Sine Waves are Stubborn Things

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The Land that God Forgot *but* NATO Remembered. When I was growing up in post-World-War-II Norway, the Cold War was in full swing, with Korea, the Berlin blockade and insurrection in Hungary. Norway was and is a member of NATO, and having a common border with Russia in the Arctic, we had compulsory military service. We did not know about Mensa then, but after the usual aptitude tests, I was told that I could use my acceptance into the infantry as a sure way to impress girls. This turned out to be a useless blessing, since the Army then sent me into the tundra, where the number of girls was far less than the number of reindeer and mosquitos.

Now we are getting closer to the point, if any, of this editorial, in that the Army bestowed upon me 50,000 rounds of WWII ammunition and proceeded to train me as a machine gunner. Hearing protection consisted of wet moss formed into little plugs and put into the ear canals. During the next happy months, I acquired notch filters in my hearing that rendered me incapable of distinguishing between certain consonants. This is what is now called NIHL, or, noise-induced hearing loss.

Other than fishing and hunting, there was absolutely nothing to do (remember the sparse female population), so when I was offered officer training with a free choice of academic subjects, I took the bait. The Army told me that I was now a gentleman, but somehow did not provide me a sufficient stipend to live like one. Hence, this infantryman, with a degree in mathematics, left the mosquitos behind and was let loose on the engineering community, first with a job at the University of Stuttgart in Germany and then on to a job in structural dynamics in Cincinnati, and through a convoluted journey to a position with ATA Engineering in San Diego.

The Point of the Story. Fast forward to today; my hearing is not getting better, and I am getting involved in acoustics, the kind where sine waves play a significant role. The aero engine industry is under immense pressure to improve fuel economy, and, community noise is now a limiting issue for passenger traffic. Military jet engines have a very low bypass ratio, possess outstanding performance, but are so loud that the military finds itself spending billions on medical care on service members who suffer noise-induced hearing loss, and are often forced to fly from remote locations to avoid community action against the aircraft noise.

While the military cannot give up on performance, the civilian aircraft engine industry is looking at two main alternatives. One is the turbofan engine with a huge bypass ratio and low RPMs, driven through a reduction gear set that lets the power plant run economically and quietly. The other is the dual open, counter-rotating rotor engine that offers superior fuel efficiency, albeit at the expense of serious noise issues.

Figure 1. Dual-open rotor.

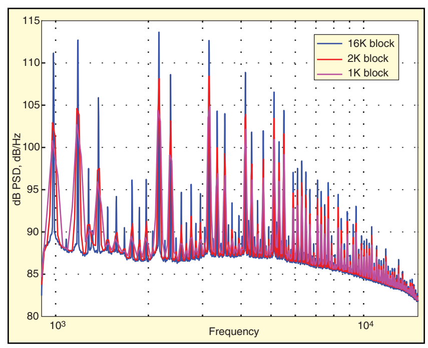

Figure 2. Power spectral density of dual-open rotor with different frequency resolutions.

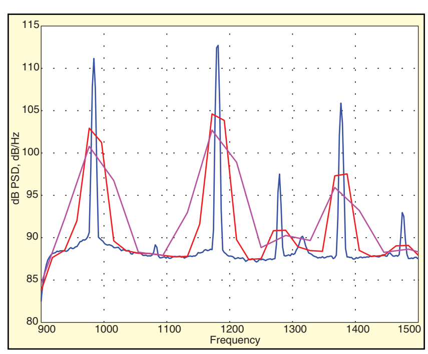

Figure 3. Zoom image of narrowband PSD with different frequency resolutions.

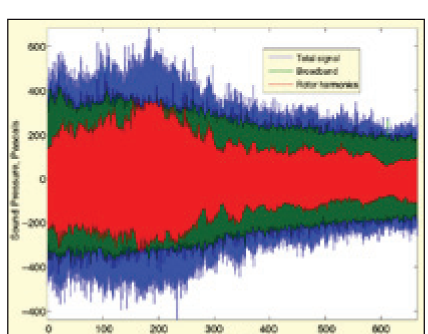

Figure 4. Wold decomposition of total signal into broadband noise and rotor harmonics.

The geared turbofan is ducted and runs with acoustic liners, but the fan noise is now becoming the dominant noise source. In both cases, the main noise sources are in the form of rotor harmonics – or sine waves. The old-fashioned low-bypass jet engine offers Mach wave noise radiation and broadband shock associated noise ((BBSAN), both of which are broadband phenomena.

