NATIONAL TRANSPORTATION SAFETY BOARD
Vehicle Recorder Division
Washington, D.C. 20594

March 29, 2016

Cockpit Voice Recorder Sound Spectrum Study

Group Chairman Report
by Bill Tuccio, Ph.D.

1. EVENT

Location:	Akron, Ohio
Date:	November 10, 2015
Aircraft:	British Aerospace HS 125-700A
Registration:	N237WR
Operator:	Execuflight
NTSB Number:	CEN16MA036

On November 10, 2015, about 1452 eastern standard time (EST), Execuflight flight 1526, a British Aerospace HS 125-700A, N237WR, departed controlled flight while on approach to land at the Akron Fulton International Airport (AKR) and impacted a 4-plex apartment building in Akron, Ohio. The pilot, co-pilot, and seven passengers were fatally injured; there were no reported ground injuries. The airplane was destroyed by impact and post impact fire. The airplane was registered to Rais Group International NC LLC., and operated by Execuflight, as a Title 14 *Code of Federal Regulations* Part 135 on-demand charter flight. Instrument meteorological conditions prevailed at the time of the accident, and the flight was operated on an instrument flight rules (IFR) flight plan. The flight originated from Dayton-Wright Brothers Airport (MGY), Dayton, Ohio, at 1413 EST and was destined for AKR.

2. DETAILS OF INVESTIGATION

The Investigator-in-Charge (IIC) requested engine speeds for this investigation. The aircraft was not equipped with a flight data recorder (FDR), nor was it required to by regulation. Further, all non-crashworthy devices that may have recorded engine speeds were destroyed in the accident. The aircraft was equipped with a cockpit voice recorder (CVR). An indirect way to determine engine speeds is by examining the frequency distribution of aircraft sounds recorded by the CVR.[1] During the development of aircraft and engines, manufacturers typically develop a dataset of component frequencies related to engine operating speeds. For example, a rotating hydraulic pump geared to the high pressure compressor (N2) may generate (“excite”) a frequency of 800 Hz at 100% N2. All components have varying amplitudes (loudness), affecting the ability of the CVR to record frequency components. As such, the component frequencies may be

[1] The CVR transcript is contained in the public docket for this investigation.

outside the frequency range of the CVR installation and/or quality at the time of recording (i.e., degradation since installation).

2.1. Purpose of the Study

The purpose of the study was to determine engine speeds from the sound spectrum of the CVR recording.

2.2. Group

A sound spectrum group was convened on January 12, 2016.

Chairman:	Dr. Bill Tuccio Aerospace Engineer NTSB
Member:	Nathan Rohrbaugh Air Safety Investigator Federal Aviation Administration
Member:	Bill Schuster Acoustics Staff Engineer Honeywell Aerospace
Member:	Greg Hayward Acoustics Textron Aviation
Member:	Brian Weber Air Safety Investigator Textron Aviation

2.3. Methodology

The CVR recorded 30 minutes of audio on four channels.[2] Honeywell provided component frequency data for the Honeywell TFE731-2/3 engines. The Honeywell data provided linear relationships between observed component frequencies, low and high pressure compressor speeds (N1 and N2, respectively), and N1 and N2 speeds expressed as percent RPM. This data was used as follows:

1. Originally recorded frequency spectrum data from the cockpit area microphone (CAM) were examined, along with supplementary frequency spectrum data from other channels when needed.

2. Frequencies were adjusted for the known playback speed discrepancy of the recorder. This adjustment was necessary because the inaccurate playback speed altered the frequencies. The frequency alteration was a linear relationship to the speed adjustment.

[2] See the CVR Group Chairman Report in the public docket for this accident for a full description of the CVR and the related transcript.

3. Frequency traces were considered as potentially related to a component identified on the Honeywell known component frequency dataset.

4. Recorded frequencies were extracted (digitized) to tabular data from the start of the recording to the end of the recording.

5. Adjusted frequencies were converted to engine speeds using the Honeywell known frequency dataset.

6. Frequencies were validated by comparing to other available frequency data in the recording, the Honeywell dataset, and engine cycle model predictions of the relationship of N1 to N2 in steady-state conditions.

7. The time axis was converted to eastern standard time (EST) to align with times in the CVR transcript.

Steps 3 through 6 were performed iteratively, to achieve convergence upon an optimum solution.

2.4. Results

2.4.1. CVR Recording Sound Spectrum Review

Figures 1 through 3 show frequency sound spectrum data before any time correction was applied for playback speed.[3] In each figure, the x-axis is time and y-axis is frequency. The brightness of lines represents the sound intensity of the respective frequency. All figures show layering of CVR channels 1, 2, and 3 (channel 4 did not have any usable data); however, the intensity of channel 2 (the CAM) was increased relative to the other channels as it contained the best representation of frequency data.

