NATIONAL TRANSPORTATION SAFETY BOARD
Vehicle Recorder Division
Washington, DC 20594

January 18, 2022

Sound Spectrum Study

Specialist's Factual Report
By Sean Payne

1. EVENT

Location:	Thomson, GA
Date:	October 5, 2021
Aircraft:	Dassault Falcon 20C
Registration:	N283SA
Operator:	Pak West Airlines
NTSB Number:	ERA22FA004

2. GROUP

A group was convened on November 3 & 4, 2021, at the NTSB's Vehicle Recorder Division laboratory in Washington, D.C. The group consisted of the following individuals:

Chairman:	Sean Payne Sr. Mechanical Engineer/Investigator National Transportation Safety Board (NTSB)
Member:	David Gridley Commercial Flight Safety Investigator GE Aviation

3. DETAILS OF INVESTIGATION

The National Transportation Safety Board (NTSB) Vehicle Recorder Division received the following Cockpit Voice Recorder (CVR):

Recorder Manufacturer/Model:	**Fairchild GA-100**
Recorder Serial Number:	**01844**

3.1. Recorder Description

For a description of the device, refer to section 3.2 of the Cockpit Voice Recorder (CVR) Group Chairman's Factual Report, which can be found in the public docket for this investigation.

3.2. Recorder Damage

For a description of the device, refer to section 3.3 of the Cockpit Voice Recorder (CVR) Group Chairman's Factual Report, which can be found in the public docket for this investigation.

3.3. Audio Recording Description

For a description of the audio files extracted from the CVR, refer to the Cockpit Voice Recorder (CVR) Group Chairman's Factual Report, which can be found in the public docket for this investigation.

3.4. Sound Spectrum Study

Recorded audio from the cockpit area mic (CAM) channel was evaluated in an attempt to determine the engines' operating speeds during the final approach phase of the accident flight.

The accident aircraft was equipped with two General Electric (GE) CF700-2D-2 turbo fan engines. The CF700-2D-2 is a compact, lightweight, high thrust turbofan engine, with an eight-stage axial flow compressor coupled directly to a two-stage turbine (HPT), behind which is a single stage free-floating aft fan. This aft fan rotor has 54 'bluckets', each consisting of 2 airfoil sections separated by a dividing platform; the inner airfoil sections are the turbine blades (LPT) and the outer airfoil sections are the fan blades.

Figure 1 is a cutaway of a CF700-2D-2 turbo fan engine. Note that the stage 1 compressor section containing 30 airfoils has been annotated, as well as the stage 2 fan section containing 54 bluckets.[1] This will be explained further below.

The audio from the CVR was reviewed for its potential use in a sound spectrum study. A spectrogram was generated showing the frequency content of the sound and how it changes over time. In the sound spectrum, it was apparent that characteristics of the aircraft's two operating engines could be determined, in various stages of the accident flight, however, the final phase of flight was determined to be of most interest. Correlating this to information from the CVR transcription, it was determined that operational characteristics of the engine could be determined in the sound spectrum from roughly 29 minutes and10 seconds (29:30) elapsed time until the aircraft's impact with terrain at approximately 30:23.5 elapsed time. These times, when correlated to information from Cockpit Voice Recorder present a time range from 5:42:58 EDT (around the time the captain canceled IFR clearance) to 5:44:11.5 EDT (the aircraft's impact with terrain).

Figure 2 is a spectrogram covering the time frame portion noted above. The x-axis represents elapsed time of the CVR recording. Times converted to EDT have been appended to the spectrogram as well as five distinct segments of the final portion of the audio recording. These segments were selected as engine speed traces indicate the aircraft's engines changed speed distinctly in each identified segment.

[1] Bluckets – General Electric uses the term blucket to describe the arrangement of blades at the tip of the fan and turbine buckets at the root.

The y-axis represents sound frequency in Hertz (Hz), and the color represents sound intensity. In the arrangement for this spectrogram, higher sound intensity is indicated by a brighter orange color.

The software used to create the spectrogram can be expanded to show frequency information in greater detail.

Figure 3 is a spectrogram with the Y-axis adjusted to show a frequency range from approximately 0 Hz to 435 Hz. The same time regions presented in figure 2 are also annotated.

The different mechanical parts of the engine produce different noises that occur and harmonize at different frequencies. The primary frequency a noise occurs at is called the fundamental frequency and the secondary and upper harmonies are referred to as harmonic frequencies. This fundamental frequency equates to the engine's rotational speed (N1) for the compressor and the fan speed (N2) for the fan rotor. This fundamental frequency is known as the "1 per rev" or "1X" state.

When a fundamental frequency is identified, it can be equated to either engine speed or fan speed. The fundamental frequency is represented as 1X and is the frequency measured in Hz (cycles or revs per sec). Using known engineering and operational data, such as the design of the engine, or the number of rotational components (blades or bluckets in this case), an operating speed can be determined.

