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Assessment of in-cabin noise of wide-body aircrafts

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ABSTRACT

The aviation industry has seen dramatic growth over the decades till the recent disruption due to the COVID-19 pandemic. Moreover, long-haul routes with a distance of more than 4000 km are common for major airlines worldwide. Therefore, aircraft cabin noise assessment is essential, especially in long-haul flights, for passenger and flight crew health wellness. In this paper, the cabin noise of five wide-body aircraft, namely Airbus A330-300ER, A350-900, A380–800, and Boeing B777-200ER and B787-900, was recorded using a calibrated in-house developed smartphone application. The sound pressure levels of in-cabin noise have been measured on two different decibel scales, namely, A-weighted [dB (A)] and C-weighted scales [dB(C)]. The sound pressure levels of Airbus A380–800 were lowest among selected models, while the in-cabin pressure level values of Airbus A350-900 were maximum. However, the difference in decibel levels between the aircraft is minimal as it is within 3 dB.

1. Introduction

The aviation industry has seen dramatic growth over the past many years till the recent disruption due to the COVID-19 pandemic, with passenger numbers rising from 1.467 billion in 1998 to 4.5 billion in 2019, based on the reported statistics from the International Civil Aviation Organization. Commercial flights are often categorized into long, medium, or short-haul by commercial airlines based on flight length. A short-haul route is shorter than 1500 km, whereas a long-haul route is longer than 4000 km. The longest commercial flight is the Singapore Airlines Flight between Singapore Changi Airport and New York Newark Airport, covering 15,344 km using an Airbus A350-900ULR aircraft with nearly 19-h flight duration. Moreover, the typical flight durations between cities in Asia are about one to seven hours. The flight duration from Singapore to Europe is about 11 to 13 h. In a BBC report in 2014, it was reported that the noise experienced in the interior or cabin of an aircraft during a typical plane journey could vary significantly. The take-off and landing operations were the loudest moments, with a potential maximum level of 105 dB(A). Fortunately, these two flight events are typical of concise duration. At cruising altitudes, noise could drop to below 85 dB(A).

The primary sources of aircraft noise are airflow noise engines and air-conditioning systems [1]. The secondary sources of aircraft noise are other aircraft systems such as landing gears, extension of flaps and slats, cockpit noise, cabin noise due to passenger conversion, public address system, toilet flushing noise, and noise caused by passenger services. Besides the cockpit noise, all the other primary and secondary noise sources contribute to the cabin noise experienced by the passengers. The noise is usually higher for older airplanes or towards the back of a plane.

Thus, aircraft cabin noise assessment is essential for passengers and flight crew's health, comfort, and psychological wellness, especially for long-haul flights. There is a potential risk of excessive noise exposure on crew and passengers, especially for long-haul flights. The early work by Begault et al. [2], based on a survey of 64 commercial airline pilots, reported that within specific age groups, the proportions responding positively regarding hearing loss and tinnitus exceeded the corresponding proportions in the general population reported by the National Center for Health Statistics. Several noise surveys conducted by the NIOSH in 1999 found noise levels exceeding its recommended exposure limit of 85 dB(A) as an 8-h TWA. The 8-h total weight average (TWA) is the permissible exposure limit (PEL) defined by the US Occupational Safety and Health Administration. Ozcan and Nemlioglu [3] classified the interior noise or cabin noise into continuous types caused by aircraft engines or motion and discontinuous types due to human activities or announcements in the plane. For their in-flight measurement of two Airbus A321 commercial planes, which were also narrow-body aircraft, the continuous noise levels were 60–65 dB(A) before takeoff, 80–85 dB(A), and 75–80 dB(A) during flight and landing, respectively. Discontinuous in-cabin noise levels were observed to reach levels as high as 81–88 dB(A). Lindgren et al.[4], based on a study of Swedish airlines cabin crews, found

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average sound levels between 78–84 dB(A) with maximum A-weighted exposure of 114 dB(A) but found no major hearing threshold shifts. More recently, Zevitas et al.[5] measured the sound levels on 200 flights, representing six aircraft groups using continuous monitors. The mean sound levels across all flight phases and aircraft groups were found to range from 37.6 dB(A) to greater than 110 dB(A), with a median value of 83.5 dB(A). The six groups of 200 aircraft of 23 different aircraft models for the study were mainly narrow-body aircrafts such as B737, B757, A320, MD80, MD88, MD 90, and a few wide-body aircrafts such as B767. In their study, the most significant proportion of aircraft types were the B757 and MD88 models, accounting for 35.5% and 28.5% of the flights, respectively. The majority of flights (91.5%) were short duration, defined as less than three hours, while the remainder (8.5%) was medium duration (3–6 h). The flight duration was divided into five phases: boarding, ascend, cruise, descent, and deplaning. Sound levels were found to increase sharply during ascent, decrease slightly during the cruise, increase again during descent, and fall during deplaning.