The trouble with sine wave noise is that the acoustic energy is concentrated at a few discrete frequencies that give it a persistent, cutting and deeply disturbing nature as perceived by humans. The challenge for us as test engineers is to measure and characterize the noise phenomena, in terms of loudness, directivity and subjective annoyance levels. In the acoustic near field, we need to understand the ensuing vibroacoustic and fatigue loads. And in the far field, we need to get a handle on shielding and community noise.

To understand and to create a public domain reference base for open rotor noise, General Electric and NASA joined forces a few years ago to reconstitute a late 1980s dual open, rotor model, tuned it to perform similarly to the old GE wind tunnel measurements, and set it up in the 9 × 15 wind tunnel at the NASA Glenn Research Center near Cleveland, OH. Aeroacoustic measurements were performed in a number of approach and takeoff conditions, and these measurements are now available to industry as reference data. This historical open-rotor system is fairly crude by today's standards, where improved rotor shapes and aerodynamic innovations are continuing to reduce the noise levels substantially.

My story is anecdotal, using data from this historical open rotor, seen in Figure 1, to illuminate the role of sine waves and broadband noise. While the two rotors ran with approximately the same speed, but in opposite directions, a traversing microphone ran a distance of 260 inches in 700 seconds along the rotors to capture the noise as heard from a continuous range of polar angles. Meanwhile, air was being forced through the tunnel at Mach 0.2 to simulate an approach condition.

The total time history was now fed into an FFT-based power spectral density calculation with three different frequency resolutions, which is shown in Figure 2. The shape of the spectrum is that of a fairly uniform broadband noise floor with a myriad of blade-pass harmonics. Upon inspection, easily seen in the zoomed image (Figure 3), the amplitude of the harmonics is a function of frequency resolution, which drives home the point that one cannot judge the strength of harmonics, or sine waves, from a narrowband power spectral density. This is because sine waves are like delta functions in the frequency domain, having all their energy at a single frequency, while

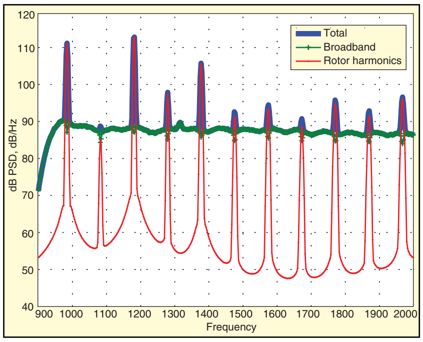

Figure 5. Wold decomposition by narrowband spectra.

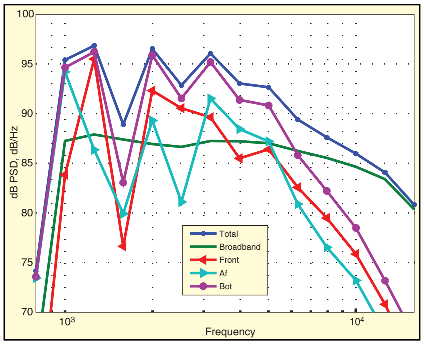

Figure 6. Wold decomposition by third octaves.

broadband noise has zero energy at a single frequency, so that broadband energy must be found by integrating a density over a finite frequency band.

This means that sine waves and broadband noise must be processed differently, even though they are superposed. To this effect, in the 1930s, Herman Wold, a young Norwegian mathematician, went to Stockholm to get his doctorate in stationary stochastic processes under the great Harald Cramer. In his thesis, he showed that under very general circumstances, any reasonable physical process could be uniquely decomposed into a collection of sine waves and a moving average of white noise (broadband process).

While this can be formulated precisely in mathematical terms, we find that the *low-falutin*' description suffices for engineering purposes. This decomposition is now known as the Wold decomposition. (Herman Wold later became a Swedish citizen, probably because he was so modest that he thought that admitting that he was Norwegian sounded like bragging.)

To obtain the Wold decomposition of the open rotor time history, we applied the Vold-Kalman filter, using the tachometer signals from each rotor as speed references and could thereby split the microphone signal into rotor harmonics and broadband noise (see Figure 4). Visually, from this time domain plot, it would appear as if the rotor harmonics are dominated by the broadband noise, but this is shown to be false when we look at objective measures of sound pressure energy in frequency bands. A zoomed narrowband PSD of the total signal, the rotor harmonics and the broadband components are shown in Figure 5. But to properly assess the energy of the rotor harmonics compared to the broadband, in Figure 6 we compute a third-octave power spectral density that simply shows the acoustic energy in finite frequency bands, regardless of the pedigree of the individual sound components. Inspection of this plot tells us about the relative importance of the broadband noise, the rotor harmonics, even how much to blame each individual rotor.

The importance of splitting a composite sound field into sinusoidal and broadband components cannot be overstated, because these components are best analyzed with special tools, and they also will have different directivities and subjective nuisance values.

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