For this engine, the following engineering data was obtained from GE:

- 100% engine core speed = 16,500 rpm = 275 Hz.
- 100% fan speed = 8,570 rpm = 143 Hz.

In this portion of the accident recording, the engine's compressor produced a clean noise signal between 133 and 220 Hz. Knowing the information above, the 1X (fundamental frequency) correlates to engine core speeds of 48% and 80% N1.

Also, knowing the number of compressor stage 1 airfoils (30 blades) and fan 'bluckets' (54 bluckets) allows a blade passing frequency to be identified (ie. 30X x N1/60 and 54X x N2/60). Furthermore, since internal components (accessories) of the engine are mechanically driven off the compressor, these frequency data can also be used to interpolate other engine component operational speeds.

In this accident, the engine's core section, specifically the stage 1 compressor, produced a clean signal between approximately 133 Hz and 220 Hz. The stage 1 compressor section contained 30 compressor blades. As such, the fundamental frequency was multiplied by 30 to determine the stage 1 blade passing frequency. Fan speed is the fundamental frequency converted to RPM. Where possible, that upper range frequency was identified to confirm the results.

This aircraft was equipped with two engines. The frequency information available is not sufficient to determine which signal is from engine 1 (left) or engine 2 (right). As such one trace is labeled "Engine A" and the other trace labeled "Engine B."

Figure 4 is a spectrogram expanded in the frequency range of the Y-Axis to show fundamental frequency data for the 30x compressor section (upper frequency range). Note that the Y-Axis scale in figure 4 has changed in order to represent upper frequency ranges of the 30X per rev stage 1 compressor airfoil blade passing frequency audio.

Figure 5 denotes the fundamental frequencies of the stage 1 compressor section. Note that in Area 3 (5:43:14 EDT to 5:43:29 EDT), only a trace for Engine B is identified. This does not mean that engine A was not operational, but rather likely that the frequency trace was obscured by other audio information, partially as a result of the poor quality CVR CAM channel recording. Furthermore, denoted on figure 4 in Area 4 (5:43:29 EDT to 5:44:06 EDT), the signal for Engine A and Engine B appear to merge. This is represented in the spectrogram by a brighter orange line. The scale for intensity is given in decibels (dB) and is also shown on the Y-axis.

Figure 6 is the same as figure 4, however, information for the stage 2 (N2) fan section is denoted. The fundamental frequency of N2 fan section was not detected in the spectrogram, however, the second harmonic of the N2 fan section sound was able to be identified. By identifying the noise as the second harmonic (2X) of the fan section, and then dividing that frequency by 2, gives you the fundamental frequency (1X), which equates to fan rotational speed (N2). If this second harmonic is then multiplied by 27 (to give 54X), that would equate to the fan blade passing frequency. In this case that would be at:

- In Area 3 – 235 Hz x 27 = 6,345 Hz.
- In Area 4 – 215 Hz x 27 = 5,805 Hz.

Engineering data for the CF700-2D-2 engine was obtained from GE to determine the associated fan speeds with a percent N1 and a percent N2 value.

Figure 7 shows a summary of the calculations from this exercise. Note that in some areas, such as Engine B's %N1 core speed calculations for Area 3, the fundamental, 2X, or 3X signal was not present in the sound spectrum. In these instances, other harmonics were observed, in this case the 30X blade pass was visible around 4,900 Hz, which is annotated in Figure 4.

Table 1 presents all of the information provided from figures 2 through 6 above and correlates those values to percent N1 and percent N2 values. When an engine reached a value of idle, the table denotes "flight idle."