The A350 and the B787 are the most recent wide-body commercial aircraft constructed extensively with lightweight composites. Airbus and Boeing use reinforced plastic composites in 53% and 50% of the A350 and B787 fuselage. It has been reported that the A350 is quieter than the B787, primarily due to the automatic Noise Abatement Departure Procedure (NADP) for the optimization of the engine thrust and flight path to reduce noise and the fuel-efficient engine. The other giant airplane, A380, is also known to have a quiet cabin. However, there is minimal open literature on the cabin noise of these modern wide-body aircraft in operation.

This paper presents the cabin noise of six major wide-body aircraft, namely Airbus A330, A380, A350, and Boeing B777 and B787. The sound has been recorded using a calibrated in-house developed app during regular commercial long-haul flights. Our in-house build apps installed in the Samsung smartphone (refer to Garg et al.[6] for more details) have been used to measure the noise levels. Also, benchmarking of the cabin noise has been done in terms of A-weight sound level dB(A) and C-weighted sound level dB(C). Finally, the sound level and other data have been used to investigate the variability of cabin noise throughout the different flight phases and evaluate the exposure relative to health-based exposure limits.

2. Methodology

2.1. Aircraft types

Commercial flights are often categorized into long, medium, or short-haul by commercial airlines based on flight length. A typical short-haul route is shorter than 1500 km, whereas a long-haul route is longer than 4000 km. The longest commercial flight is the Singapore Airlines Flight between Singapore Changi Airport and New York Newark Liberty International Airport, covering 15,344 km using an Airbus A350-900ULR aircraft with nearly 19-hour flight duration. The typical flight duration between cities in Asia is about one to seven hours, while the flight duration from Singapore to Europe is about 11 to 13 h.

In this study, five wide-body aircraft, including three Airbus models (A330-300ER, A350-900, and A380–800) and two Boeing models (B777 and B787-900), were selected for the cabin noise investigations. The aircraft A330-300ER is a twin-engine, twin-aisle, and wide-body aircraft that can carry up to 285 passengers. It has a maximum range of 11,750 km, an overall length of 63.6 m, a wingspan of 60.3 m, a cruising speed of 0.86 Mach, and a top speed of 913 km/h. The aircraft model, A350-900, is a twin-engine twin-aisle wide-body aircraft that can carry 253 (Long Haul), 161 (Ultra Long Range), and 303 (medium haul) passengers. It has a maximum range of 15,000 km, length of 66.8 m, a wingspan of 64.8 m, cruising speed of 0.85 Mach, and a top speed of 945 km/h. The other Airbus model A380–800 is a four-engine wide-body aircraft that can carry 471 passengers. It has a maximum range of 15,200 km, a length of 72.7 m, a wingspan of 79.8 m, a cruising speed of 0.85 Mach, and a top speed of 1185 km/h.

In particular, the Boeing aircraft B777-300ER is a twin-engine wide-body aircraft that can carry 396 passengers. It has a maximum range of 13,649 km, an overall length of 73.9 m, a wingspan of 64.8 m, a cruising speed of 0.84 Mach, and a top speed of 925 km/h. The airframe measurements such as wingspan, wheel track, and tail-plane of the Boeing model B777-200ER are the same as B777-300ER. The main difference is the fuselage length. B777 300ER is 10 m longer than B777-200ER with a larger passenger capacity. On the other hand, Boeing B777 200-ER has a more extended range of 15,843 km and a reported cruising speed same as B777-300 ER. Boeing B787, in particular, B787 Dreamliner for this study, is a twin-engine wide-body aircraft that can carry 337 passengers. It has a maximum range of 11,750 km, an overall length of 68.3 m, a wingspan of 60.1 m, a cruising speed of 0.85 Mach with a top speed of 1041 km/h.