Figure 1 shows the entire frequency spectrum recorded, from 0 to about 8,000 Hz. The horizontal lines are spaced about 400 Hz apart and were attributed to noise from the aircraft alternating current (AC) generators. The first 400 Hz is the fundamental frequency and frequencies above 400 Hz are harmonics of the fundamental frequency.

Figure 2 shows frequencies below 1,000 Hz. Apparent on this plot are time-variant frequencies below 400 Hz. The varied-frequencies flat segments are characteristic of what would be expected for engine power changes.

Figure 3 shows frequencies below 400 Hz. The time-variant flat segments are more well-defined at this frequency range. Apparent in this figure are discontinuities in the frequency trace in some segments, such as between 3,500 and 3,800 seconds (circled in red); these discontinuities may be due to background noise overpowering the engine component frequency intensity when engine power was reduced or the trace frequency lowering proportionate with engine speed. Undesirable flat (i.e., constant frequency vs. time) noise segments are also observed at 60, 120, 180, 240, and 300 Hz (red arrows in right margin) and were a low intensity artifact of the digitization process.

[3] Frequency sound spectrum data images in this report were produced using Sony SpectraLayers Pro (version 3).

Figure 1. All frequencies for entire recording.

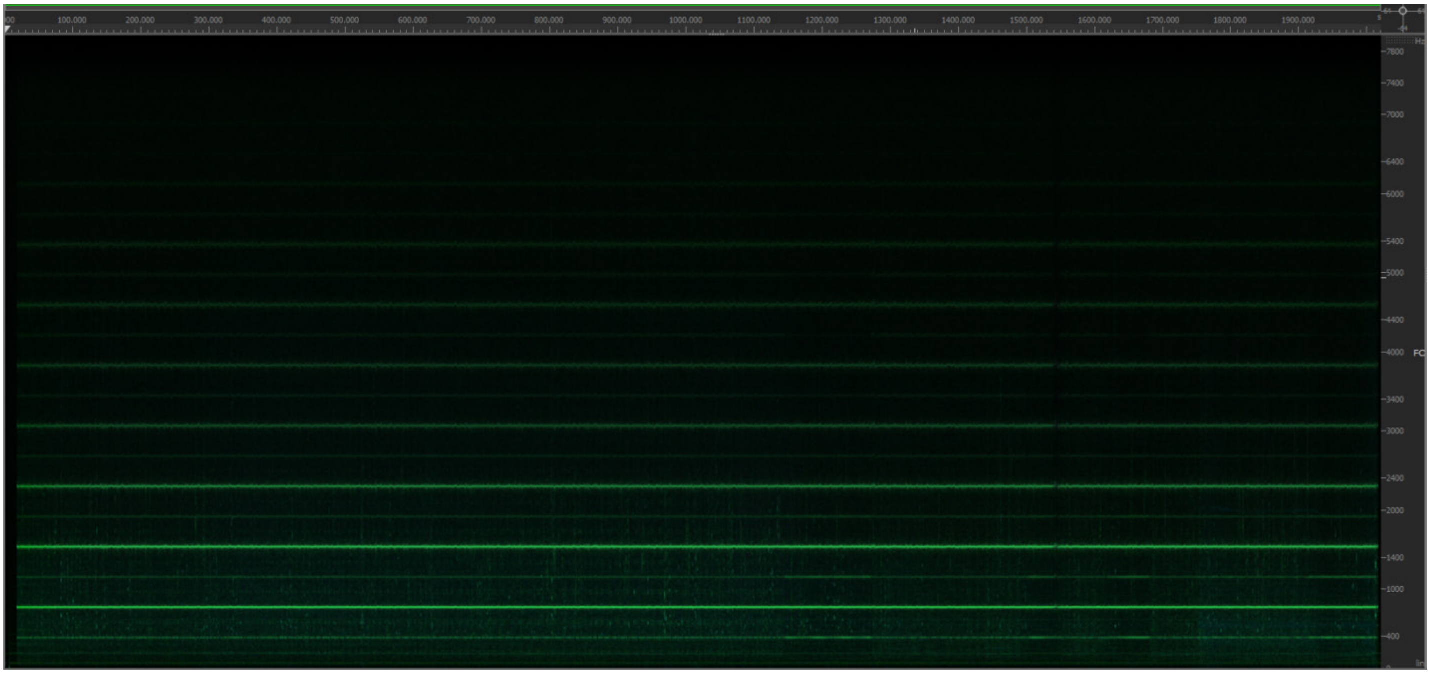


Figure 2. Frequencies below 1,000 Hz for entire recording.

