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**DE-DOPPLERIZATION OF ACOUSTIC
MEASUREMENTS**

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August 2017

Interim Report

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Summary

To ensure acoustic directivity patterns are valid across a wide range of sound source speeds the effect of Doppler shifting must be removed from acoustic measurements used to build directivity patterns. Traditionally, obtaining spectral information by analyzing acoustic measurements with Fourier transforms requires complex resampling to overcome stationary signal requirements. Here, a simple shifting of band energy obtained from fractional octave band digital filters generates a de-Dopplerized spectrum without complex resampling algorithms. An equation defining the amount of energy shifting required is derived from fractional octave center frequencies. This equation is applied to a numerical simulation and an overflight measurement to remove the Doppler affect in spectral data. The de-Dopplerization through application of energy shifting accurately removes vehicle motion effects from acoustic measurements without complex resampling.

1 INTRODUCTION

Construction of directivity patterns for acoustic emissions of airborne aircraft has been studied¹⁻⁶. Within spherical harmonic noise directivity pattern descriptions, no investigation of Doppler shifting is presented and the directivity patterns are only valid for the airspeeds at which the pattern is measured. In order to provide a more general description of the acoustic directivity patterns, de-Dopplerization is explored, specifically for application with spherical harmonic directivity patterns.

Doppler shifting is a well-known frequency modification effect observed whenever an object emitting periodic energy is moving relative to an observer. Morse provided a detailed discussion of the effects of the Doppler shift on sound energy⁷ resulting in two conditions: 1) compression of wavefronts leading to a higher observed frequency; and 2) expansion of wavefronts leading to a lower observed frequency. These two phenomena were classified by the rate of change of the direction vector pointing from the source to the observer⁸. If the vector length is shrinking, the wavefronts are compressing. Conversely, if the vector length is increasing the wavefronts are expanding. No Doppler shift is observed if the vector length is constant. The compression and expansion of the wavefronts occur due to motion of the observer or the acoustic source, but this analysis examines only the stationary observer case.

Previous efforts using a fixed array to record acoustic emissions, resulting from the motion of the acoustic source only, have been reported⁹⁻¹⁷. A number of techniques were previously used to remove Doppler effects from acoustic measurements. Among the most common method is a complex resampling of the acoustic waveform to preserve the ability to employ narrow band Fourier analysis¹¹.

In each of these instances, the determination of the sound pressure level (SPL) or power spectral density (PSD) is accomplished through a Fourier transform. Due to the coarseness of the fractional octave representation and smearing that occurs within the spectrum¹¹, digital filtering techniques were not considered by these earlier applications. Fourier transform methods assume a stationary signal^{18,19}, and the motion of the acoustic source violates that assumption. Use of Fourier transform methods require a time corrected signal^{9,11,12,15,19-21}. The general tenet of these methods is a sliding adjustment to the measured signal's sample rate.

Kelly^{12,21} examines the effect of Dopplerized measurements on analysis of aircraft flyover noise in the Fourier transform paradigm. His analysis ignores the stationary requirement with a quasi-stationary source assumption. Kelly also attempts to gain a general understanding of the noise source directivity by accounting for certain acoustic losses, but does not examine a full directivity pattern characterization.

Howell¹¹ infers that without removal of the Doppler shift, spectral levels are incorrect and often blurred in narrow band analyses of moving sources. Removing the Doppler shift corrects the spectral level in non-stationary sources and sharpens the

resolution of the frequency representation. Howell's de-Dopplerization¹¹ process requires accurate measurement of aircraft location to resample the time signal to account for the compression and expansion of acoustic wavefronts. Correcting the time history in this manner however only adjusts the signal for the source location.

Kook²⁰ examines the de-Dopplerization problem for a slightly different measurement activity: defining the location and magnitude of noise on the sides of automobiles during standardized pass-by tests. Kook reports on a beamforming array methodology that attempts to create the stationary acoustic profile from a moving source and stationary microphone array. As with the efforts of Howell¹¹ and Kelly^{12,21}, Kook recognizes the measured signal contains Dopplerized acoustic signals. Kook employs a re-sampling technique similar to Howell¹¹.

