

Jet Noise Flyover and Scale Model Tests

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Renewed interest in commercial supersonic flight has rekindled the need for accurate jet-noise predictions as this source is believed to dominate at aircraft takeoff conditions. The current study compares scale-model data acquired in the NASA Aero-Acoustic Propulsion Laboratory with data obtained using a well-instrumented Learjet 25D in a flyover test completed in September 2022. The flight test included 73 flyovers with engine conditions ranging from 1.5 to 2.0 engine pressure ratios and flight Mach numbers between 0.24 and 0.27. Acoustic data were acquired with an 800-ft linear ground plate microphone array. Wind speed data were acquired up to 1000-sft altitude with a ground-based LiDAR system. Layered ambient temperature, pressure, and humidity were acquired with a weather drone. A 6% increase in the physical scale factor for the scale-model data was found to reasonably align the peak frequencies of the scale-model and flight data and resulted in peak levels for the scale model being roughly 0.7 dB above those for the flight data at NPR = 1.56 and roughly 1 dB below those for the flight data at NPR = 1.91 in the peak jet-noise direction. Comparisons with the SAE ARP876 model were poor especially at emission angles greater than, or equal to, 110° and at high frequencies.

I. Introduction

Recent interest in commercial supersonic flight led to efforts by the International Civil Aviation Organization (ICAO) Working Group 1/Supersonic Task Group (WG1/SSTG) within the Landing and Take-off (LTO) subgroup to develop noise standards and recommended practices for the airport environment. In support of this activity, NASA conducted system studies [1, 2] to predict noise for representative supersonic aircraft performing a range of take-off and landing procedures. The studies showed jet noise to be a, if not the, dominant noise source and highlighted the need for accurate jet-noise predictions with relevant exhaust configurations. For system type studies, jet-noise predictions commonly use one of three approaches: employing empirical models, scaling data acquired in acoustic wind tunnels, or using scaled engine test-stand data from similar engines with an added flight correction. Previous studies have shown scaled data from wind tunnel tests typically underpredict flight data at peak angles [3] and this deficiency is often addressed by adding an offset to the scale-model data. The resulting predictions can have unacceptably large uncertainties for the development of standards, recommended practices, and regulations. The current study compares recent acoustic flyover data using a Learjet 25D with scale-model data acquired in the NASA Aero-Acoustic Propulsion Laboratory (AAPL) as a first step in the development of scale-model-to-flight corrections. Comparisons are also made with predictions using the empirical model in SAE ARP876 [4].

In general, plans for near-term entry-into-service supersonic aircraft are focused on business jets. These aircraft will most likely be powered by low-bypass ratio turbofans with internal mixers that produce a single exhaust stream. The exhaust velocities during takeoff will likely fall in the high subsonic to low supersonic range to meet airport noise requirements. While the CJ610-8A turbojet engine used on the Learjet 25D has a pseudo secondary stream resulting from engine-cooling air, the secondary stream has very little flow relative to the primary exhaust stream. Results from scale-model tests [3] show that the Learjet nozzle system produces similar acoustic spectra to those produced by a single-stream jet over the range of frequencies of interest. The turbojet engines on the Learjet 25D are expected to result in jet-noise dominated sound for the aircraft flyovers making the aircraft an ideal choice for this type of study. Therefore, this engine has the potential to provide a database relevant for single-stream jets. The flight dataset presented here includes high subsonic and low supersonic exhaust speeds. The exhaust speeds at the lower engine pressure ratios are close to those expected for future supersonic business jets.

Comparisons to full-scale data typically fall into three categories: (1) static engine to aircraft in flight (2) static scale model to static engine, (3) scale model with simulated flight to aircraft in flight. The first category of studies has been used for decades with the flight effects being achieved with engines mounted on aircraft as well as high-speed trains [5, 6, 7]. Bare and installed engines can be used for the static measurements. These types of studies quantify the impact of a flight stream on jet noise but do not address issues associated with predicting jet noise in

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flight from scale-model data. The second category is useful in scaling efforts and for separating the multiple noise sources of engines as the scale models can be used to isolate sound sources. These types of studies have also been used to develop static jet-noise models but do not address the impact of a flight stream on jet noise. The investigations of Ref. [8] identify the need to use turbojets or low bypass-ratio (BPR) engines for these types of investigations to limit the impact of turbomachinery noise. A reasonable agreement was obtained between the scale-model data and the engine data for an engine with $BPR \simeq 0.3$ in Ref. [8]. In the investigations of Ref. [9], models were developed from scale-model data that underpredicted jet noise near the peak jet-noise angle in full-scale ground tests. A limited number of studies have focused on scale-model-to-flight comparisons (category three). Jet-noise models are often developed from scale-model data, so category three investigations are critical for system studies predicting jet-noise of future aircraft. The studies of Ref. [3] showed the importance of a properly instruments aircraft for these types of studies. The results of Ref. [10] showed reasonable agreement between the scale-model data and aft radiation from the flight data when the scale-model was in an installed configuration in the wind tunnel.

The quantity of interest for certification is the effective perceived noise level (EPNL). However, EPNL is a rolled-up measure, and it is difficult to identify the underlying reasons for discrepancies between scale-model and flyover data from an EPNL calculation. Consequently, spectral comparisons are provided here. Only mixing noise will be considered since previous flyover tests with the Learjet 25 [3] have shown that broadband shock-associated noise is not identifiable in the spectra for the range of engine conditions used in this study.

Details of the flight test and scale model tests are presented in the Section II Experiments. The engine and aircraft data are presented in Section III. A. The background levels for the flight data are presented in Section III. B. Results from the flight test are found in Section III. C. Comparisons between flight and scale model data are shown in Section III. D and between flight data, scale model data, and the SAE ARP876 model in Section III. E.

II. Experiments

A. Flight Test

The flight test was carried out August – September of 2022 at the Niagara Falls International Airport using a Learjet 25D aircraft owned and operated by Calspan Corporation under contract with NASA. Four sorties were flown over two days with 17 – 20 flyovers completed in each sortie. An 800 ft ground-plate microphone array with nine elements was deployed on a decommissioned runway as shown in Fig. 1. For the flyovers, the aircraft approached from the east, aligned with the runway at a level flight of roughly 500 ft above ground level, and rotated

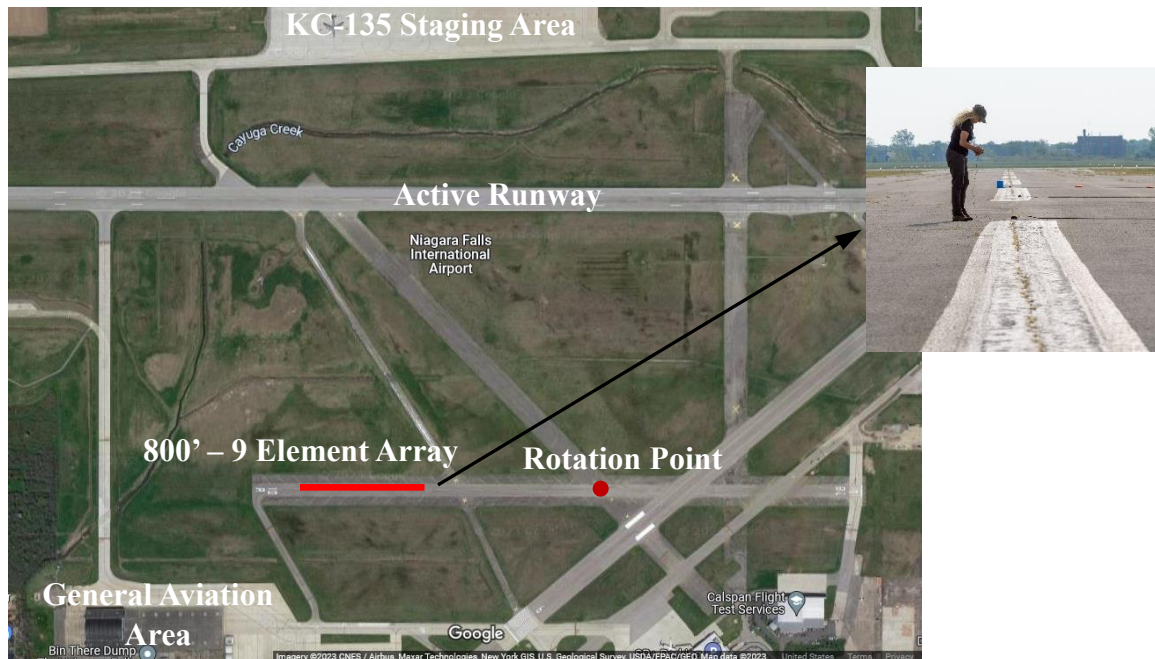


Fig. 1 A photograph of the Learjet flight location, Niagara Falls International Airport. The microphone array and aircraft rotation point are indicated in the figure.

to a nearly constant climb angle at the point indicated in the figure. The climb was maintained until the aircraft reached a specified ground location (not shown in the figure) before turning out. The purpose of the climb was to maintain a prescribed airspeed. The aircraft landing gear remained stowed, and no flaps were deployed. The rotation point was selected so that acoustic data for an emission angle of 60° from the aircraft to the first element of the microphone array could be captured during the constant climb segment of the flight. The turnout point was selected so that acoustic data for an emission angle of 160° could be captured during the constant climb segment for the last element of the microphone array. Only emission angles between 60° and 160° were of interest in this study as these are the measurement angles in the complementary scale-model tests and are the angles that will be used for future EPNL calculations. The 0° polar angle is in the direction of flight and increases to 180° in the aft direction.

For all flyovers, one engine was held at idle while the other engine was maintained at a specified engine pressure ratio (EPR) set by a dial in the aircraft and controlled by the existing engine control system. Additional research instrumentation was installed on the aircraft to monitor engine state, airspeed, and position. The pressures and temperatures necessary to compute EPR and exhaust gas temperature (EGT) were recorded continuously for both engines throughout the flight at a rate of 100 Hz. Additionally, the static and dynamic pressures from the external pitot tube were recorded for flight speed computations. All aircraft and engine data were timestamped based on GPS. The pressure and temperature instrumentation were calibrated prior to the flight campaign.

The aircraft was equipped with an active L1/L2 antenna and an L1/L2 capable VectorNAV VN210 receiver for precise aircraft positioning. The satellite data were recorded throughout each sortie at a rate of 5 Hz. The nearest base station in the NOAA Continuously Operating Reference Stations (CORS) network was 17 km from the airport. The base station and recorded aircraft satellite data were later processed using post processed kinematic (PPK) techniques to achieve centimeter accuracy for the aircraft position during the flyovers.