2.2. Noise measurement

In-cabin noise measurements were performed using an in-house developed app known as Noise-explorer with the in-built microphones of the smartphones calibrated against a typical type 1 sound level meter. Detailed information on the microphone calibration process can be found in a recently reported work by Garg et al.[6]. The app could compute the equivalent continuous sound pressure level (L_{eq}) and maximum and minimum sound levels with the time and Global Positioning System (GPS) information in a text file. The app was used under the flight mode as required by the airline regulation, and therefore the GPS information was not available for the current study. Sound recording for each flight started in several discrete segments when the aircraft was on the ground during taxiing until the aircraft's landing. The portable microphone was held by the traveler sitting at the aisle seat.

During several long-haul flights, the measurements were performed for different aircraft types, namely Airbus A330-300ER, A380–800, A350-900, and Boeing B777 and B787. The noise levels were computed and presented in both A-weighted decibel scale dB (A) and C-weighted decibel scale dB(C). The dB(A) sound level applies to the mid-range frequencies instead of the dB(C) sound level that measures low and high frequencies. The sound level values in terms of dB(C) could be significantly higher than dB(A) when there is significant low-frequency content. The scaling curve for C-weighting is generally flat over several octaves and thus includes more of the low-frequency range of sounds. The dB(C) was initially developed to reflect the frequency sensitivity of the human ear to high sound levels in access of 85 dB. The dB(C) scale is suitable for subjective measurements at high sound pressure levels.

The dB(C) has been widely used in recent research studies [7–9]. For example, a recent article by Lee et al.[10] for the measurement of noise profiles emitted from construction equipment and processes commonly done in the construction industry highlighted the significant presence of low-frequency noise at construction sites for some construction equipment and techniques, especially for large construction equipment such as BC trench cutters. There is also increased interest in the dB(C) scale to study noise from the giant offshore wind turbine due to the presence of significant low-frequency noise [11].

Furthermore, the cabin noise measurement locations during the commercial flights were usually along the aisle at the front of the economy section. The measurements were carried out in several segments of the recording. The total trip time was the duration from the beginning of the first recording to the last recording. The duration for each recording was typically a few minutes. There was no intentional effort to make each measurement duration the same due to the long flight duration.

3. Results and Discussion

3.1. Airbus A330-300ER

Table 1, 2 to Table 3 show the measured sound pressure levels obtained in three different journeys of the same aircraft model A330-300ER. Each flight had a particular air travel time. Therefore, the sound measurements were performed on five occasions, namely during taxiing (initial), takeoff, cruising, landing, and taxiing (final). The average A-weighted L_{eq} for three trips during cruising were 72.8, 71.2, and 69.9 dB(A), respectively, with an average value of 71.3 dB(A). The average C-weighted L_{eq} for the three trips during cruising were 87.8, 86.0, and 83.1 dB(C), respectively, with an average value of 85.6 dB(C). The average C-weighted L_{eq} was therefore on average 14.3 dB higher than the A-weighted L_{eq}. The spectrum for C-weighted measurements for segment 8 of Table 3, as shown in Fig. 1. showed several dominating low-frequency peaks below 600 Hz. The spectrogram is shown in the same figure. For A-weighted measurements, the SPL spectra and their corresponding spectrogram are presented in Fig. 2. Several low-frequency peaks diminished if presented in dB(A). The average A-weight L_{eq} of 71.3 dB (A) and C-weighted L_{eq} of 85.6 dB(C) were lower than the corresponding values for A350 and B787. It should be noted that the cruising speed of A330-300ER was lower than the cruising speeds of A350-900 and B787. This could be the reason for the lower cabin noise for A330.

Table 1
Measured sound levels for the aircraft A330-300ER (flight 1), total measurement duration 19 m 26 s, entire trip duration 4 h 22 m.

Segment	Duration (s)	L_{eq} [dB(A)]	L_{max} [dB(A)]	L_{eq} [dB(C)]	L_{max} [dB(C)]	Flight stage
1	65.6	68.7	85.6	79.2	86.7	Taxiing
2	22.1	62.0	65.3	80.1	81.7	Taxiing
3	48.1	64.1	70.8	89.1	93.3	Taxiing
4	70.4	63.1	68.7	81.9	87.2	Taxiing
5	213.1	75.7	80.7	95.4	104.0	Takeoff
6	176.8	74.6	77.1	88.3	89.6	Cruising
7	108.5	71.6	72.4	86.2	86.9	Cruising
8	48.5	72.6	74.9	87.1	89.4	Cruising
9	114.1	69.2	70.3	85.3	87.3	Cruising
10	137.5	76.0	82.2	92.0	99.8	Cruising
11	42.5	72.9	73.7	89.8	90.8	Landing

Table 2
Measured sound levels for the aircraft A330-300ER (flight 2), total measurement duration 26 m 37 s, entire trip duration 4 h 31 m.