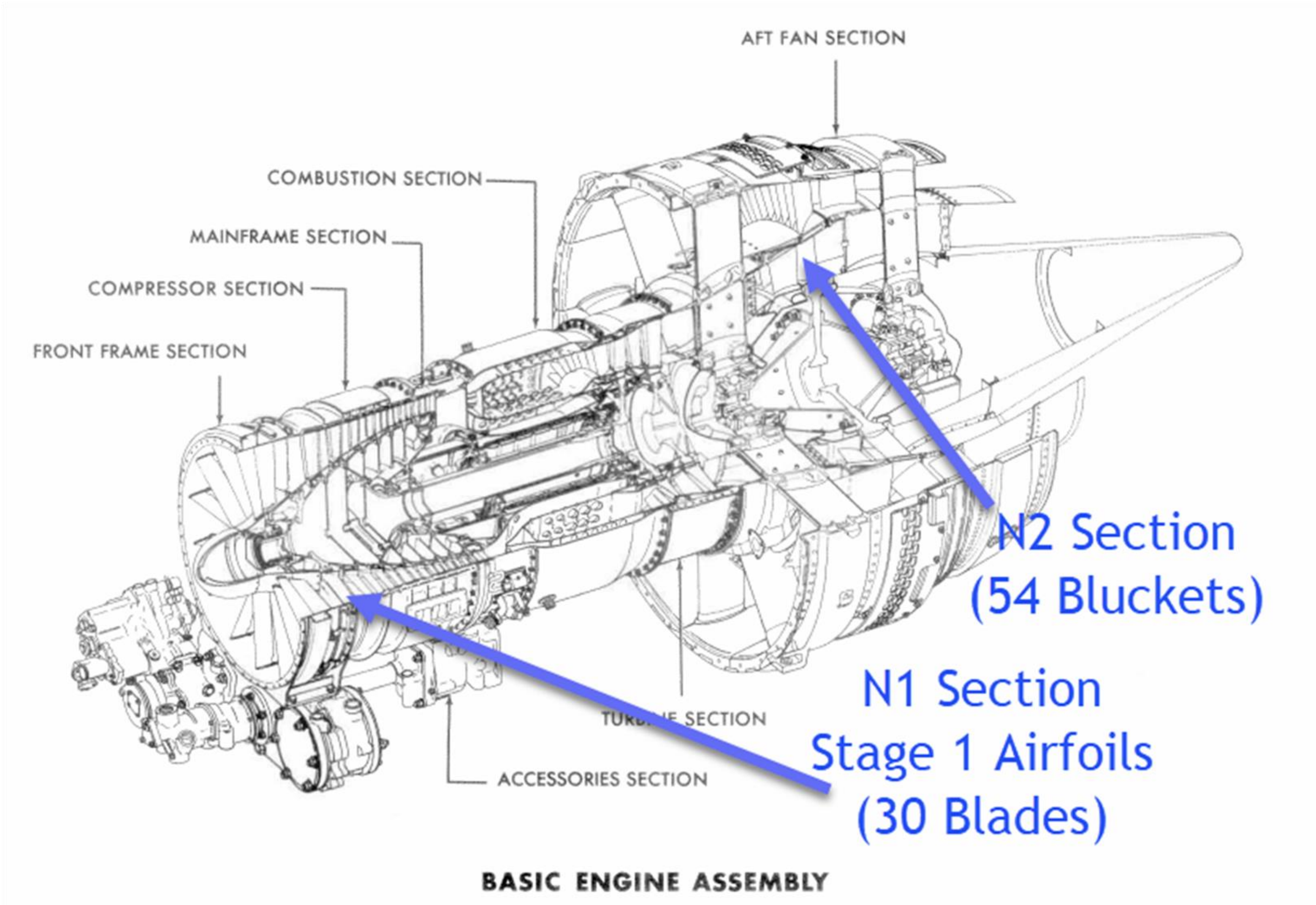

Figure 1. An annotated cutaway diagram of the General Electric CF700-2D-2. The 30-blade stage 1 compressor section has been annotated, as well as the 54 blucketed stage 2 hot section.