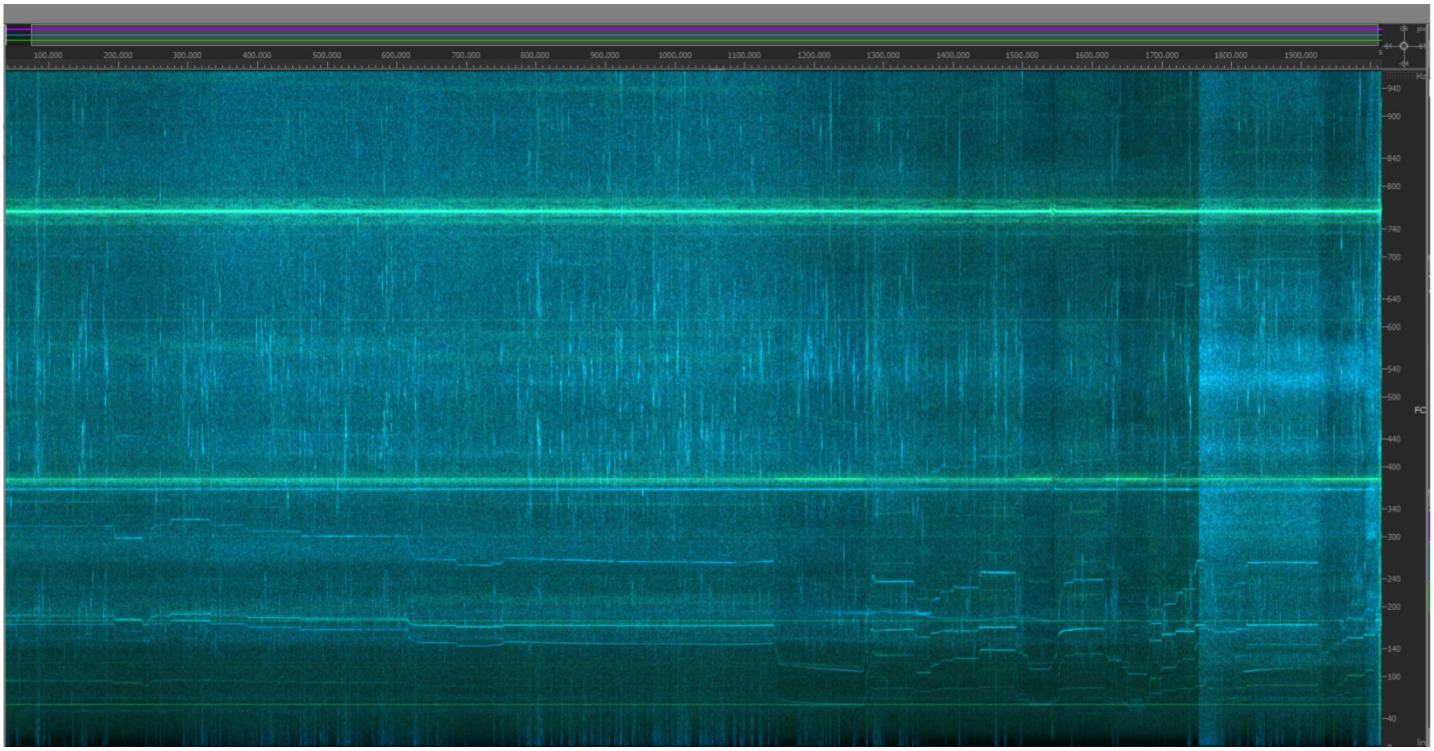