Unlike the characterization methods described above, metrics describing the human auditory system's response to acoustic stimuli utilize fractional octave spectral levels²². Since the Air Force Research Laboratory (AFRL) is concerned with human audition, a new method to remove the Doppler shift based on adjusting the fractional octave band number is defined. This fractional octave band shifting (FOBS) determines the amount of energy within a fractional octave that is shifted to adjacent bands due to Doppler effect. The numerical calculation of this shifting is accomplished through a simple formula derived from the fractional octave center frequency. FOBS is shown to accurately remove the Doppler effect in a numerical simulation and a real measurement without complex resampling or addressing acoustic losses.

2 FRACTIONAL OCTAVE BAND SHIFTING

2.1 Definition of Doppler shift frequency

Definition of the fractional octave band shifting requires an examination first of the definition of the Doppler frequency shift. Textbooks^{7,8} define this frequency shift between a stationary observer and moving source as:

$$f' = f \frac{1}{1 \mp \frac{v_s}{c_0}} \quad (1)$$

where the '-' sign is when the source is approaching; '+' when the source is moving away; and c_0 is the reference speed of sound. More generally, the Doppler frequency is described as a dot product of a unit vector pointing from the source to the receiver and the velocity vector^{13,21}:

$$f' = f \frac{1}{1 - \vec{M}(\tau) \cdot \vec{n}(\tau)} = f \frac{1}{1 - |\vec{M}| |\vec{n}| \cos \vartheta} = f \frac{1}{1 - M \cos \vartheta} \quad (2)$$

where $M = v/c_0$ is the MACH vector magnitude and ϑ is the angle between the MACH vector and the unit vector pointing ($\vec{n}(\tau)$) from the source to the receiver. By translating

Kelly's coordinate system to a source center of mass coordinate system²³ Eqn. 2 becomes:

$$f' = f \frac{1}{1 - M \cos \theta \sin \varphi} \quad (3)$$

The angles θ and φ are the spherical angles defined by the canonical transformations of the vector pointing from the source to the receiver where: $\theta = \tan^{-1}(y/x)$, $\varphi = \cos^{-1}(z/R)$ and R is the radial distance between the source and observer.

2.2 Definition of Fractional Octave Band Shifting

Glegg suggests that the time delay inherent in acoustic measurements of moving sources can be addressed through digital filters with time varying coefficients¹⁷. Howell uses digital filters to correct for external acoustic losses¹¹. From Howell¹¹ and Glegg¹⁷, filtering methods are not susceptible to the stationary requirement of Fourier transforms.

Definition of FOBS starts with the definition of the center frequency of a fractional octave filter. For example, one-third-octave (TOB) filter shapes are defined along with center and edge frequencies²⁴, where the center frequencies are represented by:

$$f = 1000 \cdot 2^{(n-30)/3} \text{ Hz} \quad , \quad (4)$$

where n is the TOB band number ($n = 10 \rightarrow 10 \text{ Hz}$, $n = 20 \rightarrow 100 \text{ Hz}$, $n = 30 \rightarrow 1 \text{ kHz}$, and $n = 40 \rightarrow 10 \text{ kHz}$). Inversion of Eqn. 4 defines the TOB band number (base-2 logarithms are used for simplification purposes):

$$n = 3 \left[\log_2 \left(\frac{f}{1000} \right) / \log_2(2) \right] + 30 \quad . \quad (5)$$

FOBS employs the fractional band shift defined by the difference in the band number of Eqn. 5 due to Doppler effects:

$$\Delta n = n - n' = 3 \left[\frac{\log_2 \left(\frac{f}{1000} \right)}{\log_2(2)} \right] - 3 \left[\frac{\log_2 \left(\frac{f'}{1000} \right)}{\log_2(2)} \right] \quad (6)$$

Define the Doppler shift multiplier as $\chi = 1/(1 - M \cos \theta \sin \varphi)$ and Eqn. 6 becomes

$$\Delta n = \frac{3}{\log_2(2)} \left[\log_2 \left(\frac{f}{f'} \right) \right] = 3 \left[\log_2 \left(\frac{f}{f \chi} \right) \right] \quad . \quad (7)$$

The final FOBS equation is

$$\Delta n = -r [\log_2(1 - M \cos \theta \sin \varphi)] \quad , \quad (8)$$

where r is the fractional octave resolution. For example, the one-third-octave representation is $\Delta n_{TOB} = -3 [\log_2(1 - M \cos \theta \sin \varphi)]$, and $\Delta n_{TwOB} = -12 [\log_2(1 - M \cos \theta \sin \varphi)]$ is the twelfth octave band resolution formula.

