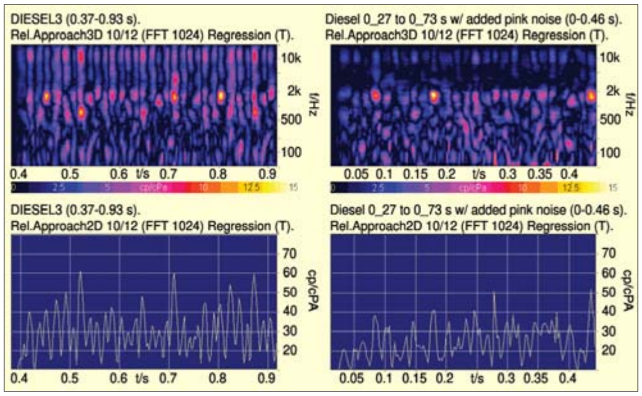

Figure 6. Adding random noise to a patterned sound, such as the diesel engine situation above, lowers pattern strength in accordance with human perception. The original diesel sound situation is on the left, the added-noise version on the right. Immediate A/B comparison would reveal that the absolute loudness and level of the added-noise version exceed the original, yet when heard in isolation and measured with the Relative Approach 3D (upper) and 2D (lower), the added-noise situation is perceived as significantly 'quieter' (less impulsive) than the original.

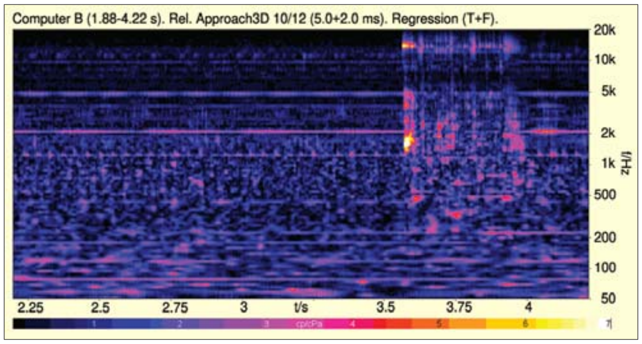

Figure 7. PC workstation, hard disk access. Relative Approach 3D, optimized for simultaneous temporal and tonal pattern recognition by using a combination of the time- and frequency-sensitive methods. Note the time structure in some of the tones, as well as the fine time structure in the 'seek' operations.

Wind gusting heard in a vehicle interior is another clearly audible and annoying pattern extremely difficult to quantify via absolute measures (see Figures 3 and 4). This includes conventional metrics such as levels and spectra versus time, or psychoacoustic metrics, such as specific loudness, roughness or fluctuation strength versus time. Relative Approach analyses clearly detect all gusts individually according to human perception as shown in Figure 5.

The example in Figure 6 shows the application of the Relative Approach for the evaluation of patterned sounds with the addition of random noise to reduce pattern strength. The "added noise" situation is perceived as quieter than the original engine noise.

Information Technology (IT) manufacturers deal with a potpourri of tonal and temporal patterns, often simultaneously. Figure 7 shows a Relative Approach 3D analysis of a PC workstation performing a hard disk access.

An unusual application in architectural/musical acoustics has been found,[4] quantifying perceived time/frequency patterns in the decay of a concert room's reverberant field. Figure 8 shows that a relative structure may be seen over a considerable time interval far into the absolute magnitude decline, in good accordance with the perceived structure of musical reverberant decays.

References

1. Genuit, Klaus, "A New Approach to Objective Determination of Noise Quality Based on Relative Parameters," Proceedings of Inter-Noise 1996, Liverpool, UK.
2. Sottek, Roland, Personal communication.
3. Sottek, Roland, "Modelle zur Signalverarbeitung im menschlichen Gehör," (dissertation, RWTH Aachen, 1993).

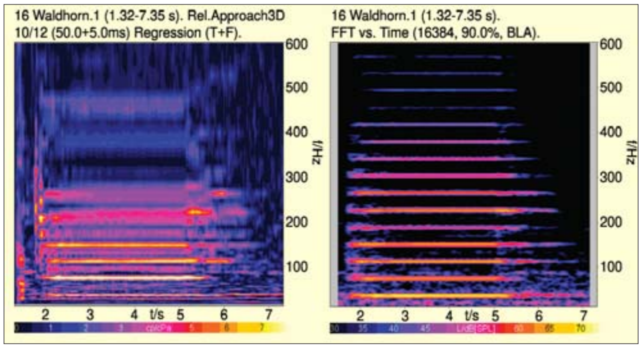

Figure 8. Reverberant field decay time/frequency structure. Left graph – Relative Approach 3D, sensitive to both time and frequency patterns. Right graph – FFT spectrum vs. time. Frequency scales are identical. Signal is from a single pipe organ pedal note, 16-foot E-flat, Waldhorn, in a moderately reverberant church. Much more perception-related information is detected in the Relative Approach measurement than in the conventional frequency spectrum vs. time. The wide diffuse-looking bands in the relative measurement indicate rapid time pattern (perceived as roughness) due to beating of harmonics. Information to the right of ~5.2 seconds follows release of the note. Speech-onset transients are also visible. The Relative Approach result in the region between about 300 and 450 Hz, where harmonics seen in the spectrum vs. time do not appear but their temporal interactions do, sensitively matches the auditory impression – the 8th through 11th harmonics of this musical note convey little individual timbral significance but distinctly affect evaluated time structure. A full-size diagram reveals fine time structure, especially in the reverberant decay.

4. Bray, Wade R., "Relationships of Level, Loudness and Time Structure in Pipe Organ, Registration and Design," 2aNS2, Session 2aNS, Noise and Psychological and Physiological Acoustics: Noise Impact Evaluation: Old and New I, 147th Meeting, Acoustical Society of America, New York, May 2004.

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