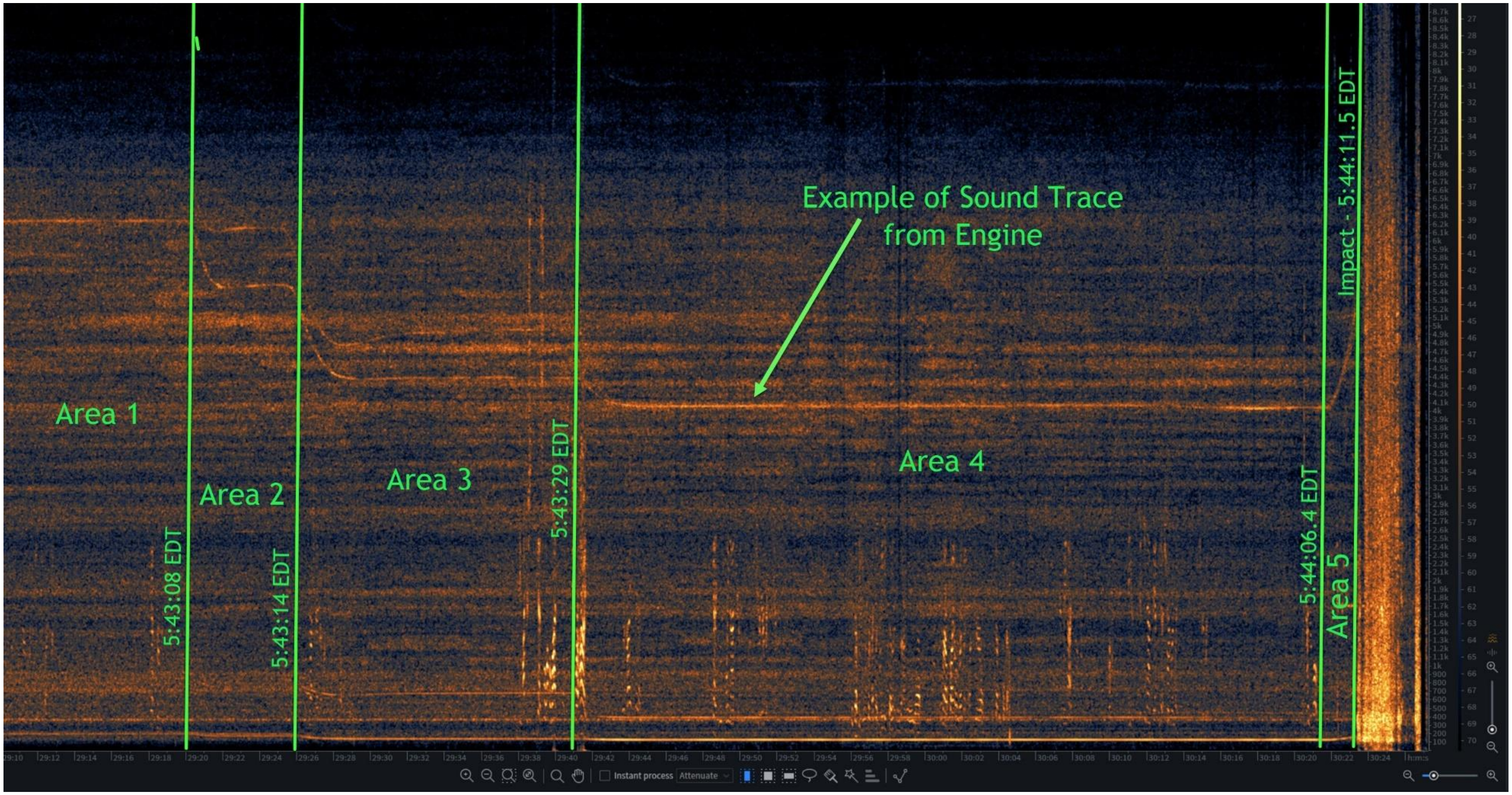

Figure 2. A spectrogram of the final portion of the accident flight with different times correlated from the CVR displayed.