Unlike Fourier transforms, which possess constant bandwidth, fractional octave bands possess logarithmically increasing bandwidth with increasing center frequencies. The fractional octave bandwidth for any given center frequency is represented by:

$$BW = f [2^{1/2r} - 2^{-1/2r}] \quad , \quad (9)$$

where r is the fractional number used in Eqn. 8. If the frequency variables in Eqn. 7 are replaced with corresponding BW variables, the multiplicative factor in Eqn. 9 divides out leaving Eqn. 8.

Employing Eqn. 8 to de-Dopplerize a measured data set is accomplished by first obtaining the sound pressure level spectrum at a chosen resolution through application of digital filter bank. This spectrum is defined at a measurement time, or time of arrival for acoustic energy at the receiver. The spherical angles used in Eqn. 8 are determined at emission time. In other research efforts the emission time is referred to as the retarded time^{2,3} and is defined as $t_{emission} = t_{arrival} - R/c$, where R is the propagation distance and c is the adiabatic speed of sound. A corresponding $t_{arrival}$ for each Δn is determined, and this is interpolated to the acoustic measurement time to define the band shift. An example of this Δn for a flyover measurement, calculated at 1/12 OB, is shown in Fig. 1. Notice that the band shift represents the shifting required to restore the original signal. Thus the Δn is negative for the approaching, forcing a shifting from higher to lower frequency and positive for receding.

Now that the band shift for a single spectrum is obtained, a proportional distribution of the energy within the spectrum is determined. For example, the Δn value in Fig. 1 at $t_{arrival} = 830 \text{ min}$ equals -2.8059. This value represents the number of frequency bands that must be shifted at any specific frequency to compensate for the Doppler effect. At this time, the aircraft is still approaching the observer location and the frequencies are compressed due to the Doppler shift. To compensate, the energy of the sound pressure level spectrum is shifted to lower frequencies by nearly three bands.

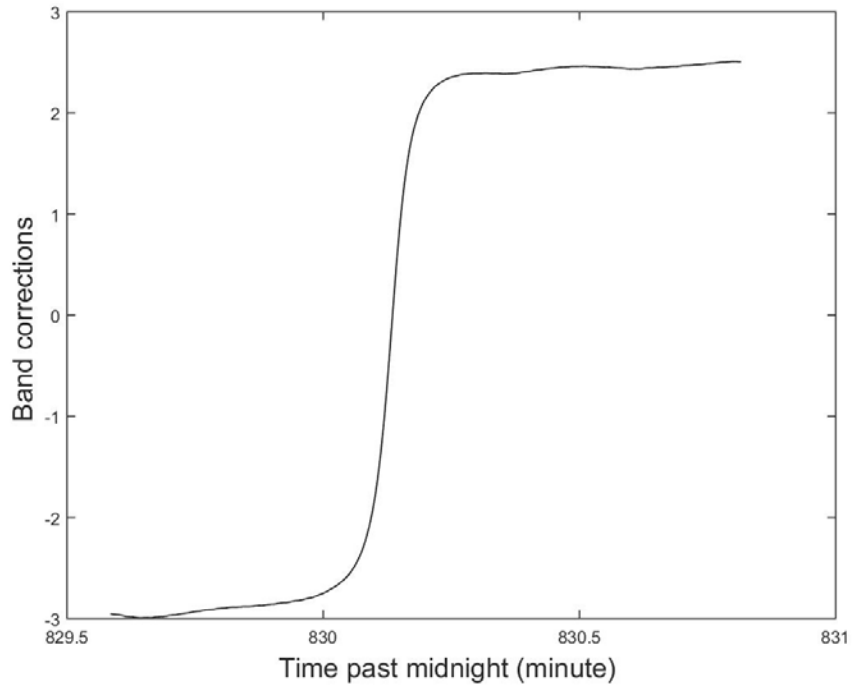


Figure 1. FOBS due to overflight conditions

FOBS employs two temporary spectra: one shifted three bands ($SPL_{\lfloor \Delta n \rfloor + 1}$) and one shifted two bands ($SPL_{\lfloor \Delta n \rfloor}$) to a lower frequency (here $\lfloor \Delta n \rfloor$ is the integer floor of Δn). The correct spectrum is partway between these two spectra and is a linear combination of the acoustic pressure within the two temporary spectra.