The microphone array consisted of nine GRAS 67AX ground array microphones (with included wind screens) spaced 100 ft apart. The microphones were calibrated for sensitivity at the beginning and end of each flight day. Prior to the test, the microphones were calibrated for frequency response. Microphone locations were determined using a real-time-kinematic (RTK) precise positioning systems which provided centimeter accuracy.

Acoustic data were recorded for each flyover at 40,000 samples per second. A GPS related timestamp was recorded at the beginning of each acquisition. Each two-minute acquisition began when the pilot radioed in, "Final Approach Fix," which was well before the rotation point for the constant climb segment. The two-minute acquisition ended well beyond the turnout point for the flyover. Airport background levels were recorded before each sortie. Background measurements will be discussed in subsequent sections of this paper.

Layered temperature, pressure, and relative humidity data from roughly 30 ft to 1000 ft above ground were acquired with a drone. Three measurements were obtained for each sortie: one just before the Learjet takeoff, one in the middle of the sortie, and one just after the final Learjet flyover. Each Learjet sortie had a duration of approximately two hours resulting in atmospheric measurements recorded at roughly one-hour intervals. Atmospheric temperature, pressure, and humidity were interpolated in time using the data from the three drone flights associated with each sortie. Wind speed and direction were recorded continuously throughout each sortie for altitudes up to 1000 ft above ground using a ground-based LiDAR system. The LiDAR system was used to omit data that exceeded the specified wind speed limits. The limits were 13 knots maximum, 10 knots average, a maximum crosswind component of 9 knots, and an average crosswind component of 6 knots. The LiDAR system acquired data from 33 ft to 984 ft above ground level in less than 30 seconds.

For the acoustic processing, 0.512 s time segments for each microphone and each flyover were extracted from the data for the times associated with emission angles between 60° and 160° in 5° increments. Conversions of reception times at the microphones to emission times at the aircraft were obtained using the precise aircraft and microphone positioning and an average speed of sound determined from the atmospheric measurements. The narrowband power spectral density (PSD), expressed in terms of decibels (dB), is given by $10\log[(p^2/\Delta f)/(t_{ref}P_{ref}^2)]$, where p^2 and Δf are the contribution to the rms pressure from a spectral bin and the binwidth, respectively. The normalization quantities are $t_{ref} = 1\text{ s}$ and $P_{ref} = 20\mu\text{Pa}$. The PSD were obtained with a 4096-point Discrete Fourier Transform through the MATLAB function `pwelch` with Hamming windowing and 50% segment overlap for each time segment. The 0.512 s interval, rather than 0.5 s typically used for certification, resulted in the maximum number of FFT averages for each time segment. The change in aircraft position for the added 0.012 s was insignificant. The resulting PSD were corrected for microphone frequency response and 6 dB was subtracted for the ground effect. Background levels were subtracted using a 5 dB threshold. Any flyover that did not produce levels that were 5 dB above the background were excluded from the analysis. Determination of a representative background for each flyover will be discussed later. The narrowband spectral data were depropagated to a one-foot sphere centered on the VectorNAV

VN 210 receiver² located in the main cabin, aft of the main passenger door and forward of the leading edge of the wing (between fuselage stations 283.99 and 321.24), using spherical spreading and atmospheric attenuation [11]. For each flyover, the processed data on the virtual one-foot sphere for all microphones in the array were averaged for each emission angle. The resulting PSD at each emission angle thus represents an average based on 81 time segments. The averaged PSDs were deDopplerized for comparisons with the scale-model data.

The operating conditions for the flight test are shown in Table 1. The nozzle pressure ratio (NPR) and nozzle

Table 1 Flight Conditions

NPR	NTR	Flight Mach #
1.56	2.63	0.24
1.69	2.72	0.25
1.80	2.80	0.25
1.90	2.88	0.26

temperature ratio (NTR) are used in scale-model testing and are given by the ratios of the stagnation pressure of the jet to the ambient pressure and the stagnation temperature of the jet to the ambient temperature, respectively. The NPR was computed using the turbine exit pressure and the static pitot-tube pressure. The EGT was converted to NTR using the emission-angle averaged interpolated atmospheric temperature for each flyover.

Only a subset of the data for the first sortie is presented here. The conditions will be referred to by the NPR and the other relevant conditions will be assumed to be those in Table 1 unless otherwise specified.

B. Scale-Model Test

The scale model tests were conducted in the NASA Glenn Aero-Acoustic Propulsion Laboratory (AAPL) shown in Fig. 2. The AAPL facility [12] is a 65 ft radius geodesic dome treated with acoustic wedges that houses the Nozzle Acoustic Test Rig (NATR). The NATR is a 53-in diameter simulated flight stream facility capable of Mach numbers up to 0.35 and contains the High Flow Jet Exit Rig (HFJER). The HFJER is a three-stream jet-engine exhaust simulator capable of replicating most commercial turbofan exhaust temperatures and pressures. Acoustic measurements are made with a 24-microphone far-field array located on a 45-ft constant radius arc covering polar angles between 45° and 160°, where angles greater than 90° are in the downstream direction relative to the nozzle exit. Data are acquired using ¼ inch GRAS constant current microphones without grid caps. The microphones are pointed directly at the nozzle exit. Microphone sensitivity and frequency-response corrections are applied to all measurements.

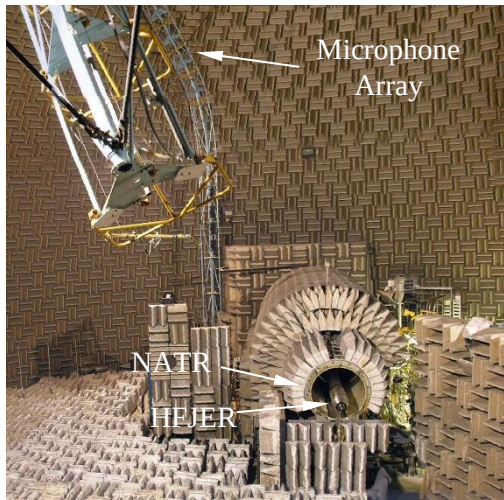


Fig. 2 The Aero-Acoustic Propulsion Laboratory.

The nozzle system used in the scale-model tests replicated the scaled internal flow lines of the nozzles on a CJ610-6 engine obtained from previous detailed measurements [3] of the nozzles on a Learjet 25. It should be noted that a Learjet 25D with CJ610-8A engines was used in the current flight test. The CJ610 engine has a secondary nozzle (see Fig. 3) that exhausts cooling air entering through a NACA scoop near the front of the nacelle and a vent on the side of the nacelle. The secondary nozzle has a slight asymmetry relative to the core nozzle. While the nozzle system asymmetry was captured in the scale model, no attempt was made to replicate the contour of the plug. Previous measurements verified no azimuthal dependency in the acoustic radiation associated with the scale-model nozzle system [3], so only data from one nozzle clocking position will be shown here.

The Learjet scale model (designated Lear) is illustrated in Fig. 4. The exit diameter of the primary nozzle is equal to 3.51 in which leads to a scale factor of 3.21 for the 11.5 in diameter nozzle on the CJ610-8A engine.

A second nozzle without the secondary stream (designated SGL) was also used in the scale-model test to determine the impact of the secondary stream on the resulting acoustic field. The single-stream nozzle had the same internal flow lines and exit diameter as that of the Lear scale-model core nozzle.

In the scale-model test campaign, similar conditions to those for the flight test were used for the core NPR and NTR. It was not possible to determine the conditions of the secondary flow in the flight test as that stream could not be instrumented. However, the predominant source of the secondary flow was the single NACA scoop so the mass flow rates can be assumed to be quite small. To determine the sensitivity of the acoustic field to slight changes in the

² The Center of the on-foot sphere will be translated to the powered engine nozzle trailing edge in future analyses.

conditions of the secondary stream, a range of NPR and NTR for the secondary stream were investigated previously [3]. The conditions used in the scale-model tests are shown in Table 2. The subscript b indicates the bypass flow.

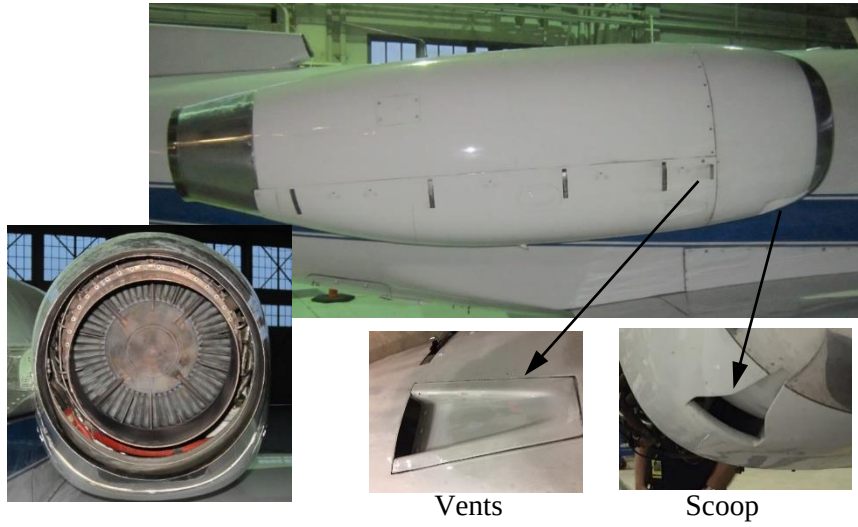


Fig. 3 The nozzle system on a Learjet 25.

All data had background levels subtracted and were corrected for atmospheric absorption [7] and free-jet shear layer effects [13] assuming the source at the nozzle exit. The impact of source location has been investigated previously [3] and has been shown to impact spectral shape and levels. Unless otherwise specified, the scaled data are presented as PSD on a one-foot lossless arc using emission coordinates. The data are not Doppler shifted. The conditions will be referred to by NPR and the other relevant conditions will be assumed to be those in Table 2 unless otherwise specified.

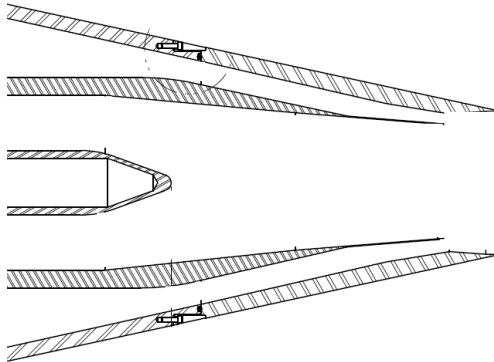


Fig. 4 The Learjet scale-model nozzle system used in the scale model tests.