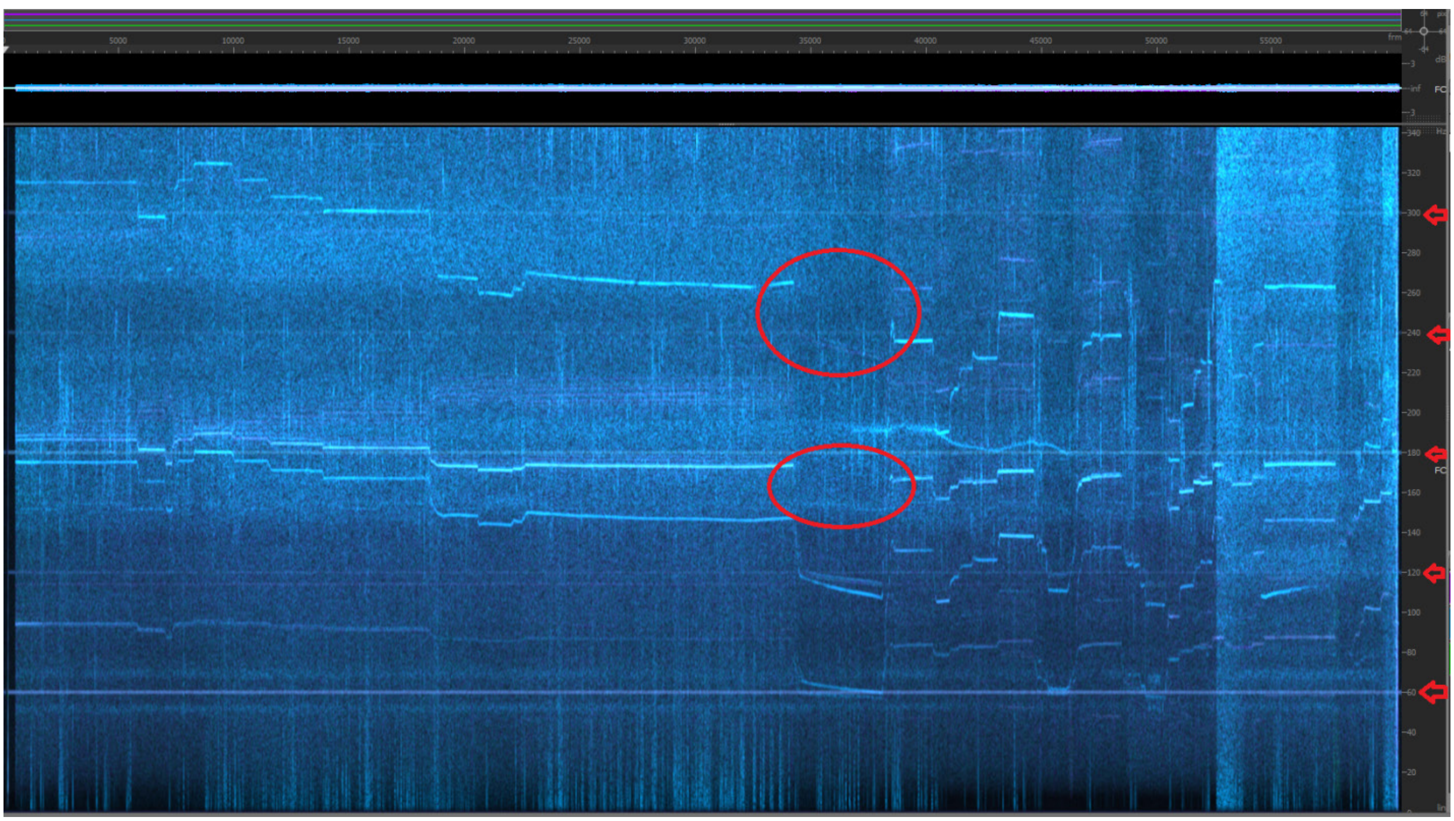