$$SPL = (\Delta n - \lfloor \Delta n \rfloor) \cdot SPL_{\lfloor \Delta n \rfloor} + (1 - (\Delta n - \lfloor \Delta n \rfloor)) \cdot SPL_{\lfloor \Delta n \rfloor + 1} \quad (10)$$

3 VALIDATION OF FOBS

3.1 Simulated acoustic source motion

To test the validity of the FOBS method, a noise source simulation is employed. The simulation places a 500 Hz acoustic source 500 m away from a simulated receiver. The acoustic source moves in a straight line toward the receiver at constant velocity of $v = 50$ m/s. The received waveform is calculated once per period at a sample rate of 48 kHz, with the amplitude modified by the spherical spreading loss only. After computing a single period waveform, the acoustic source is moved along the straight line for the length of that period ($l_{period} = T \cdot v$), and then the frequency is updated. This continues until

the virtual source is 500 m away from the receiver. The source moves a total of 1000 m during the simulation.

Two simulations are generated with this period-by-period method. The first is the control, where the frequency is constant throughout the simulation. The second simulation modifies the frequency each period with Eqn. 3. In both simulations the period is dynamically calculated based on the frequency to ensure that the transition between periods occurs at a zero thus producing no auditory artifacts. The sound source position is modified by the period and constant speed. Spectrograms for both signals are shown in Figs. 2 and 3 and are calculated with a one-third-octave band filter bank employing Butterworth digital filters.

To examine the results of the FOBS correction, Fig. 4 shows the 500 Hz trace from the control (black trace). The 500 Hz trace from the FOBS method is displayed in red. Finally, the original 500 Hz trace from Fig. 3 is displayed to show the magnitude of the corrections produced by FOBS. The difference between the control (black) and corrected (red) data at the peak is zero. This is directly due to the polar angle (θ) equaling zero, resulting in $\Delta n = -3[\log_2(1)] = 0$.

3.2 de-Dopplerization of acoustic measurements

Definition of the acoustic levels during an overflight measurement requires de-Dopplerization^{11,21}. However, use of fractional octave analysis and spherical harmonics is not addressed in methods requiring de-Dopplerized measurements^{4,5,25}. Presented here is data collected from a UH-1 Iroquois aircraft measurement which has been employed for testing enhancements to spherical harmonic source construction⁵.

Source construction employs a large outdoor acoustic array²⁶ similar to the array used by Swiss Federal Laboratories⁴. The one-twelfth-octave resolution sound pressure level time history is shown in Fig. 5A for one microphone and one pass. The tonal nature of the signature is evident from this spectrogram. It is also noticed that the tonal lines possess a clear Doppler shift due to the aircraft's 100 knots indicated airspeed.

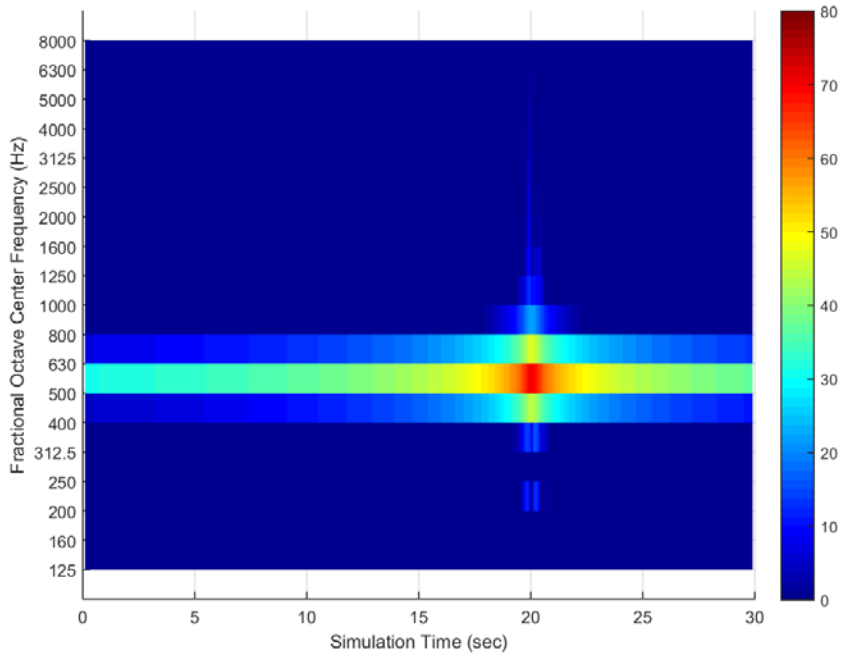


Figure 2. Control data for the simulation, without the Doppler shift modifying the frequency of the simulated source