Table 2 Scale-Model Conditions

NPR	NTR	NPR _b	NTR _b	Flight Mach #
1.56	2.62	1.05	1.25	0.23
1.71	2.72	1.05	1.25	0.25
1.80	2.79	1.03	1.25	0.26
1.91	2.87	1.03	1.25	0.27

III. Results

A. Engine and Flight Conditions

The aircraft data for four of the 22 flyovers in sortie one are shown in Fig. 5 and the corresponding NPR and NTR in Fig. 6. The time intervals used in the plots are those of relevance for the acoustic processing. The non-constant climb angle for some of the flyovers, indicated by the altitude plots in Fig. 6 (a), did not impact the data analysis due to the precise aircraft positioning used in the post processing. The EPRs, EGTs, NPRs, and NTRs were reasonably constant for each flyover. There was some variation in the flight Mach number during the flyovers. The variation in flight Mach number decreased with increasing EPR. The impact of flight Mach number variation on the resulting acoustic radiation will be investigated in the future.

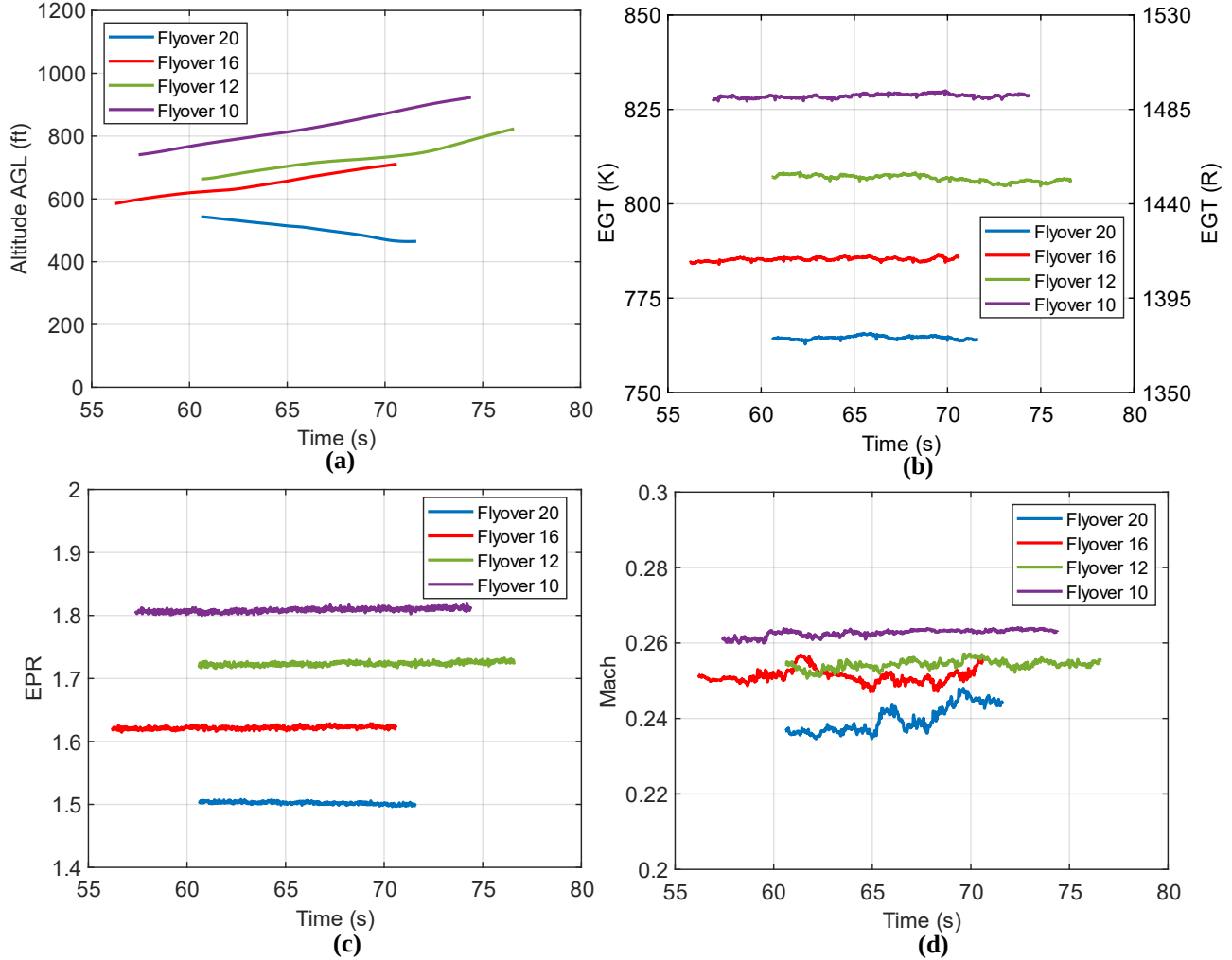


Fig. 5 The engine and flight conditions for four of the 22 flyovers in the first sortie. The altitude, EGT, EPR, and flight Mach number are given in (a), (b), (c), and (d), respectively.

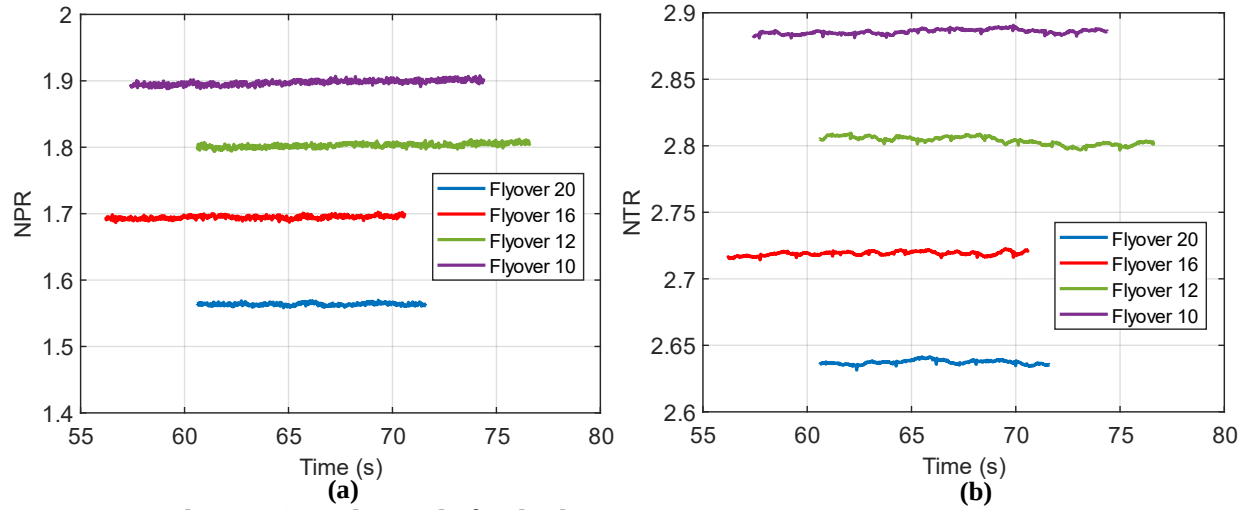


Fig. 6 The NPR (a) and NTR (b) for the data in Fig. 5.

B. Flyover Background Measurements

Niagara Falls International Airport is used for general aviation and regional commercial flights. The runways are shared with the adjacent Niagara Falls Air Reserve Station. While the traffic is reasonably light, the microphone array was close to an area used by general aviation aircraft and across from the area used by the Air Reserve Station for engine run-ups of their KC-135 aircraft (see Fig. 1). Due to the airport activity, the background levels are time dependent, and the spectra used for background subtraction for each flyover need to reflect the levels for that flyover.

The spectra for two different flyovers at an NPR of 1.56 are shown in Fig. 7 along with the spectra obtained from the first 30 seconds of each acquisition. The data in the top row were acquired while a KC-135 was performing engine run-ups. The data in the bottom row were obtained when the KC-135 turned and began taxiing toward the runway for takeoff. The spectra have been corrected for microphone frequency response and 6 dB subtracted for ground effects. The data have not been depropagated. The average spectra from the nine microphones are also shown on the plots. The data clearly show the changes in background levels with airport activity. The levels produced while the KC-135 was taxiing were well below those for the Learjet. The levels produced during the KC-135 engine run-ups were close to those for the Learjet flyovers and, therefore, the data acquired during this type of airport activity were excluded from the data analysis. Fortunately, there were very few flyovers impacted by the KC-135 engine run-ups. The levels associated with the general aviation aircraft were always well below those for the Learjet. Takeoffs, landings, and go-arounds for other aircraft did not occur simultaneously with the Learjet flyovers.

For the data presented here, the first 30 seconds of each flyover is used to compute background spectra for that flyover. The background subtraction is performed for each microphone using the first 30 seconds of data from that microphone. The spectra obtained from two-minute acquisitions for background levels were compared to the 30 second background spectra with similar, acceptable from a signal-to-noise ratio perspective, airport activity and the levels were comparable.