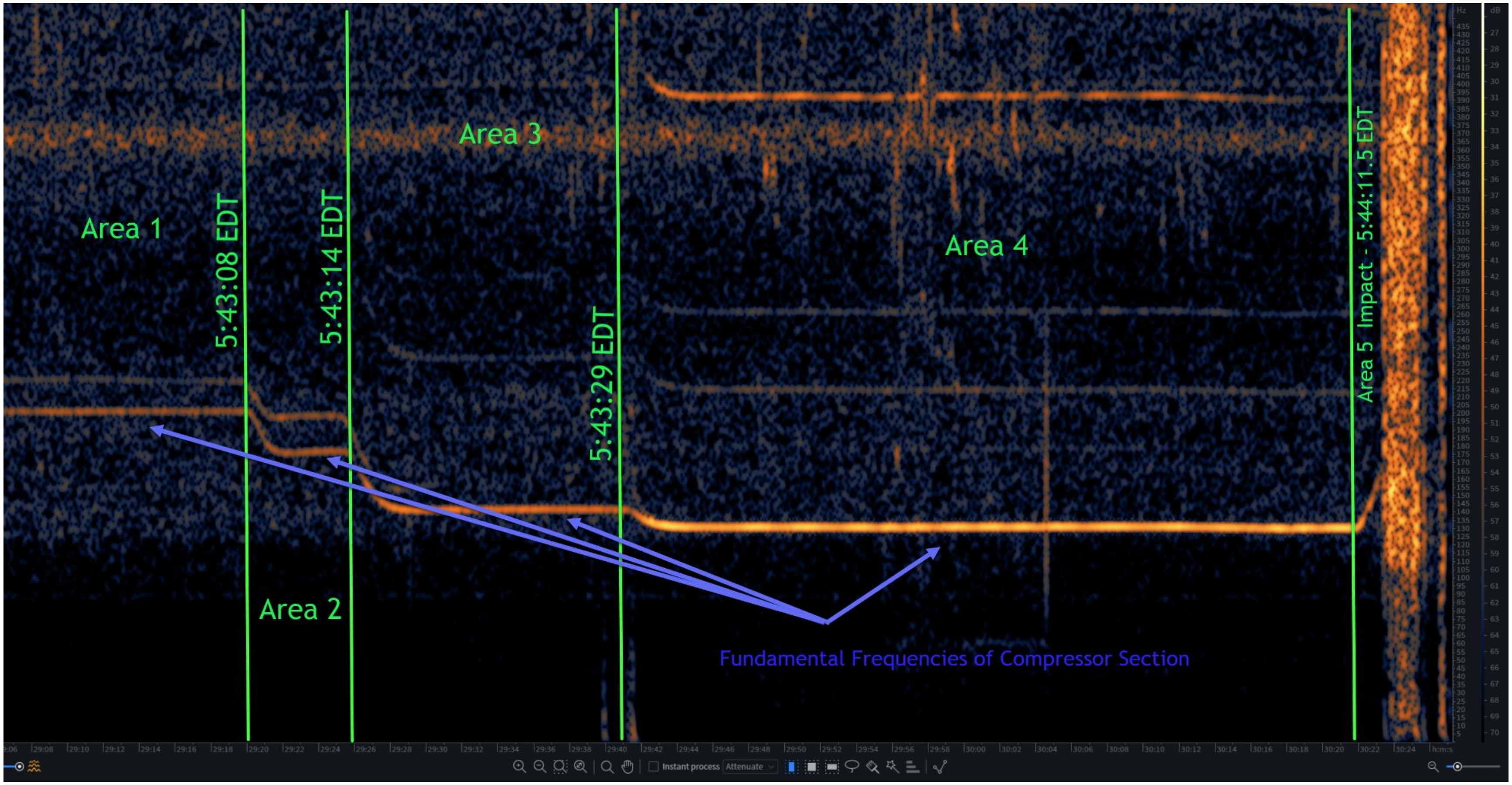

Figure 3. A spectrogram expanded in the frequency range of the Y-Axis to show fundamental frequency data for the compressor section.