Figure 3. Frequencies below 400 Hz for entire recording.



2.4.2. Frequency Spectrum Digitization

Figure 4 shows the frequency spectrum after digitization and validation, with annotations for lines 1, 1A, 2, and 2A. The group digitized lines 1 and 2 by following the line from the start of the recording to the end of the recording.

In order to validate the assumption that line 1 was related to N1, digitized values in line 1 were multiplied by a known mechanical relationship between various N1 components. Specifically, it was hypothesized that line 1 represented the frequency excited by the Fan Speed/Ring Gear. The frequency of the LP Spool/Quill/Sun Gear, which Honeywell knows to be different by a factor of 1.8, is then,

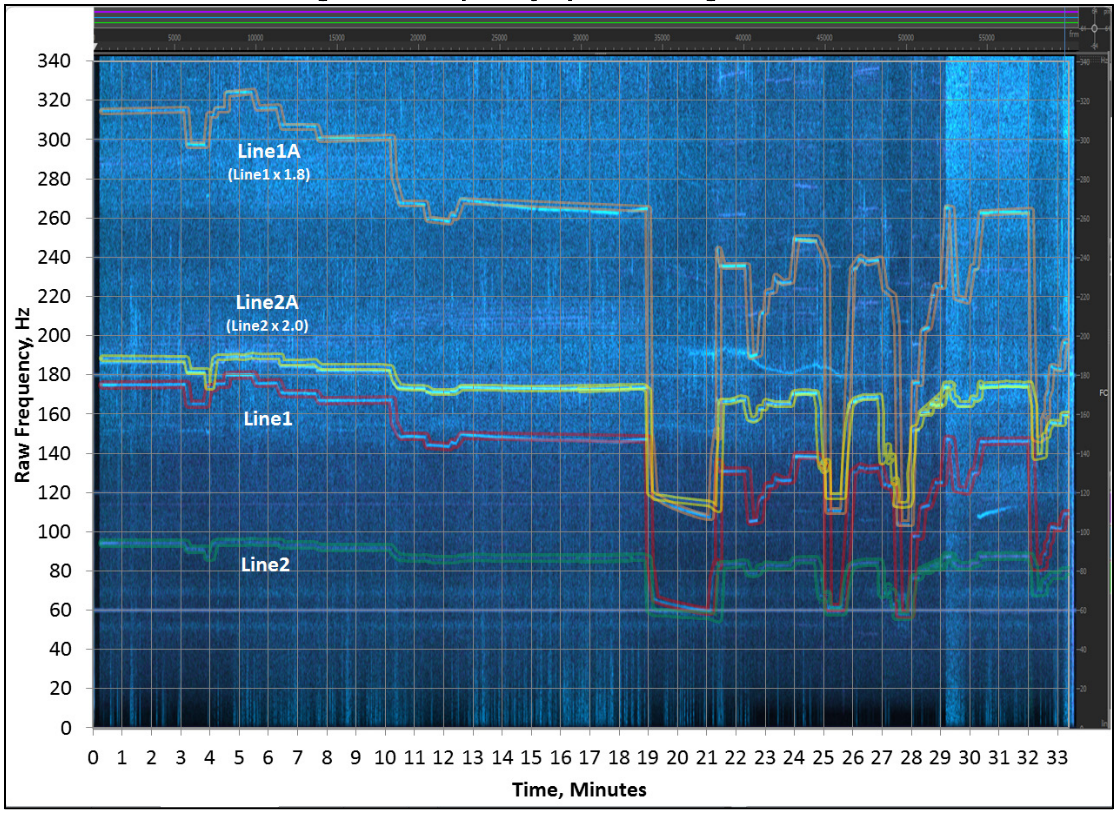
(Fan Speed/Ring Gear) Hz * 1.8 = (LP Spool/Quill/Sun Gear)

Figure 4 shows that line 1A, generated by multiplying line 1 by 1.8, aligned nicely with frequencies observed in the CVR data, thus supporting the proper digitization of line 1 and the physical relationship between 1 and 1A.

Similarly, the digitization of line 2 was hypothesized to represent the frequency excited by the hydraulic/fuel pump pads, which is related to the rotation of the N2 spool. Line 2A was derived by multiplying line 2 by a factor of 2 and assuming line 2A was the 2^{nd} harmonic of the hydraulic/fuel pump pads. The existence of frequency data in the sound spectrum at line 2A supports the digitization of line 2.

However, unlike N1 where the derived values represented a different physical component, for N2 the derived values are a harmonic and do not imply a different physical component.

Figure 4. Frequency spectrum digitization.



2.4.3. Frequency and Time Conversions

Lines 1 and 2 were converted to %N1 and %N2, respectively, in two steps. First, the frequency was adjusted for the improper playback speed. As described in the CVR Group Chairman's Factual Report, the playback speed was reduced by a factor of 0.954; thus, the frequencies were adjusted by multiplying all digitized frequencies by 1.048. Next, frequencies were converted to %N1 and %N2 using the following equations:[4]

Low Pressure Spool, Quill, Sun Gear Component
%N1 = (Corrected Frequency) * 60 / (20688/100)

Hydraulic and Fuel Pump Pads Component
%N2 = (Corrected Frequency) * 60 * 100 / (0.207*29692)