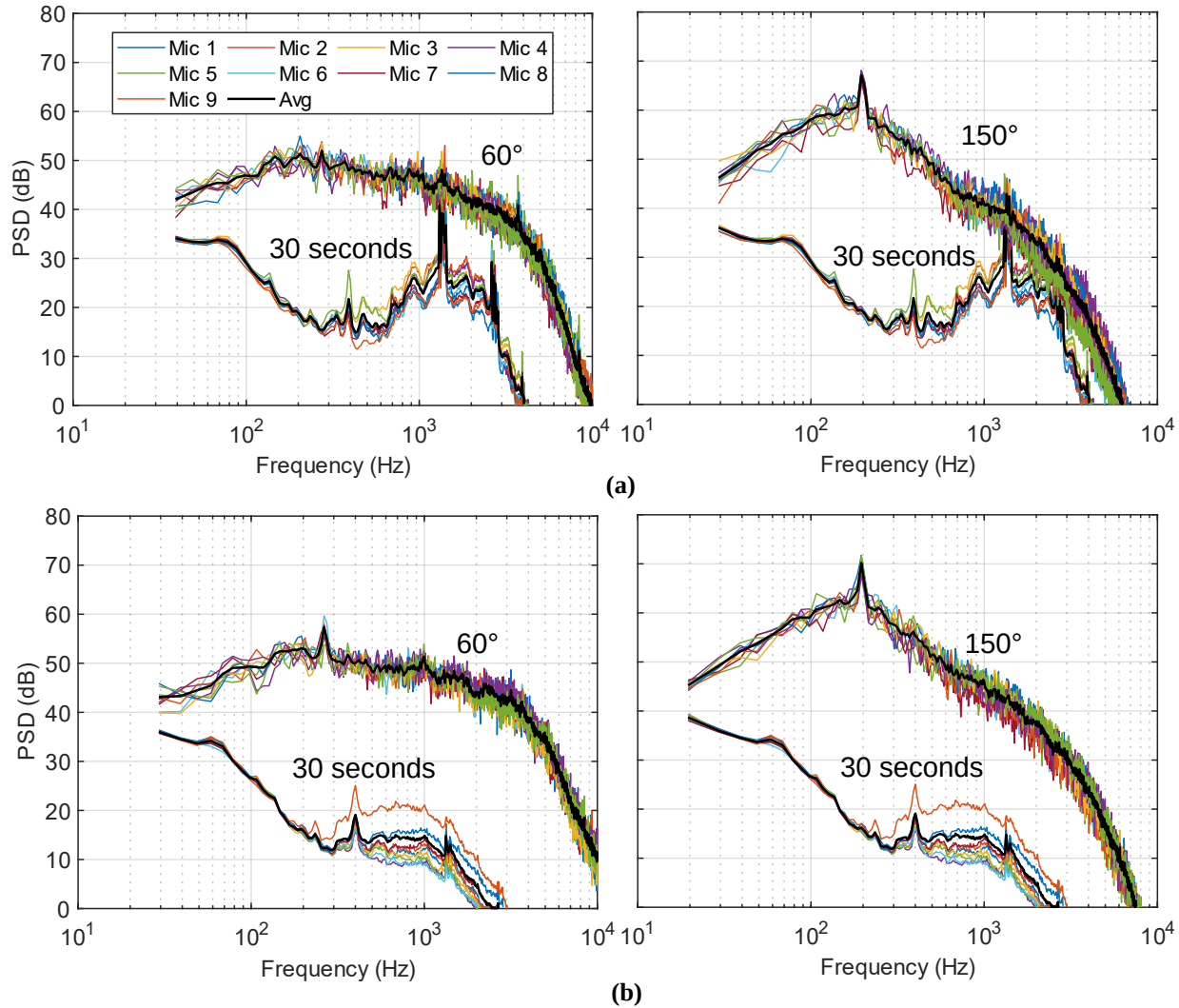


Fig. 7 The spectra for the nine microphones and their average for NPR = 1.56 and two different flyovers. The spectra are for flyovers (a) 18 and (b) 20. The emission angles are indicated on the plots. The spectra obtained from the first 30 s of each flyover are also shown in the plots.

C. Flyover Data

The flyover spectra for NPR = 1.56 and 1.9 are shown in Figs. 8 and 9, respectively, for emission angles between 70° and 150°. The data in each figure were acquired for a single flyover. The level differences between the spectra for the different microphones is typical of the data acquired at other flight conditions. The tone at roughly 250 Hz is associated with the first shaft order of the powered engine. There is evidence of haystacking or sidebands around the tone as expected for sound scattering by a shear layer [14, 15, 16]. A suspected secondary noise source not associated with jet noise is evident in the data at higher frequencies and is indicated by red circles in the spectra for 70°. There is evidence of the secondary source at other emission angles, and it is particularly noticeable for NPR = 1.90 and an emission angle of 130°. The secondary source may be airframe noise but cannot be associated with flaps or landing gear as these were not deployed during the flyovers. There is no evidence of shock noise in the data shown in Fig. 9. The elevated levels for the secondary source at 130° for the supersonic exhaust condition were also present for the subsonic exhaust at NPR = 1.80 (not shown here). It should be noted that the flyover for NPR = 1.56 had the lowest flight speed and angle of attack of all flyovers.

The data from multiple flyovers and nominal NPRs equal to 1.56 and 1.80 are shown in Figs. 10 and 11, respectively. The flyovers had slightly different engine conditions and flight speeds. The variation in the NPR, NTR, and flight Mach number all had a range of 0.02 for the data in Fig. 10. In Fig. 11, the ranges were 0.01 and 0.02 for the NPR and flight Mach number, respectively. There was no variation in NTR between the multiple flyovers shown in Fig. 11. The level differences between the spectra produced during each flyover are similar for NPR = 1.56 and

1.80. The largest differences in the spectra from different flyovers occurred for frequencies near the tone and for high frequencies at 130° where a secondary source is believed to impact the data.

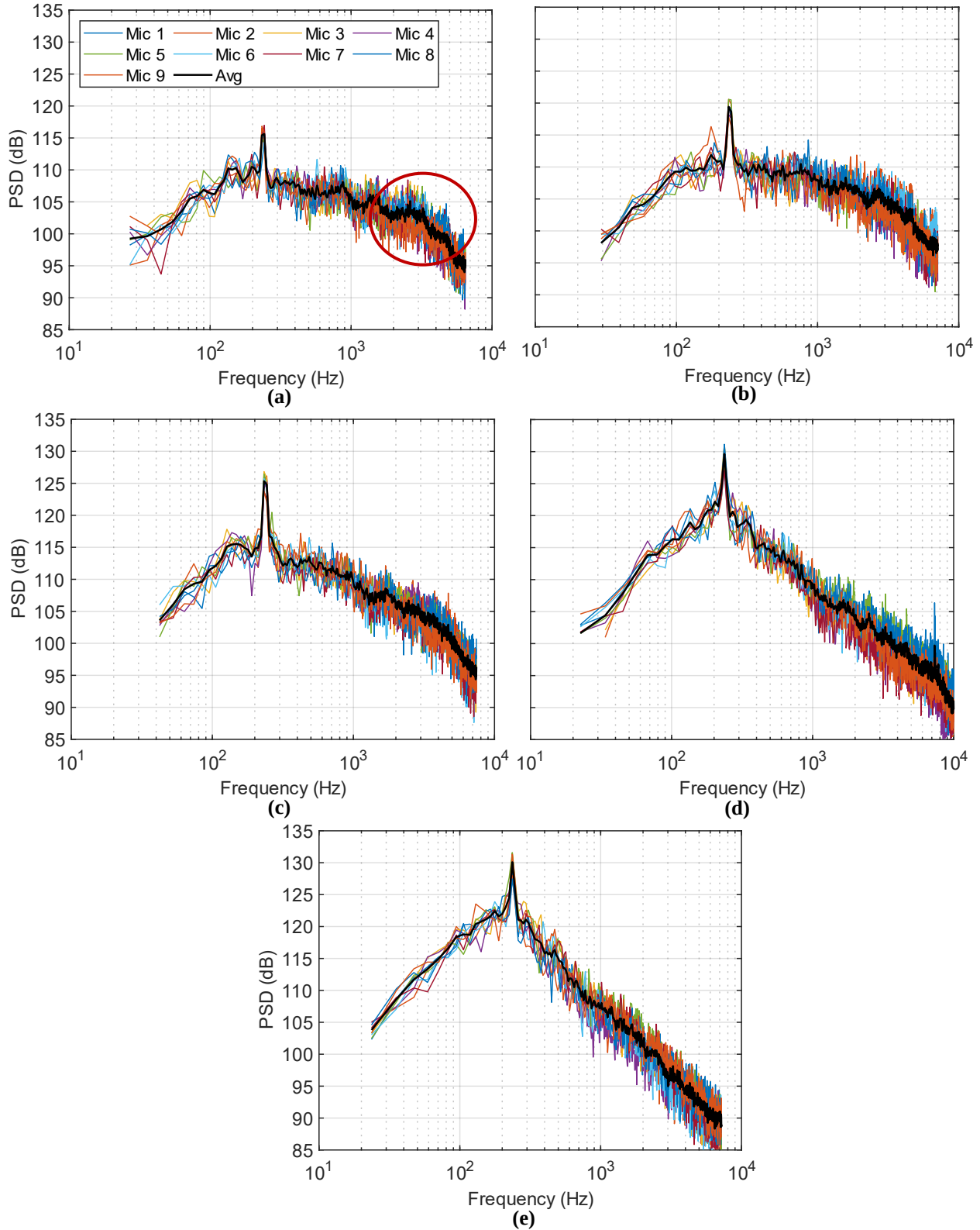


Fig. 8 The spectra for the nine microphones (Mic) and their average (Avg) at NPR = 1.56 and emission angles equal to (a) 70°, (b) 90°, (c) 110°, (d) 130°, and (e) 150°.

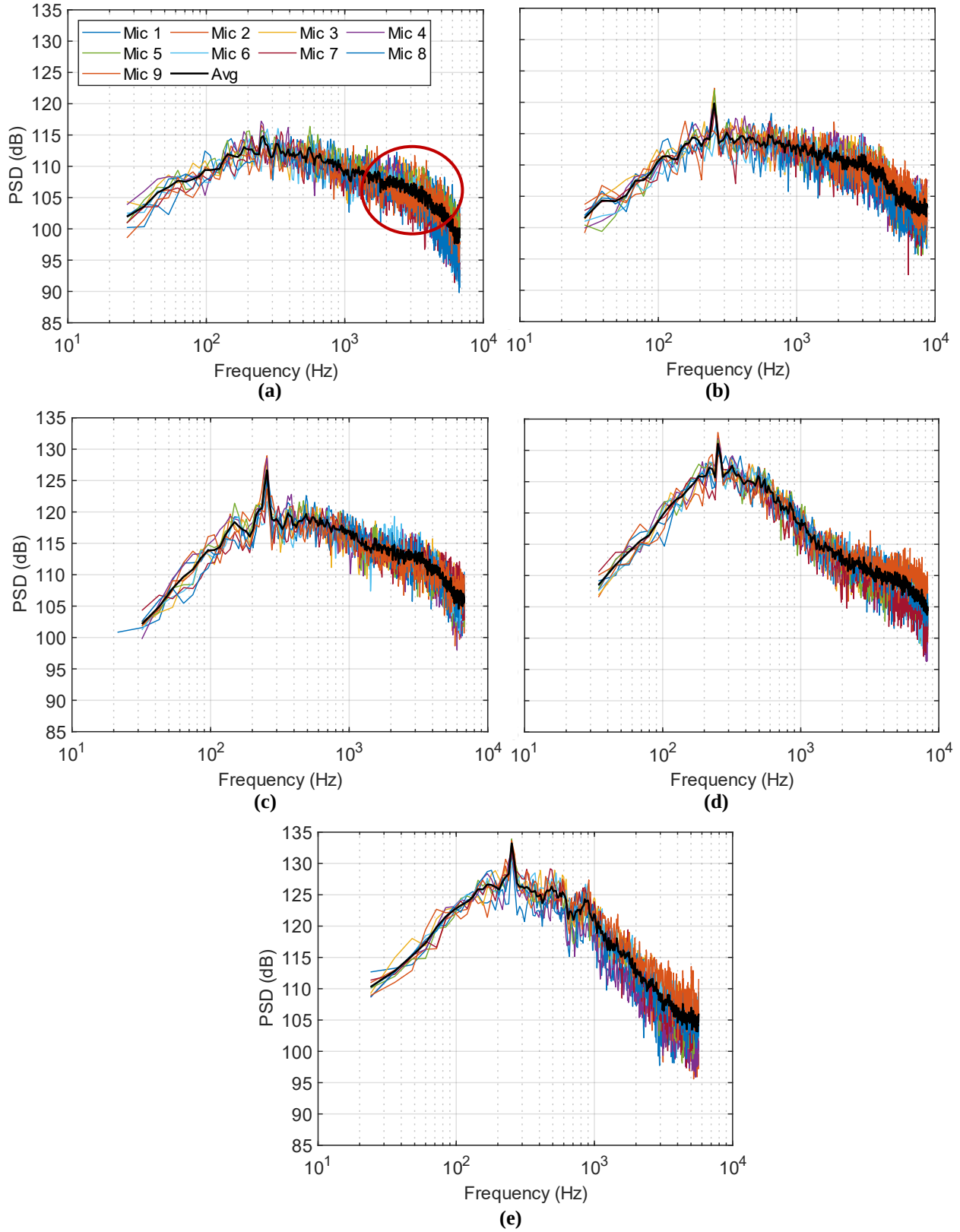


Fig. 9 The spectra for the nine microphones and their average at NPR = 1.91 and emission angles equal to (a) 70°, (b) 90°, (c) 110°, (d) 130°, and (e) 150°.