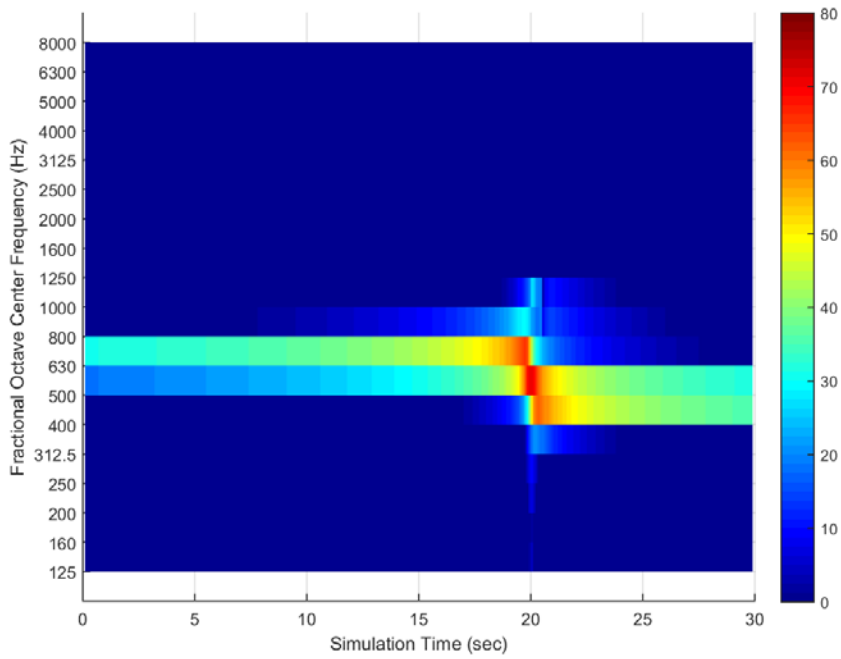


Figure 3. Resultant spectrogram from 500 Hz acoustic simulation

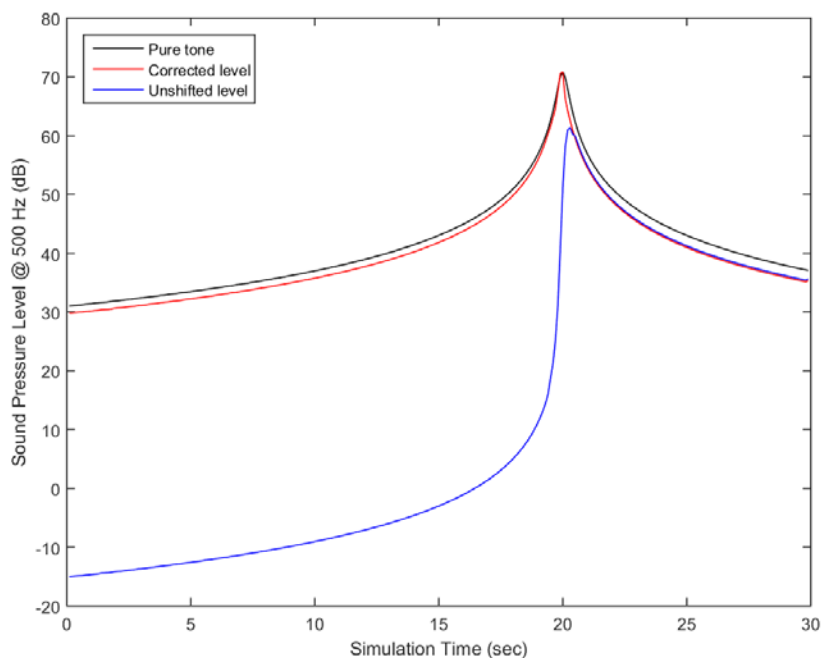


Figure 4. Corrected sound pressure level for 500 Hz of the acoustic simulation

The numeric band shift is determined for this flight track and applied to the spectrogram in Fig. 5A. The resulting spectrogram is shown in Fig. 5B. Unlike the simulation in Sec. 3.1, there is no known control for the de-Dopplerization of the measured signature. In Fig. 5B the tonal components have been shifted to line-up on approach and receding. There does appear to be smearing around time 830.1, but this may be due to the downdraft of the aircraft rather than the smearing suggested by Howell¹¹.