Segment	Duration (s)	L_{eq} [dB(A)]	L_{max} [dB(A)]	L_{eq} [dB(C)]	L_{max} [dB(C)]	Flight stage
1	222.2	75.4	79.3	94.6	102.5	Takeoff
2	132.8	72.1	78.0	87.4	88.9	Cruising
3	106.1	73.7	74.4	87.1	88.3	Cruising
4	148.1	74.7	75.6	87.7	88.6	Cruising
5	98.6	74.9	75.6	88.0	88.8	Cruising
6	74.7	70.2	70.8	83.9	85.2	Cruising
7	59.1	70.2	70.8	84.1	85.9	Cruising
8	78.2	70.7	72.2	85.0	89.4	Cruising
9	73.4	68.7	69.5	85.0	88.7	Cruising
10	111.8	69.6	70.9	87.6	92.1	Cruising
11	81.2	69.1	74.4	84.2	86.5	Cruising
12	116.5	69.6	71.8	86.0	89.4	Cruising
13	86.6	68.7	72.2	85.5	88.9	Landing

Table 3
Measured sound levels for the aircraft A330-300ER (flight 3), total measurement duration 26 m 24 s, entire trip duration 4 h 41 m.

Segment	Duration (s)	L_{eq} [dB(A)]	L_{max} [dB(A)]	L_{eq} [dB(C)]	L_{max} [dB(C)]	Flight stage
1	502.7	65.6	70.8	80.2	87.1	Taxiing
2	59.4	66.0	67.8	78.6	80.9	Taxiing
3	660.9	72.1	79.0	87.1	96.5	Take off
4	64.8	70.8	77.1	84.0	85.1	Cruising
5	81.0	70.3	71.3	83.9	85.7	Cruising
6	150.3	70.7	71.7	84.1	85.1	Cruising
7	101.4	70.9	73.7	83.8	86.5	Cruising
8	107.2	67.9	69.4	81.6	82.6	Cruising
9	83.8	67.4	69.1	81.2	82.1	Cruising
10	113.9	71.6	82.1	83.2	85.6	Cruising
11	135.4	69.2	75.4	86.2	90.8	Landing
12	61.1	74.7	81.7	92.0	97.3	Landing

3.2. Airbus A350-900

The sound level measurements for Airbus A350-900 were conducted on four different flights. The results obtained from these flights are shown in Table 4–6 to Table 7. The average A-weighted L_{eq} for the four trips during cruising were 73.6, 75.4, 73.6, and 76.9 dB(A) with an average value of A-weighted L_{eq} of 74.9 dB(A) for the four trips. The average C-weighted L_{eq} for the four flights during cruising was 87.6, 87.9, 87.7, and 88.5 dB(C), with an average C-weight L_{eq} value of 87.9 dB(C). The average C-weighted L_{eq} was, therefore, on average, 13 dB higher than the A-weighted L_{eq}. For illustration, Fig. 3 shows the spectrum for C-weighted measurements for segment 9 of Table 4. It showed several dominating low-frequency peaks below 600 Hz. The spectrogram is shown in the same figure.

The takeoff and landing events could be identified from the spectrogram. For example, for the flight presented in Table 6, the spectrogram for takeoff (segment 3) and landing (segment 20) is shown in