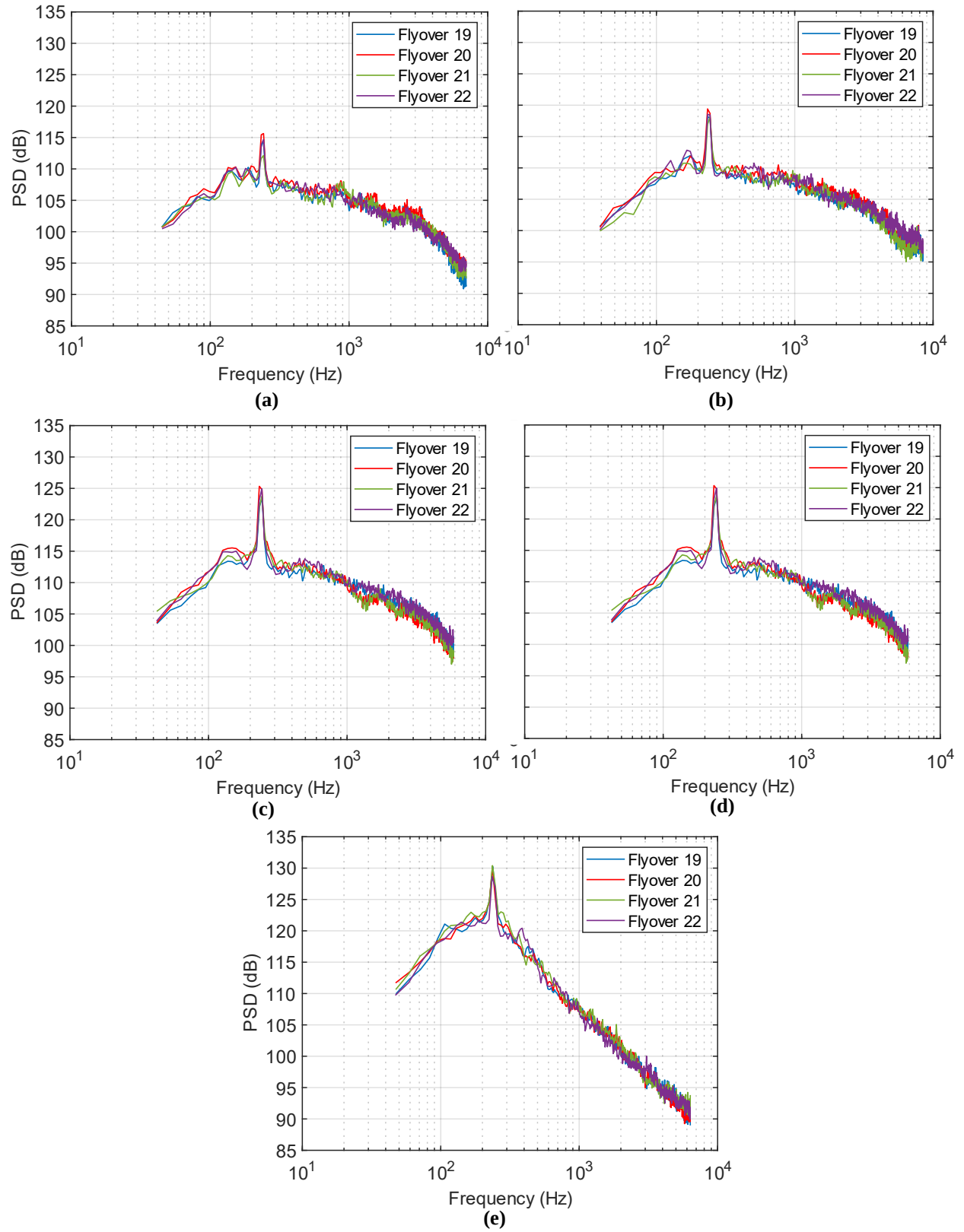


Fig. 10 The average spectra from the nine microphone for three different flyovers at a nominal of NPR = 1.56 and emission angles of (a) 70°, (b) 90°, (c) 110°, (d) 130°, and (e) 150°.

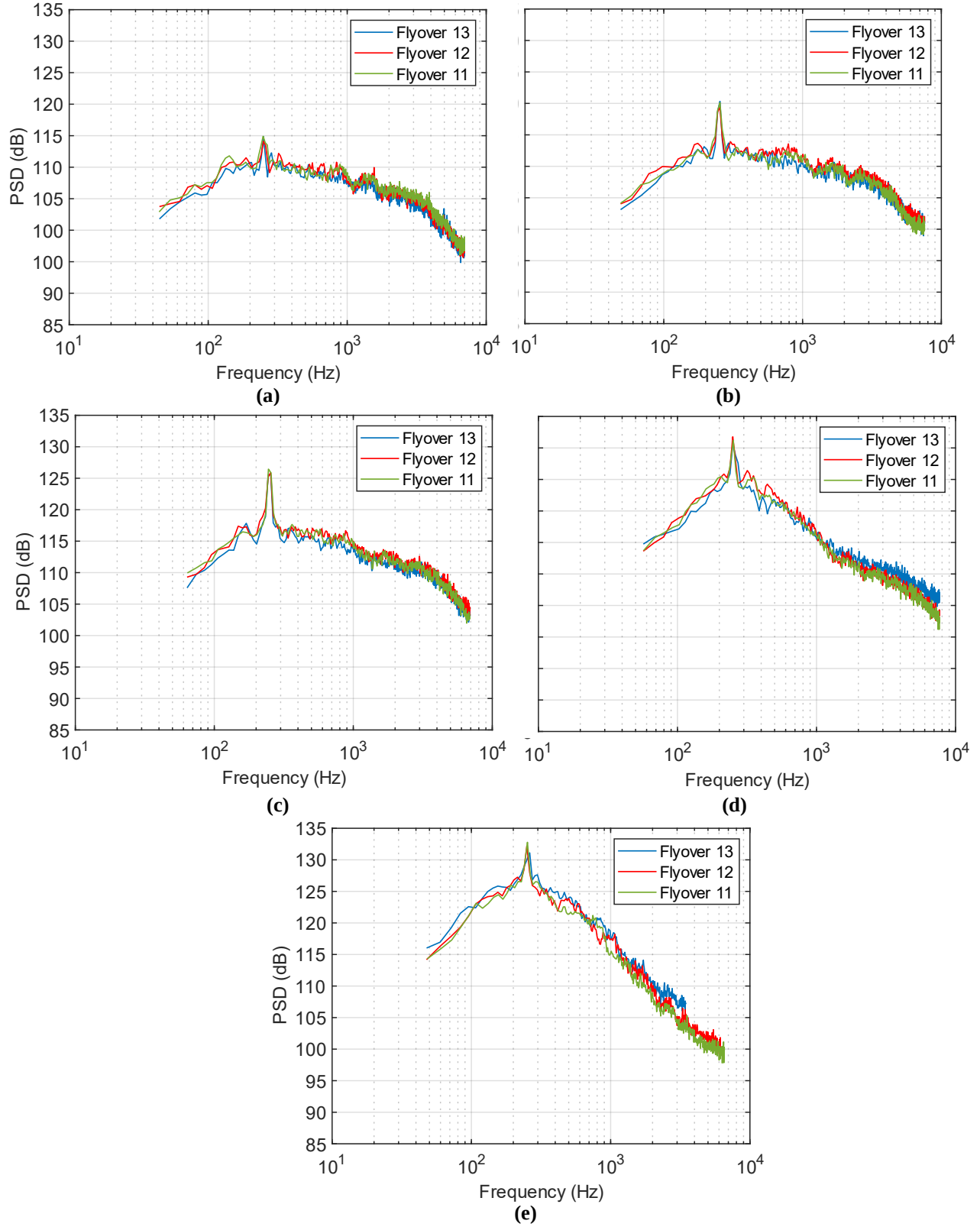


Fig. 11 The average spectra from the nine microphones for three different flyovers at a nominal of NPR = 1.80 and emission angles of (a) 70°, (b) 90°, (c) 110°, (d) 130°, and (e) 150°.

D. Flight and Scale Model Comparisons

The Lear scale-model data for $NPR = 1.8$ are shown in Fig. 12. The legend indicates the bypass flow conditions. No scale factor has been applied to the data. A value of $NPR_b = 1.05$ is obtained if the stagnation pressure of the flight stream is used for the stagnation pressure of the jet. The slight differences in the bypass condition had no discernable impact on the resulting spectra. As noted earlier, large flow rates through the bypass are not expected as the NACA scoop and side vent are the only sources of air for that stream.