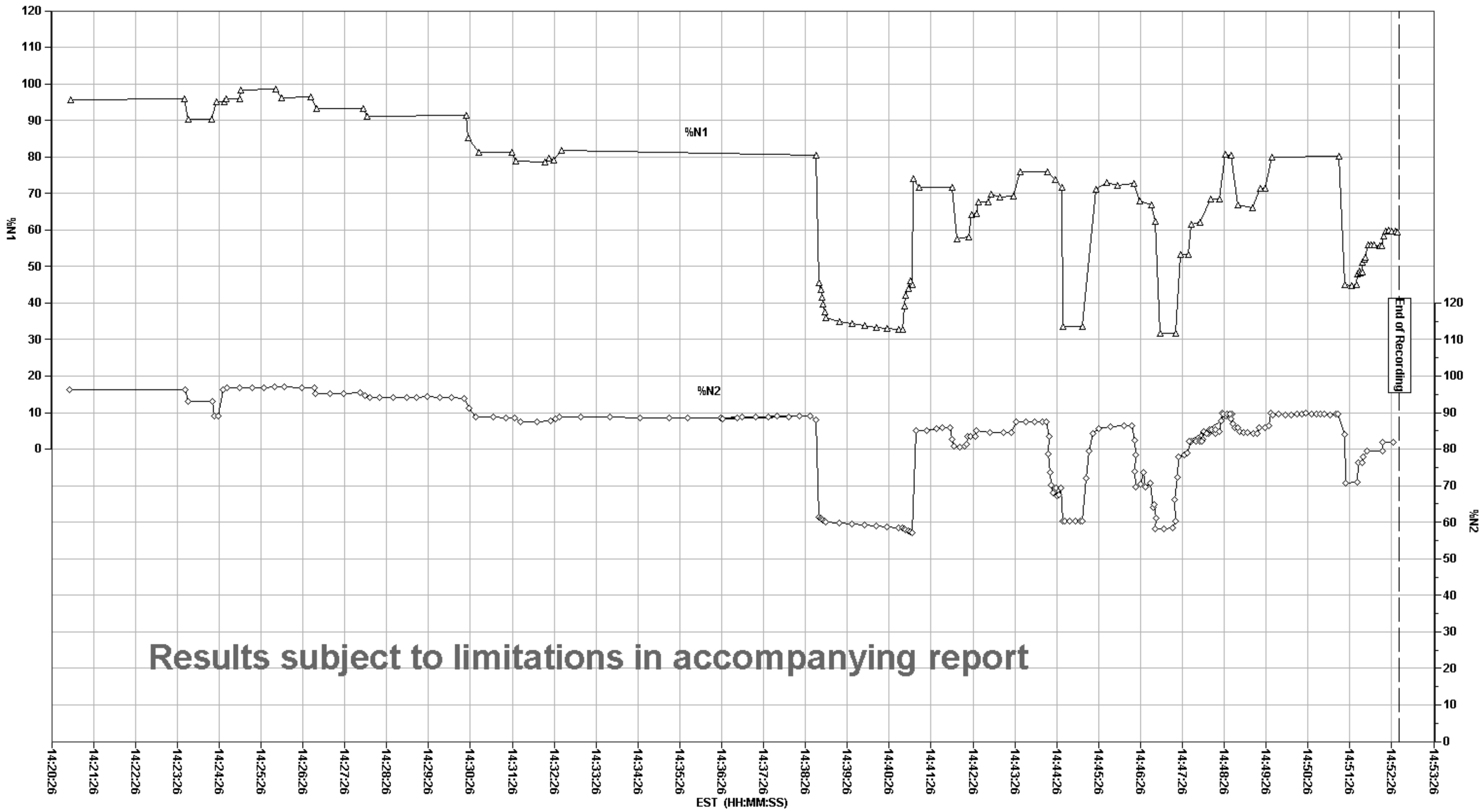
Note: Equations express % as a decimal number (i.e., 0 to 100 rather than 0 to 1.0).

Corrected playback speed was offset by a 51,633.5 seconds to convert to the local time of the accident, expressed as EST.

Figure 5 shows the final result with %N1 and %N2 on the y-axes, and EST on the x-axis.

[4] All relationships between frequency and engine speed were the result of Honeywell engine development, as explained in section 2 of this report.

Figure 5. Derived %N1 and %N2 (for the entire recording).



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2.4.4. Engine Cycle Predictions

As explained in the methodology section, engine cycle modeling was used to assist in the selection of the sound spectrum frequencies. Figure 6 shows four sets of N1 and N2 values from the sound spectrum analysis used for comparison to engine cycle steady-state modeling.

Figure 6. Engine cycle model comparison points.