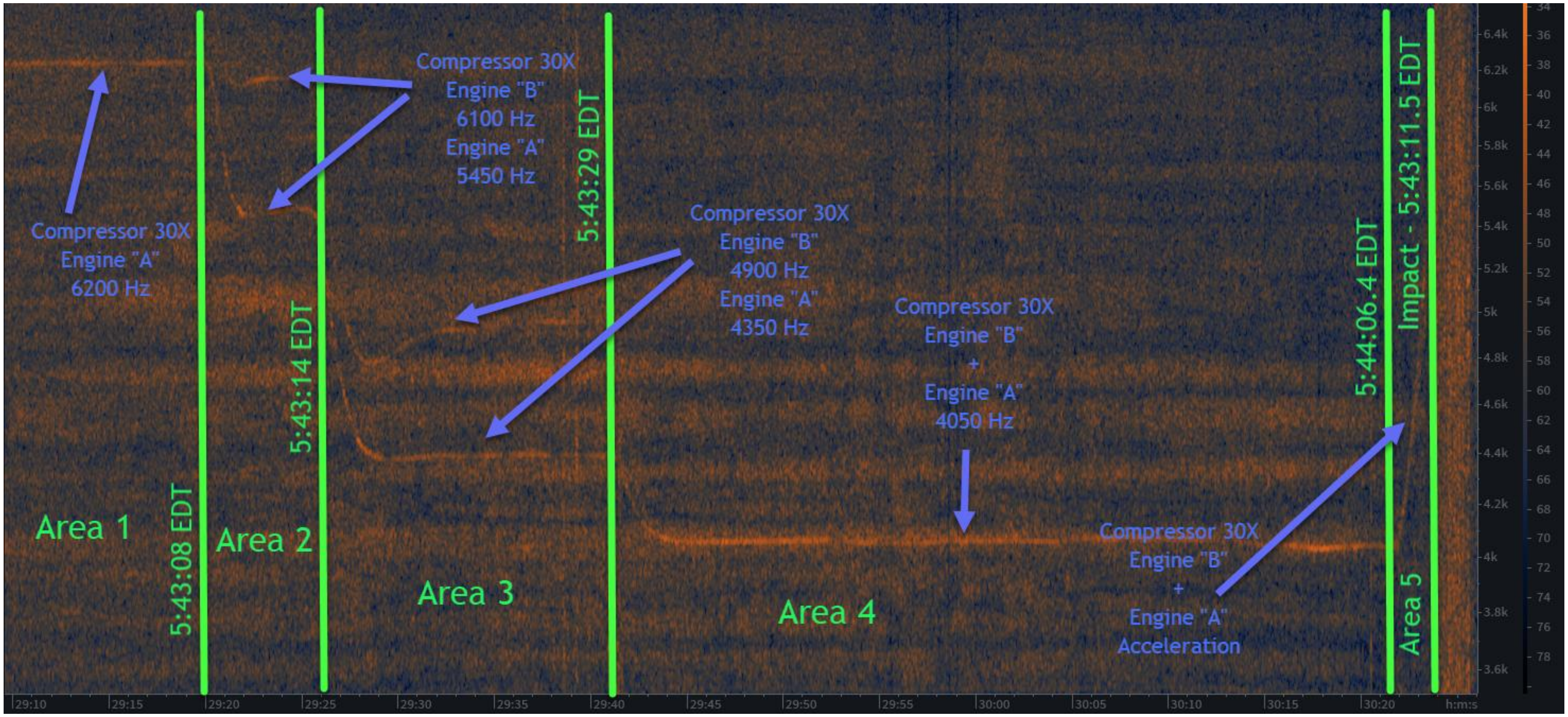

Figure 4. A spectrogram expanded in the frequency range of the Y-Axis to show fundamental frequency data for the 30x compressor section (upper frequency range). Note that the Y-Axis scale here has changed in order to represent upper frequency ranges of the 30X per rev stage 1 compressor airfoil blade passing audio.

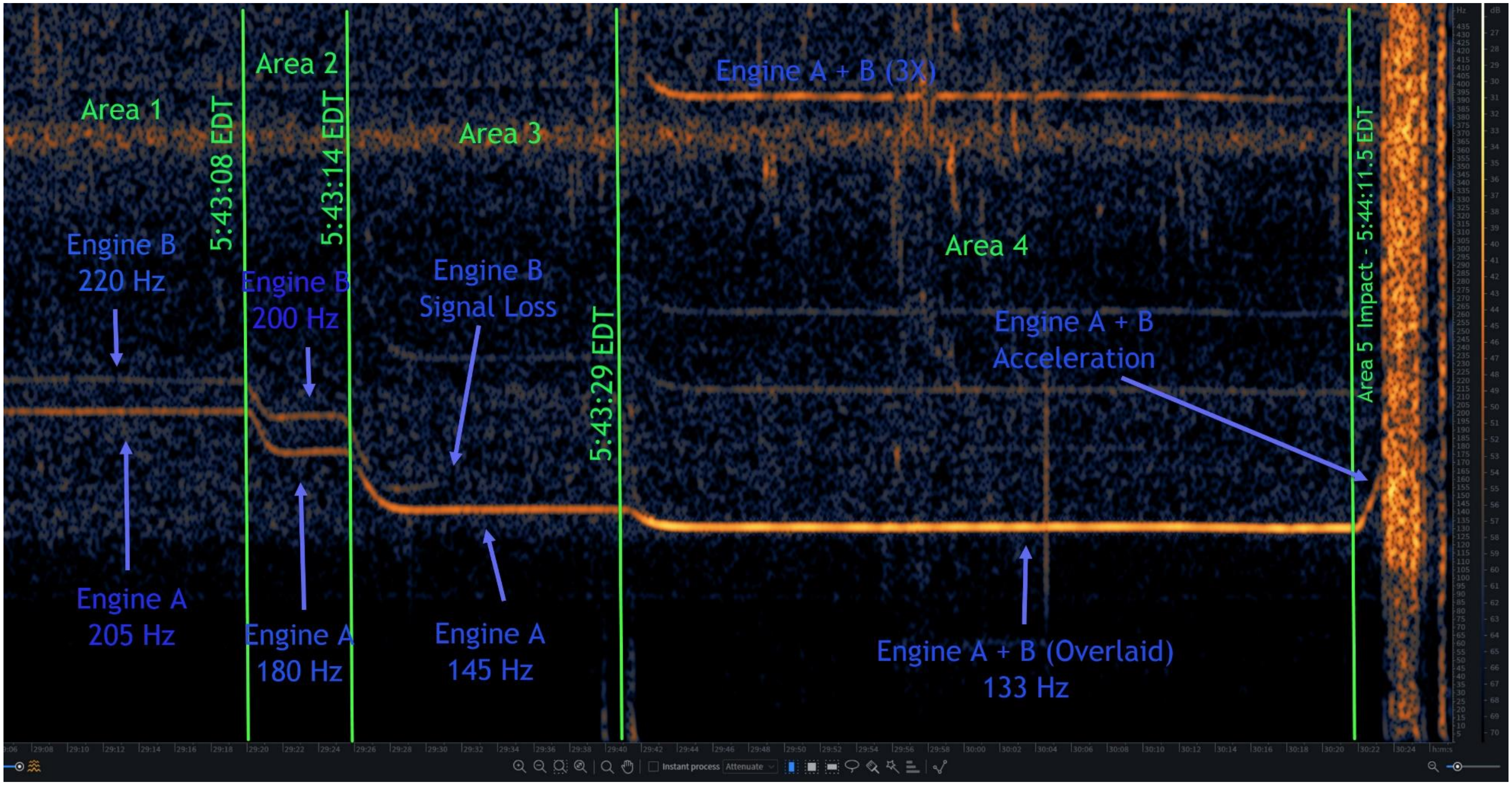

Figure 5. A spectrogram showing frequency information identified for the fundamental and harmonic frequencies of the compressor section.