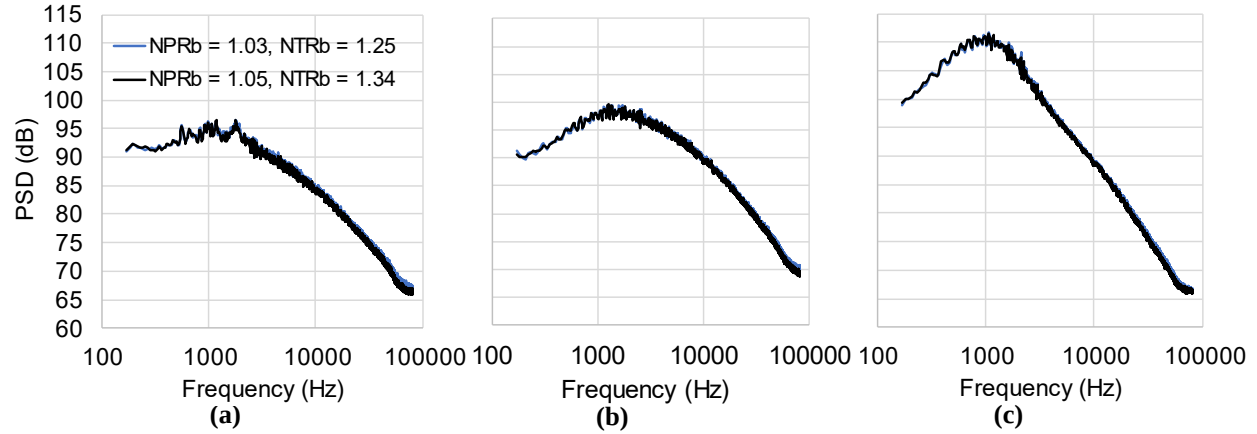


Fig. 12 The spectra for the Lear scale-model and $NPR = 1.8$ are shown at emission angles of (a) 70° , (b) 110° , and (c) 150° . The values in the legend are for the bypass stream.

A comparison between the scale-model and flight data for $NPR = 1.56$ and 1.90 are shown in Figs. 13 and 14, respectively. A scale factor of 3.21 has been applied to the scale-model data. Also shown in the figures are segments of the flight spectra where the first shaft order tones have been removed and replaced with second or third order polynomials (green lines). The spectra at an emission angle of 130° show significant haystacking around the tones which made the tone removal process challenging. The levels of the tones are lower relative to the jet noise for the supersonic jet than for $NPR = 1.56$ due to the higher jet-noise levels produced by the supersonic jet. Additionally, there is no tone present for $NPR = 1.91$ at 70° .

The peak frequencies for the scale-model data are slightly higher than those for the flight data near the peak jet noise angle where the spectra have reasonably pronounced peaks which is an indication that the scale factor determined from the measured dimensions of the nozzles may be too low. The boundary layer thicknesses for the scale-model and aircraft nozzles are expected to be comparable as the jet velocities and the nozzle contours are similar and nozzle lengths are close; although the scale-model may be slightly longer than the CJ610 nozzle due to the adapters needed to mount the scale-model nozzle system on the HFJER. The result of having comparable boundary layer thicknesses is that the effective diameter relative to the measured diameter for the scale-model may be smaller than that obtained from a diameter ratio of the corresponding aircraft nozzle. This would result in a larger scale factor than that computed directly from the nozzle diameters. Additionally, the boundary layer on the exterior of the scale-model nozzle is expected to be thicker than that for the CJ610 nozzle due to the length of the HFJER and nozzle system. External boundary layer thickness have been shown to impact acoustic levels.

The scale-model spectra in Figs. 15 and 16 have a scale factor of 3.40 (a 6% increase over that used in Figs. 13 and 14). Better agreement is found for the peak frequencies and the peak levels when using this scale factor than that used for the spectra in Figs. 13 and 14. The spectral shapes for the scale model and flight data are similar except in regions near the tones and the secondary source. The peak levels for the scale model and flight data are close at 70° and 150° for both NPR . The peak levels at 90° and 110° are higher for the flight data than for the scale-model data. A further increase in the scale factor to 3.5 produced even better comparisons between flight and scale-model data than those shown in Figs. 15 and 16.

It is unlikely the relative boundary layer thicknesses account for an increase in the scale factor as large as 6%. Other scale-to-flight factors likely contribute to the increase that was used for the improved comparisons. As mentioned earlier, the assumed location of the jet-noise sources in the refraction corrections for the scale-mode data impact the spectral shape and peak levels. Future attempts to improve the agreement between the scale model and flight data will include investigations into the impact of the boundary layers as well as the source location assumption in the refraction correction.

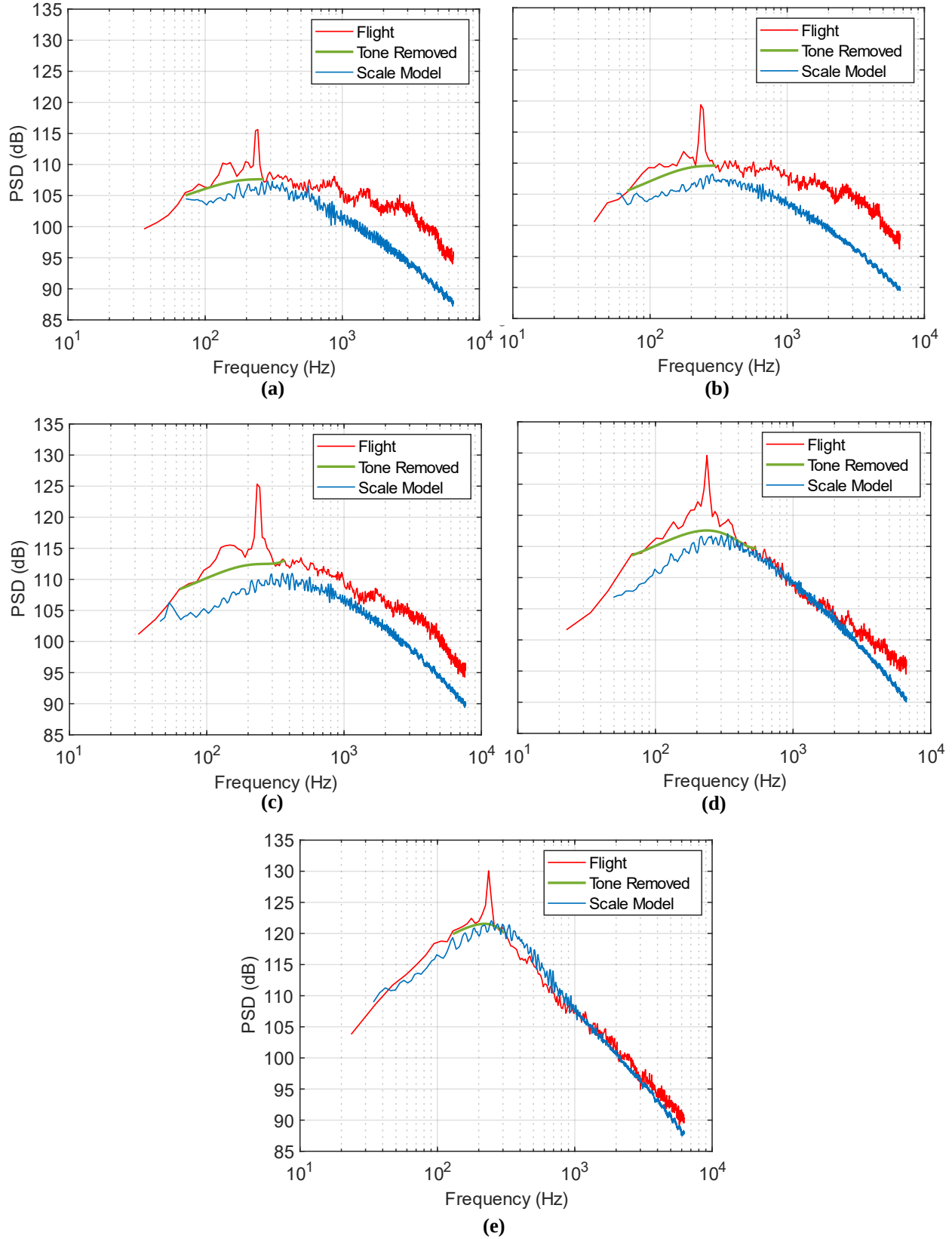


Fig. 13 Comparisons between the flight data and the Lear scale-model data using a scale factor of 3.21 for an NPR = 1.56 and emission angles of (a) 70°, (b) 90°, (c) 110°, (d) 130°, and (e) 150°. Also shown in the figure are polynomial curves used to remove tones and haystacking in the flight data.

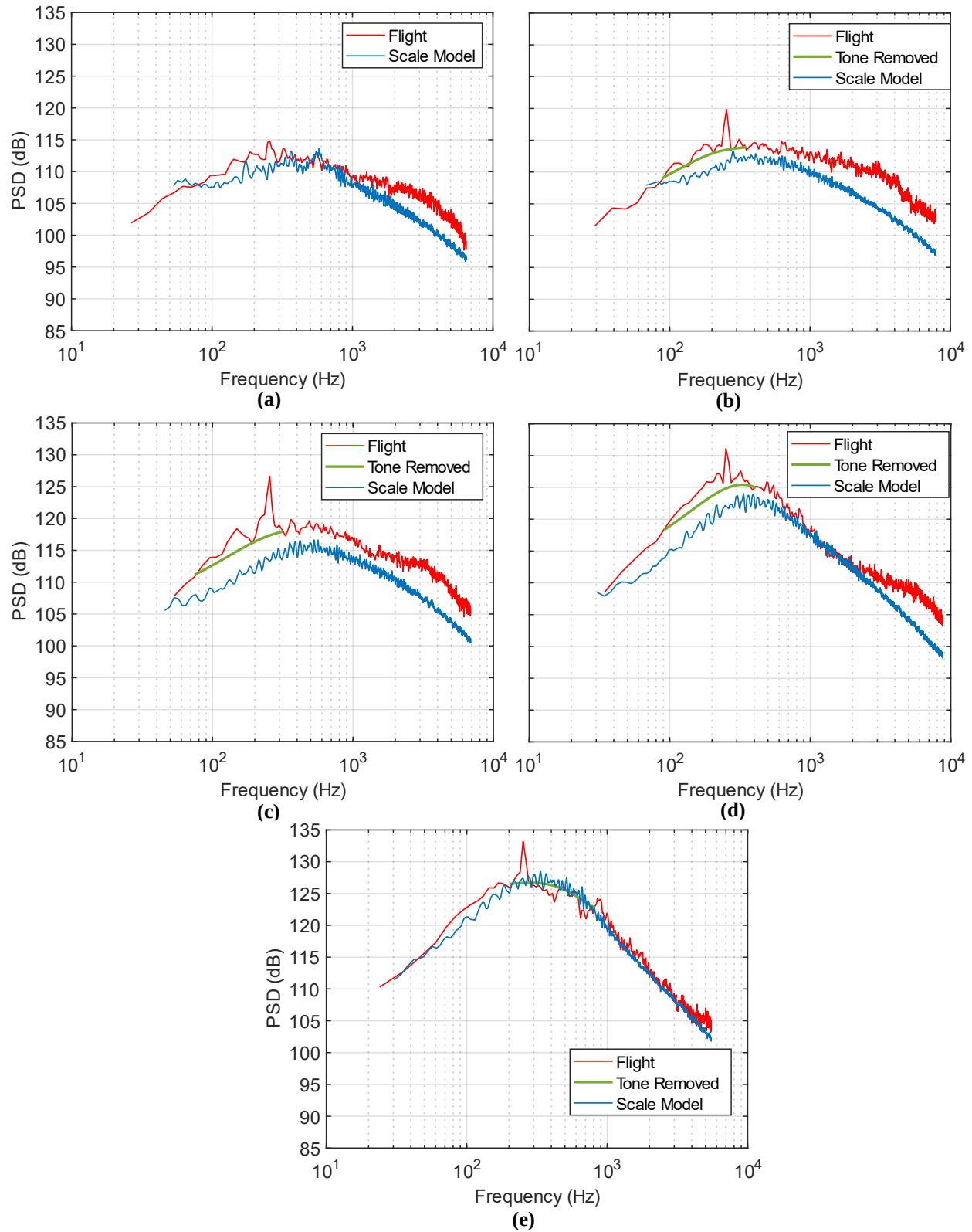


Fig. 14 Comparisons between the flight data and the Lear scale-model data using a scale factor of 3.21 for an NPR = 1.91 and emission angles of (a) 70°, (b) 90°, (c) 110°, (d) 130°, and (e) 150°. Also shown in the figure are polynomial curves used to remove tones and haystacking in the flight data.