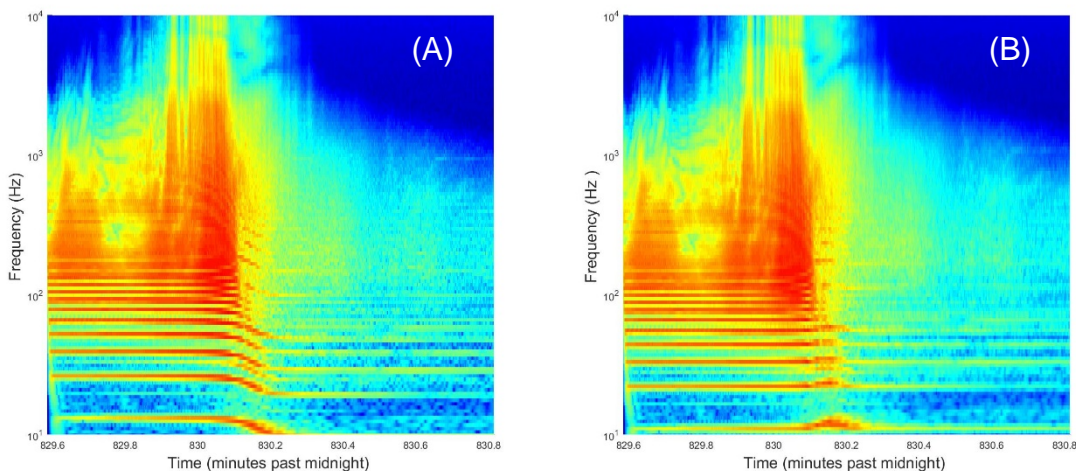


Figure 5. The original spectrogram from the UH-1 I measurement (A) and the FOBS corrected spectrogram (B)

4 DISCUSSION

The removal of the Doppler shift using FOBS is successful in both the simulation and real measurement. The simulation result possesses deviations during the sound source's transition, with a less than 3 dB error at the tail of the measurement. However, the shape of the 500 Hz trace matches better than the un-shifted data at 500 Hz (see Fig. 4).

Plotting the delta between the control (black trace in Fig. 4) and FOBS output (red trace) provides insight to the areas where the method produces uncertainty (see Fig. 6). The approaching and receding errors are roughly equivalent, separated by a single decibel. When the sound source is closest to the virtual receiver, there is a large shift in uncertainty, the magnitude shifting to as much as 5 dB. Part of this is due to the transition between compression and expansion of the wavefronts, it is changing the mechanism of the Doppler shift.

This discontinuity at the overhead time requires additional examination of the linear combination coefficients. Figure 8 shows the $[\Delta n]$ and $[\Delta n] + 1$ values with the Δn . Also shown is the computed linear coefficients. There is a dramatic inversion of the values of the two linear coefficients at the 20 second simulation time. This is when the virtual sound source is directly overhead of the virtual receiver and the Doppler correction is zero. The rapid transition from the compression to expansion of the wavefronts causes the discontinuity observed in the error between the control and the FOBS result (Fig. 6).