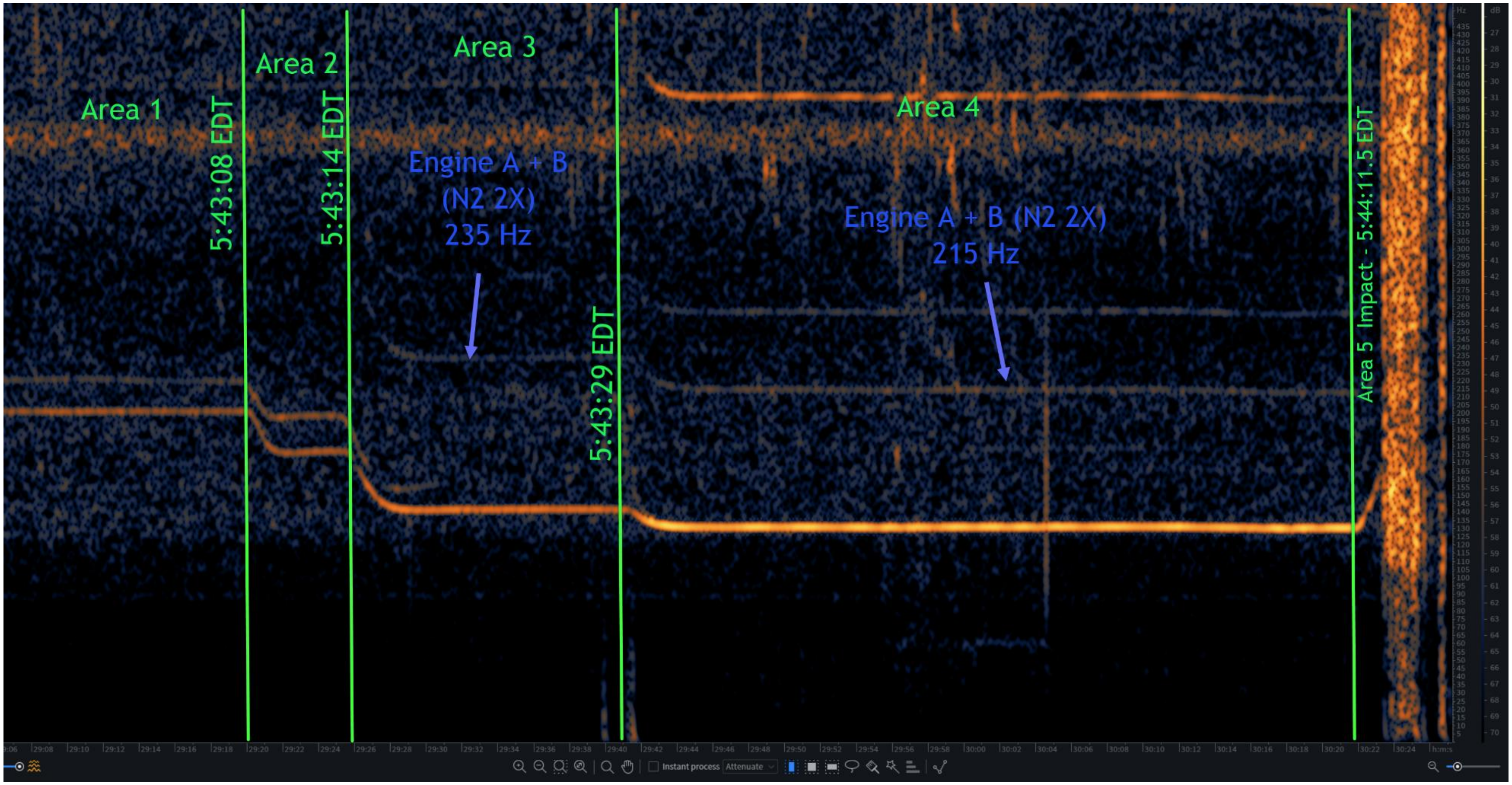

Figure 6. A spectrogram showing frequency information identified for the harmonic frequencies of the N2 fan section.