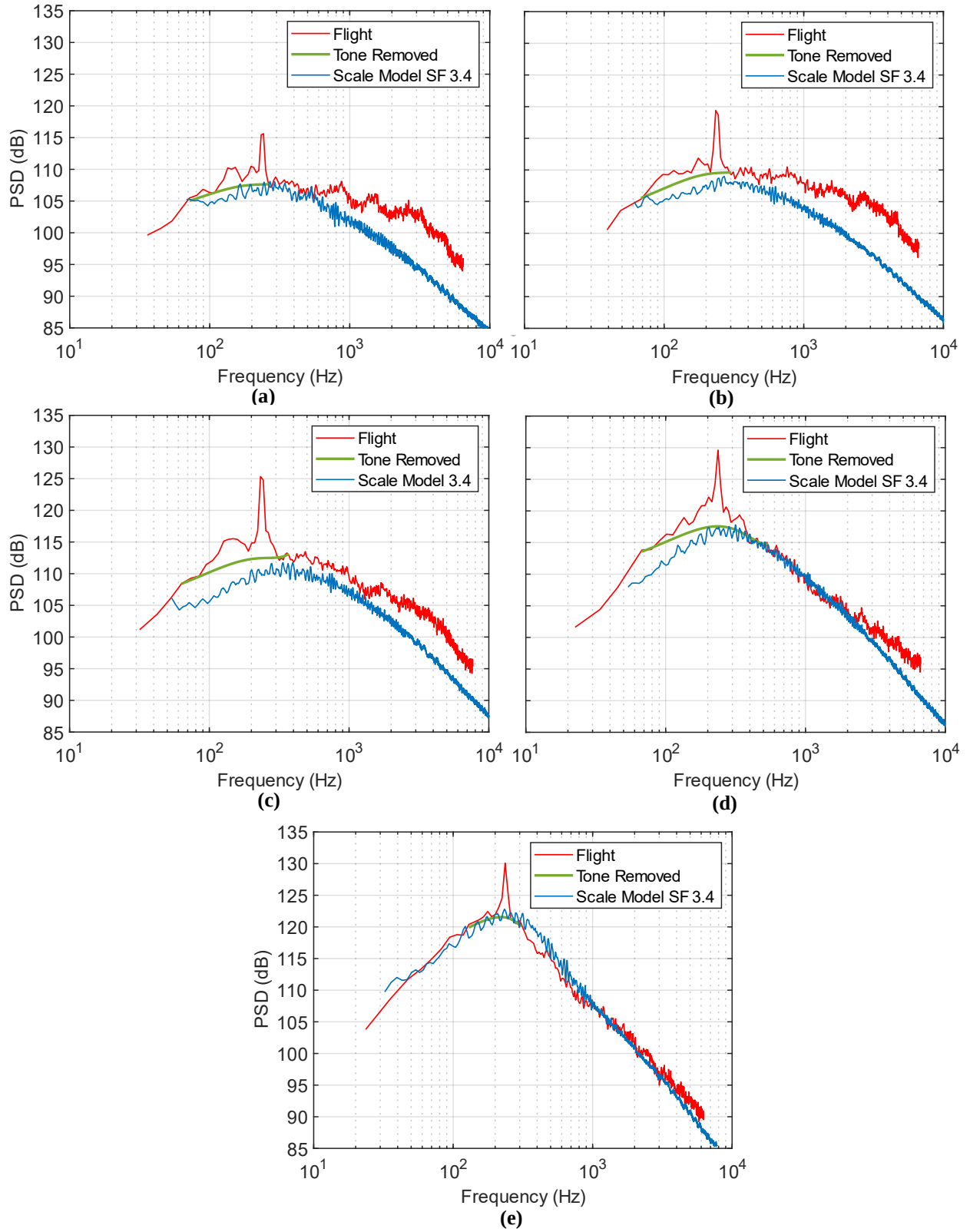


Fig. 15 Comparisons between the flight data and the Lear scale-model data using a scale factor of 3.40 for an NPR = 1.56 and emission angles of (a) 70°, (b) 90°, (c) 110°, (d) 130°, and (e) 150°. Also shown in the figure are polynomial curves used to remove tones and haystacking in the flight data.

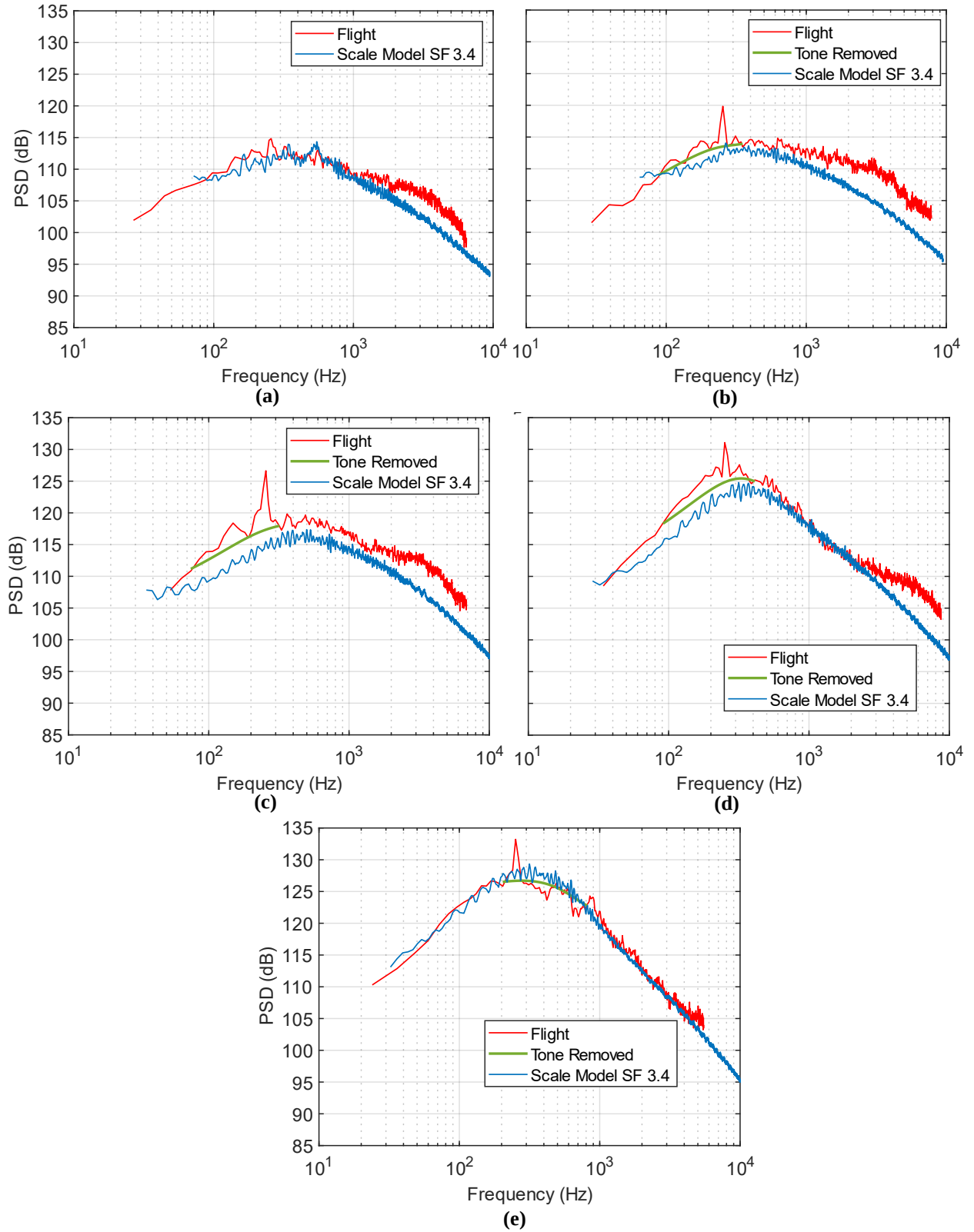


Fig. 16 Comparisons between the flight data and the Lear scale-model data using a scale factor of 3.40 for an NPR = 1.91 and emission angles of (a) 70°, (b) 90°, (c) 110°, (d) 130°, and (e) 150°. Also shown in the figure are polynomial curves used to remove tones and haystacking in the flight data.

E. Comparisons with SAE ARP876

One-third octave spectral comparisons between the SAE ARP876 jet-noise prediction model and the present flight and scale-model data are shown in Fig. 17 for $\text{NPR} = 1.56$. A dashed line is used for the flight data in regions where there is suspected influence from a secondary noise source. The peak levels for the flight data are higher than those for the scale model and the SAE model for 90° and 110° . The peak levels for the scale model are close to the flight data for 130° and 150° with a difference of 0.7 dB at 150° . The scale model data and SAE model compare well at 70° and 90° . For angles greater than 90° , the Lear model has increased high-frequency and peak levels relative to those for the SAE model.