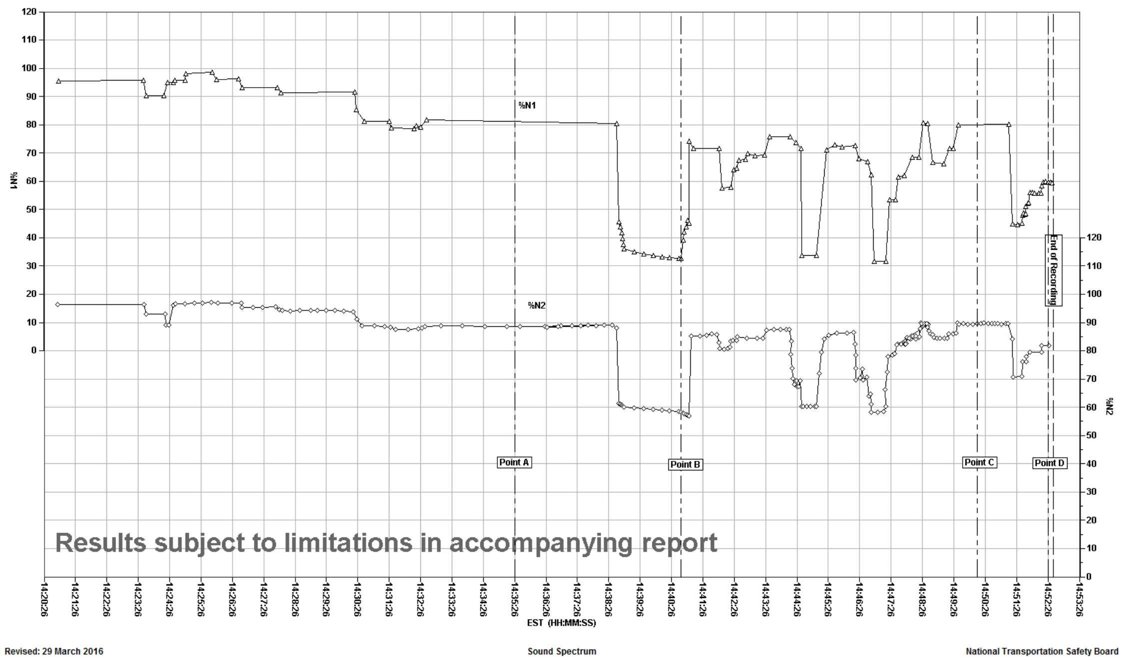

Table 1 shows sound spectrum derived values for N1 and N2 at points A through D. Also shown are engine cycle model predictions for N2, generated using the spectrum-derived N1 values as inputs. In all cases except B, the N2 values predicted by the engine cycle model are very consistent with the N2 values derived from the sound spectrum. For case B, the agreement is not perfect, but the changing engine power conflicts with the steady-state limitation of the engine cycle model. Overall, the engine cycle model comparison lends support to the proposition that the sound spectrum traces represent N1 and N2 related frequencies.

Table 1. Sound spectrum N1 & N2 versus engine cycle model predictions.

Spectrum Point	Spectrum N1%	Spectrum N2%	Model Predicted N2%
A	81.0	89.0	89.2
B	32.7	58.3	51.1
C	80.0	90.0	89.3
D	59.7	81.8	81.4

2.5. Limitations

Converting sound frequency data to engine speeds incurs a number of limitations.

Recording quality impacts a number of areas, including: the threshold at which amplitude of sound may be observed for a given frequency, frequencies being obscured by noise, and the ability of human analysts to discern continuity of frequencies across time. Quality degraded further towards the end of the recording when additional noise was added by the gear extension and windshield wipers.

Only one %N1 and one %N2 resulted from this study, although there were two engines. There were times when possible splits were observed in the frequency spectrum, as shown in figure 7. Splits such as figure 7 may occur during power changes or abnormal engine operations. Because no obvious parallel tracks were identified in the recording, occasional splits were ignored during the digitization.

The accident aircraft was manufactured in 1979. Since manufacture, the aircraft had a number of modifications. Values for %N1 and %N2 are based on known information about the basic engine model performance. It is possible aircraft or engine modifications may have changed and/or scaled %N1 and/or %N2 values shown in the cockpit, for example, if the thrust ratings of the engines had been increased.

As discussed in section 2.4.2, two traces attributed to different N1 components were identified; however, the validating trace for N2 was a harmonic of the same physical component. The lack of a second physically distinct component related to N2 reduces the confidence in the validity of the N2 result.

The process of converting the original recording from analog to digital and/or deficiencies in the recording mechanism may introduce frequency aliasing,[5] as shown in figure 8. Frequency aliasing further confounds the interpretation of the frequency data. There was little frequency aliasing on the CAM channel, but other CVR channels exhibited some aliasing.

Playback speed corrections used a limited amount of air traffic control (ATC) known timing information. The limited time span of the ATC correlative information means the time multiplier previously discussed may be imprecise and accordingly make the frequency conversions imprecise. Thus, final %N1 and %N2 values have degraded accuracy.

The methods used to scale the playback speed for the CVR transcript and this Sound Spectrum Study were different; consequently, alignment between the two products may be off by as much as 1 second.

The end points of the digitization were chosen based on the ability of the group to reliably discern frequency data in the spectrum; accordingly, extrapolations beyond the digitized data are not valid.

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[5] Aliasing occurs when a high frequency component takes on the identity of a lower frequency component (see Oppenheim, A. V. & Schafer, R. W. (1975). *Digital Signal Processing.* Englewood Cliffs, NJ: Prentice-Hall).

Figure 7. Example of possible power split.