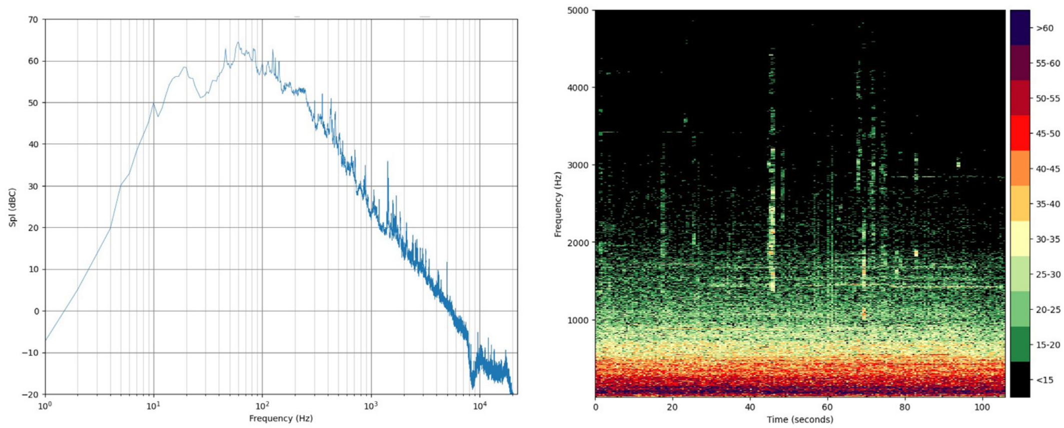

Fig. 1. The spectrum (left) and spectrogram (right) for C-weighted measurements dB(C) for segment 8 (A330-300ER, Flight 3) showed several dominating low-frequency peaks below 600 Hz.

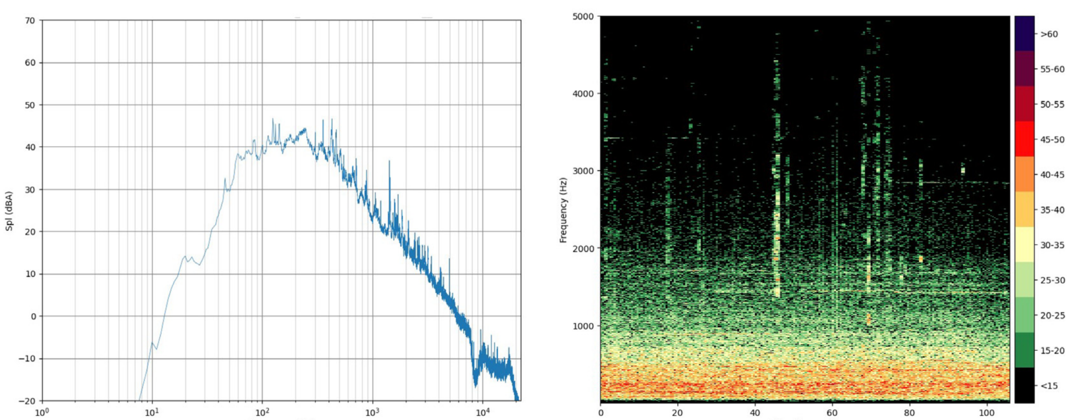

Fig. 2. The spectrum (left) and spectrogram (right) for A-weighted measurements dB(A) for segment 8 (A330-300ER, Flight 3) showed several dominating low-frequency peaks below 600 Hz.

Table 4
Measured sound levels for the aircraft A350-900 (flight 1), total measurement duration 33 m 19 s, an entire trip duration was 12 h 5 m.

Segment	Duration (s)	L_{eq} [dB(A)]	L_{max} [dB(A)]	L_{eq} [dB(C)]	L_{max} [dB(C)]	Flight stage
1	71.3	64.0	70.6	79.8	87.0	Taxiing
2	82.5	64.4	72.2	82.5	87.9	Taxiing
3	96.6	63.5	65.8	83.3	88.1	Taxiing
4	161.1	65.1	67.0	81.8	84.2	Taxiing
5	300.0	74.3	82.6	93.6	102.2	takeoff
6	121.1	73.4	76.5	87.9	91.4	Cruising
7	11.5	74.8	76.0	88.5	89.1	Cruising
8	159.2	77.6	79.7	90.9	92.2	Cruising
9	190.0	75.2	84.3	88.1	90.3	Cruising
10	204.2	74.6	75.4	87.7	88.5	Cruising
11	71.3	71.8	75.5	87.0	92.4	Cruising
12	83.2	71.4	73.4	85.8	87.3	Cruising
13	101.1	70.3	72.2	84.6	85.7	Cruising
14	185.6	73.4	81.5	90.0	98.6	Landing

Table 5
Measured sound levels for the aircraft A350-900 (flight 2); Total measurement duration 39 m 22 s, total duration of trip 3 h 36 m.