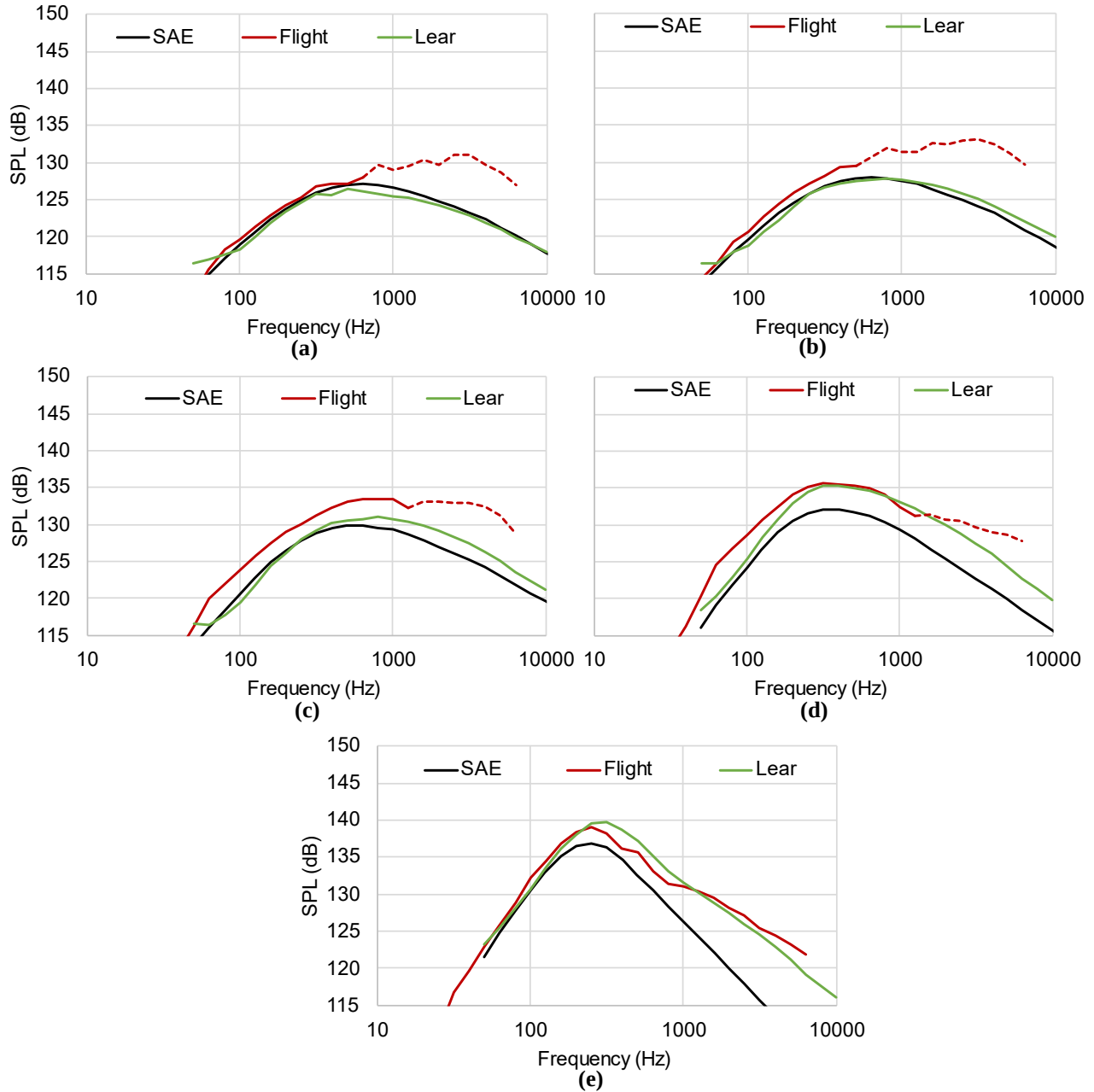


Fig. 17 One-third octave spectra obtained from SAE ARP876, the flight data, and the scale model using a scale factor of 3.4 for $\text{NPR} = 1.56$ and emission angles of (a) 70° , (b) 90° , (c) 110° , (d) 130° , and (e) 150° . The dashed lines indicate regions of the flight spectra most likely associated with a secondary noise source.

One-third-octave comparisons between the SAE ARP876 model, the flight data, and both scale-model nozzles are shown in Fig. 18 for $\text{NPR} = 1.91$. The peak levels for the flight data are higher than those for the scale-model data for angles greater than, or equal to, 90° . At 150° , the peak level for the flight data is roughly 1 dB above that for the scale model. SAE ARP876 under predicts high frequency levels for all angles relative those for the scale model. The peak levels for SAE are below those for the flight data and scale model data for angles greater than, or equal to, 110° . The levels for the Lear and SGL models are close for all angles and, therefore, the differences in the Lear data and the SAE model are not due to the dual nozzle configuration and the secondary stream of the Lear model.

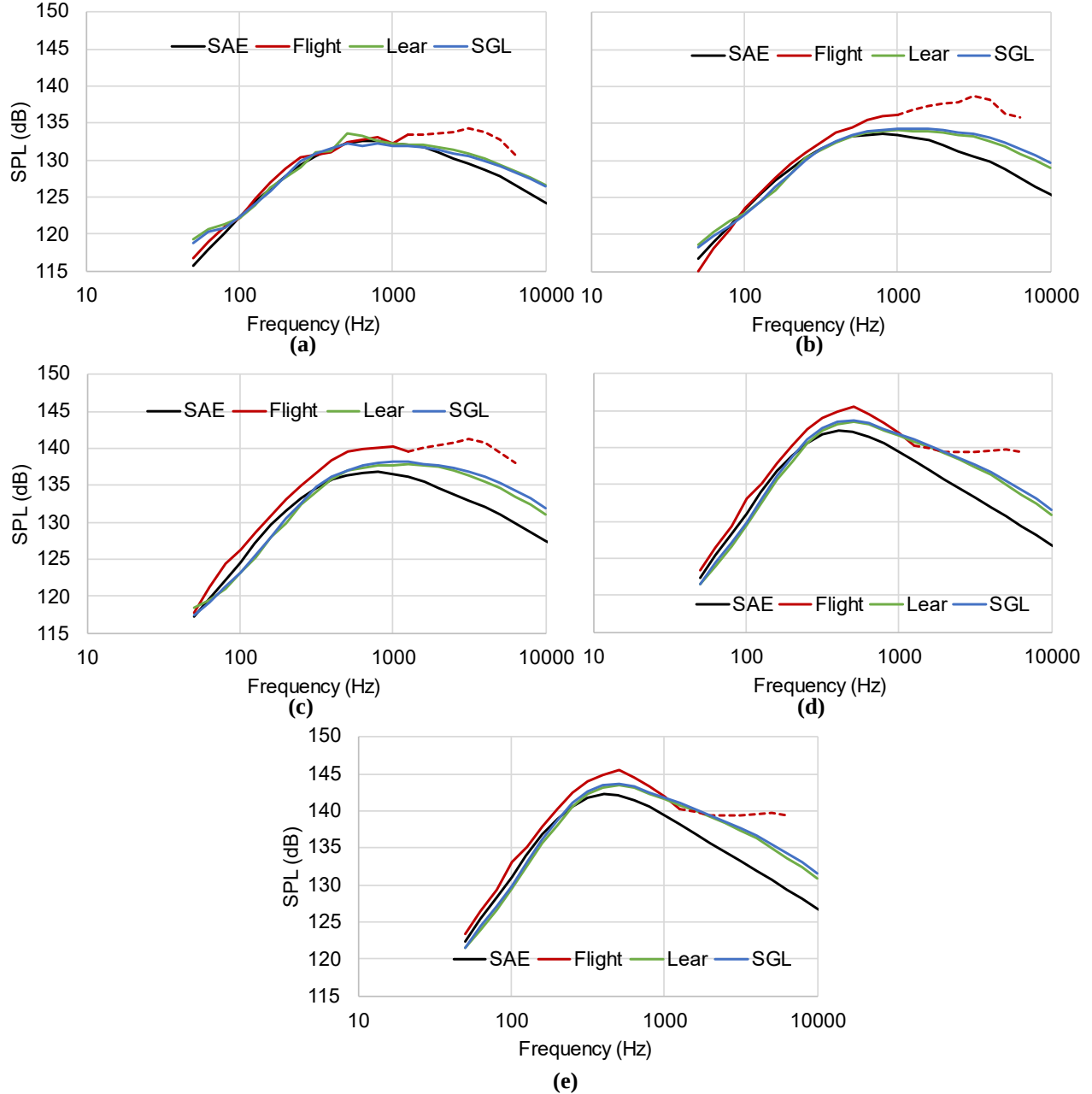


Fig. 18 One-third octave spectra obtained from SAE ARP876, the flight data, the Lear scale model, and the SGL scale model for $\text{NPR} = 1.56$ and emission angles of (a) 70° , (b) 90° , (c) 110° , (d) 130° , and (e) 150° . A scale factor of 3.4 has been used for the Lear and SGL models. The dashed lines indicate regions of the flight spectra most likely associated with a secondary noise source.

IV. Conclusions

An acoustics flight test and a complementary model-scale test have been conducted. The intent of the effort was to acquire the data necessary for the development of scale-model-to-flight corrections for jet noise and to quantify the uncertainty associated with jet-noise predictions for future supersonic aircraft. For the flight test, the engine parameters, aircraft position, and pressures necessary to compute airspeed were recorded throughout the flight. The aircraft nominally executed a steady climb, which allowed for control of the airspeed as it flew over a ground microphone array. A weather drone was used to collect ambient temperature, pressure, and humidity in vertical layers up to 1000 ft. A ground-based LiDAR system was used for wind speed. For the scale-model tests, acoustic measurements were made in the Aero-Acoustic Propulsion Laboratory at NASA Glenn using a scaled version of the Learjet nozzle system and operating conditions that were equivalent to those of the flight test.

The spectra obtained from the flight data displayed tones associated with the first shaft order for the powered engine. The tones were removed from the spectra during the comparison to the scale-model data. An apparent secondary source, possibly associated with airframe noise, was also identified in the spectra and will be investigated in the near future. A 6% increase in the physical scale factor was found to reasonably align the peak frequencies of the scale-model and flight data. Near the peak radiation angle, the peak levels for the scale model were roughly 0.7 dB above those for the flight data at NPR = 1.56 and were roughly 1 dB below those for the flight data at NPR = 1.91. Spectra produced by the SAE ARP876 model compared poorly with scale-model data for emission angles greater than, or equal to, 110°, especially at high frequencies. The spectral shapes and peak levels produced by the Learjet scale-model nozzle system and a single-stream nozzle were close indicating the poor comparisons between SAE ARP876 and the datasets in this study were not the result of the dual-nozzle configuration of the Learjet 25.

Future investigations will include an assessment of the impact of boundary layer thicknesses and source distribution assumptions for the refraction correction on the acoustic radiation from the scale model. EPNL comparisons for the flyover and scale model data will be made at sideline and flyover locations. An uncertainty analysis for the scale-model and flight data will be performed as well as an uncertainty estimation for a scale-model-to-flyover transformation.

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