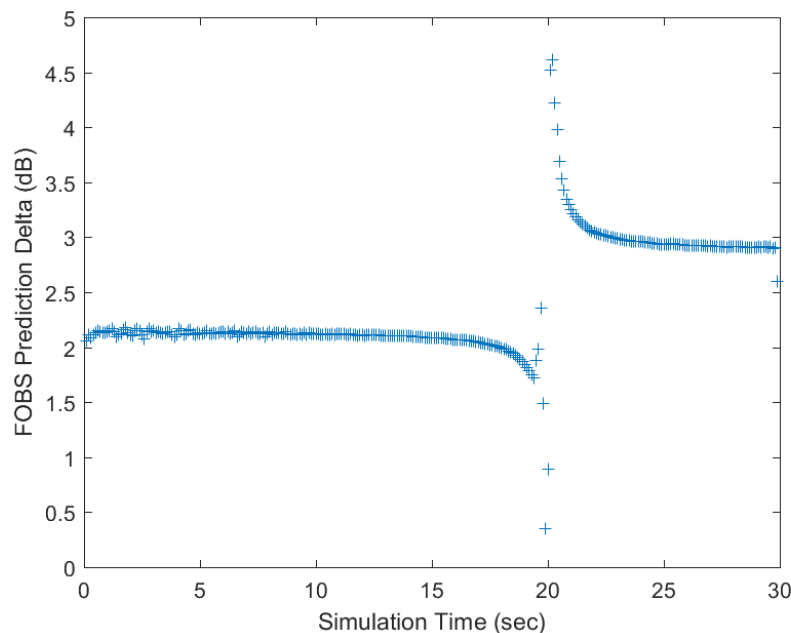


Figure 6. Difference between the control 500 Hz trace and FOBS 500 Hz trace over the simulation time

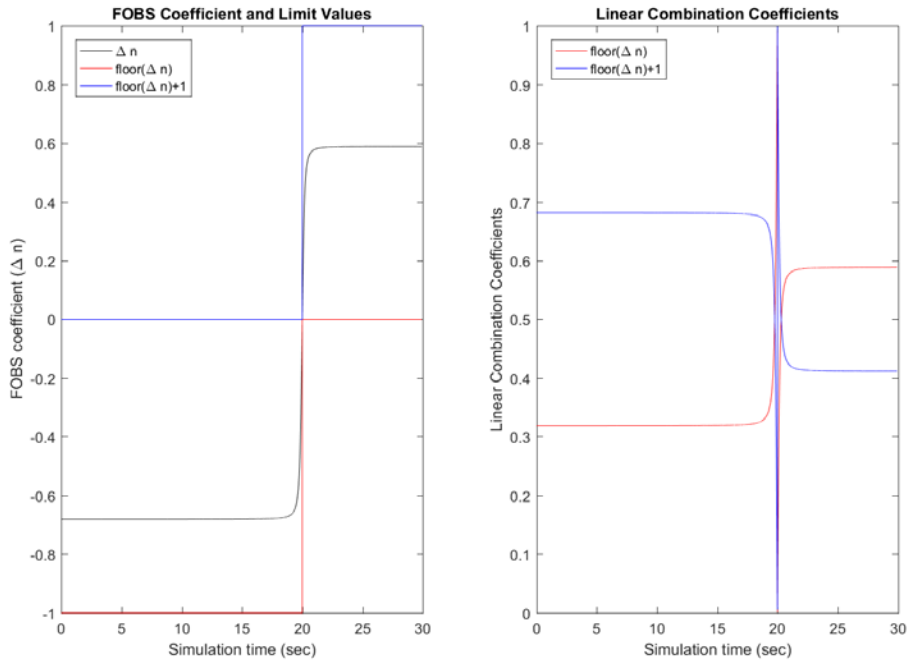


Figure 7. Comparison of the Δn and the limits on the linear coefficients

5 CONCLUSIONS

Removal of Doppler shifting effects is vital to accurate representation of acoustic signals. Analysis using Fourier transformations requires sound source to be stationary, which is obviously not possible during over-flight conditions.

The effects of acoustics on humans is more accurately represented through fractional octave analysis. Digital filters are independent of the stationary requirement of Fourier transforms. A method to shift energy into adjacent fractional octave bands is shown effective in a simple simulation and field measurements. The fractional octave band shifting (FOBS) method removes the complex resampling proposed for use with Fourier transforms, and is applied to any fractional octave bandwidth.

FOBS removes the shifting caused by the Doppler shifting in an over-flight of a UH-1 Iroquois. The simplicity of the FOBS method makes it more applicable to acoustic measurements over the complex resampling of the waveform.

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SYMBOLS, ABBREVIATIONS, & ACRONYMS

711 HPW/RHCB

Air Force Research Laboratory, Human Performance Wing, Human Effectiveness Directorate, Warfighter Interface Division, Battlespace Acoustics Branch

dB
FOBS
Hz
m

Decibel
FRACTIONAL OCTAVE BAND SHIFTING
Hertz
Meter