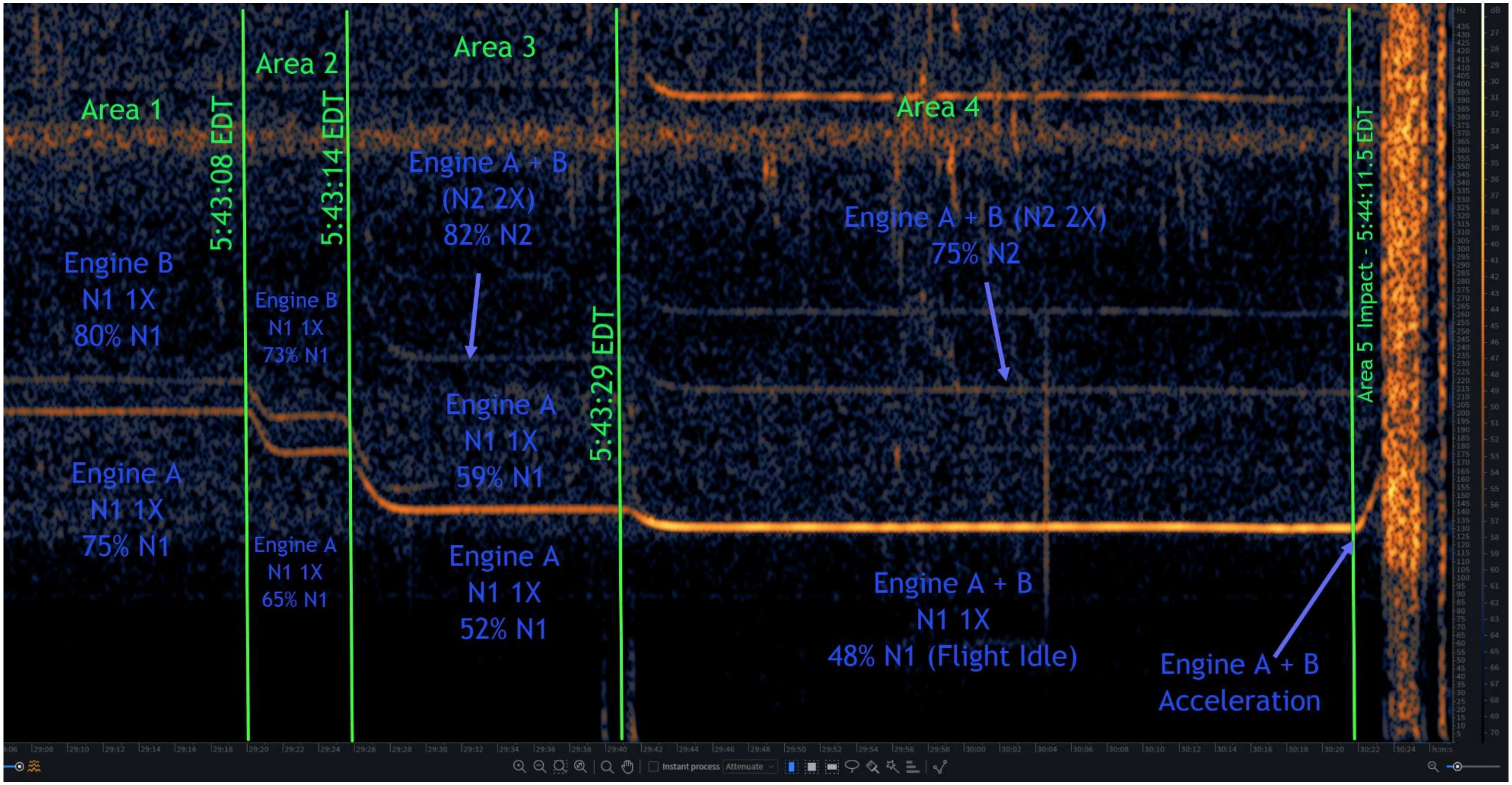

Figure 7. A summary of the information calculated in this sound spectrum exercise.

Table 1. Rotational Frequency Information Correlated to %N1 and %N2 Speed for Each Segment.

Time	ENGINE	Core (Compressor) (Cold Section)					Fan (Hot Section)	
		1X (Fundamental)	2X	3X	30X (Stage 1 Blades)	%N1	2X	%N2
Area 1	A	205 Hz	N/A	N/A	6200 Hz	75%	N/A	N/A
	B	220 Hz	N/A	N/A	N/A	80%	N/A	N/A
Area 2	A	180 Hz	N/A	N/A	5450 Hz	65%	N/A	N/A
	B	200 Hz	N/A	N/A	6100 Hz	73%	N/A	N/A
Area 3	A	145 Hz	285 Hz	N/A	4350 Hz	52%	235 Hz	82%
	B	N/A	N/A	N/A	4900 Hz	59%	235 Hz	82%
Area 4	A	133 Hz	262 Hz	400 Hz	4050 Hz	48% (Flt. Idle)	215 Hz	75%
	B	133 Hz	262 Hz	400 Hz	4050 Hz	48% (Flt. Idle)	215 Hz	75%
Area 5	A	Acceleration	N/A	N/A	Acceleration	N/A	N/A	N/A
	B	Acceleration	N/A	N/A	Acceleration	N/A	N/A	N/A