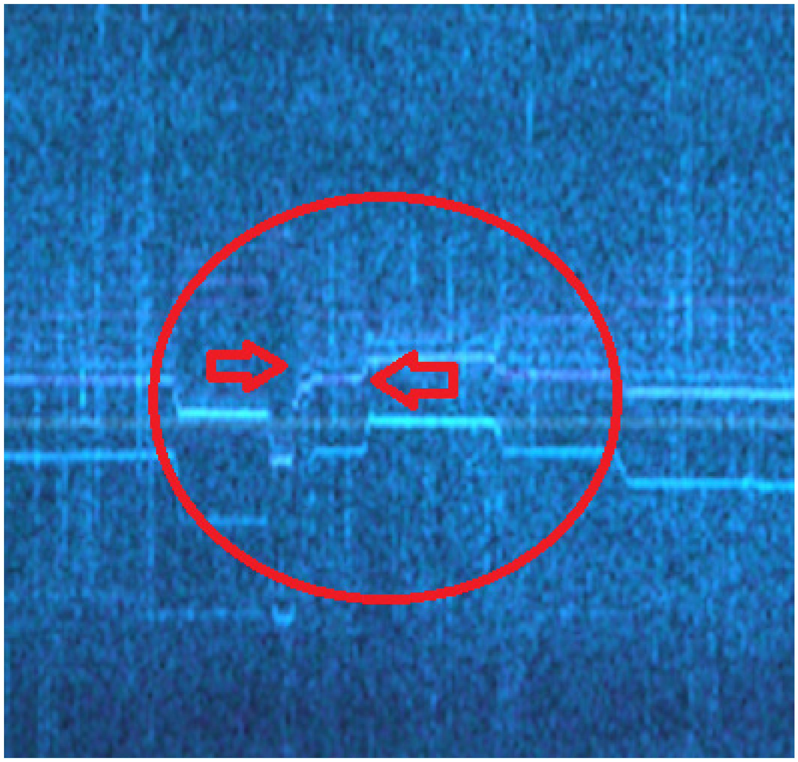
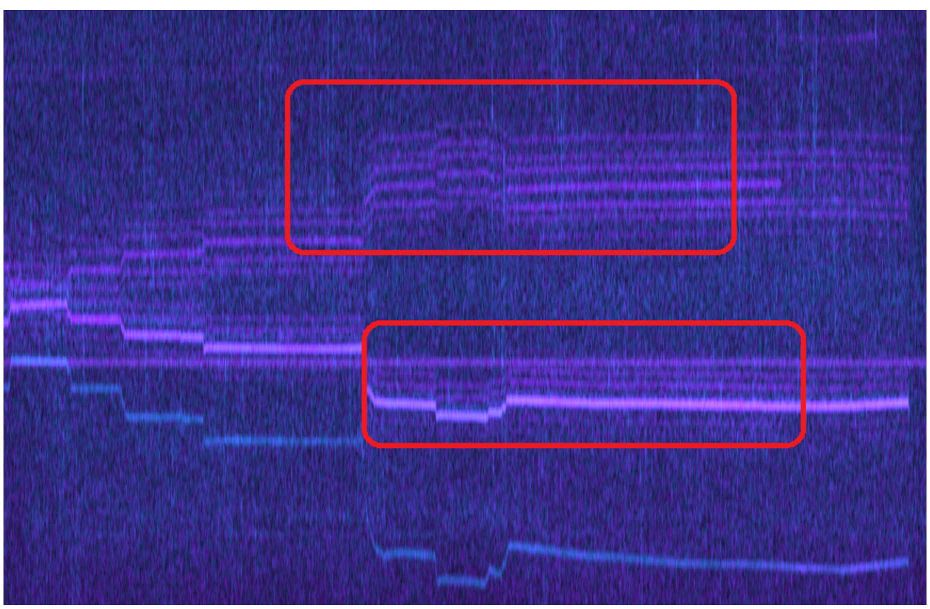


Figure 8. Example of aliasing.



2.6. Discussion and Conclusions

Figure 5 contain values attributed to %N1 and %N2. The flat areas separated by discrete changes in magnitude are characteristic of power changes expected for a climb, level off, descent, and approach. From 14:47:15 EST, the power incrementally increased until a notable decrease at 14:51:18 EST, followed by increasing power.

From 14:51:35 EST until the end of the recording, the power increases to a final %N1 and %N2 values of 59% and 82%, respectively. As stated in the limitations, there is confidence in the power trends, but less confidence in the actual values for %N1 and %N2.

Finally, the traces show %N1 and %N2 without attribution to the left or right engine. Given other areas in the trace showed ostensible splits in engine power during transient conditions (figure 7); it is more likely than not both engines were producing nearly equal power throughout the recording. However, this conjecture should be validated with other investigative information.

Attachment 1 contains the tabular data used to generate the plots in figure 5.