Segment	Duration (s)	L_{eq} [dB(A)]	L_{max} [dB(A)]	L_{eq} [dB(C)]	L_{max} [dB(C)]	Flight stage
1	158.8	63.6	69.5	88.2	96.0	Taxiing
2	83.4	64.0	77.2	78.0	82.1	Taxiing
3	321.2	72.4	81.9	92.7	102.7	Takeoff
4	102.0	74.1	77.2	87.7	88.8	Cruising
5	39.6	81.2	81.9	92.5	93.4	Cruising
6	157.9	81.3	82.1	92.5	93.6	Cruising
7	262.1	77.4	81.7	88.6	91.7	Cruising
8	131.3	76.9	78.0	88.4	89.3	Cruising
9	133.4	76.0	77.2	87.8	88.8	Cruising
10	116.3	74.8	80.9	86.9	87.8	Cruising
11	71.3	76.1	78.4	90.4	93.7	Cruising
12	172.0	68.4	74.4	82.4	83.3	Cruising
13	202.3	67.1	70.9	81.6	83.5	Cruising
14	276.6	66.9	74.5	84.3	93.6	Landing

Table 6
Measured sound levels for the aircraft A350-900 (flight 3), total measurement duration 55 m 21 s, entire trip duration 3 h 26 m.

Segment	Duration (s)	L_{eq} [dB(A)]	L_{max} [dB(A)]	L_{eq} [dB(C)]	L_{max} [dB(C)]	Flight stage
1	27.5	65.1	72.1	79.5	81.0	Taxiing
2	8.0	62.3	62.8	79.8	80.4	Taxiing
3	85.3	62.8	72.7	78.4	80.8	Taxiing
4	368.2	65.3	73.7	82.5	89.4	Taxiing
5	292.9	64.1	72.6	82.2	86.8	Taxiing
6	423.5	73.7	80.2	90.7	100.1	Takeoff
7	363.5	76.3	78.0	89.5	90.6	Cruising
8	52.4	77.4	79.3	90.1	91.0	Cruising
9	300.0	77.9	79.7	90.7	91.9	Cruising
10	172.8	74.9	77.0	87.8	88.7	Cruising
11	112.4	75.8	76.7	88.6	89.4	Cruising
12	152.9	74.3	76.1	87.2	89.2	Cruising
13	181.1	73.0	76.8	86.3	88.6	Cruising
14	57.0	75.3	76.3	88.3	89.4	Cruising
15	11.0	72.4	72.9	85.6	86.3	Cruising
16	120.9	72.0	75.6	87.9	92.0	Cruising
17	81.5	68.8	69.8	83.8	84.7	Cruising
18	120.7	69.3	77.5	83.4	84.9	Cruising
19	165.7	69.3	72.8	84.5	86.8	Cruising
20	110.2	76.2	82.3	91.3	98.7	Landing

Table 7
Measured sound levels for the aircraft A350-900 (flight 4), total measurement duration 29 m 35 s, entire trip duration 2 h 5 m.

Segment	Duration (s)	L_{eq} [dB(A)]	L_{max} [dB(A)]	L_{eq} [dB(C)]	L_{max} [dB(C)]	Flight stage
1	26.4	70.4	83.7	84.3	88.5	Taxiing
2	32.9	61.6	63.2	83.0	87.2	Taxiing
3	78.6	61.1	65.2	80.7	87.6	Taxiing
4	163.1	74.3	79.8	97.6	106.7	Takeoff
5	293.9	74.8	79.3	88.5	91.1	Cruising
6	126.9	79.4	80.4	91.2	92.4	Cruising
7	47.9	79.3	80.9	89.9	91.0	Cruising
8	192.1	82.3	83.8	91.0	92.4	Cruising
9	57.0	82.5	84.0	90.8	91.6	Cruising
10	15.2	79.9	80.9	90.7	91.3	Cruising
11	39.8	77.8	79.3	90.4	91.6	Cruising
12	64.5	78.0	82.7	87.7	88.9	Cruising
13	50.9	76.0	77.0	88.3	89.1	Cruising
14	18.4	75.9	76.3	86.3	86.7	Cruising
15	70.4	71.3	72.7	84.1	86.7	Cruising
16	146.6	72.4	73.8	89.4	92.2	Cruising
17	143.8	70.5	78.1	82.6	85.9	Cruising
18	86.2	71.5	76.8	87.5	94.4	Landing

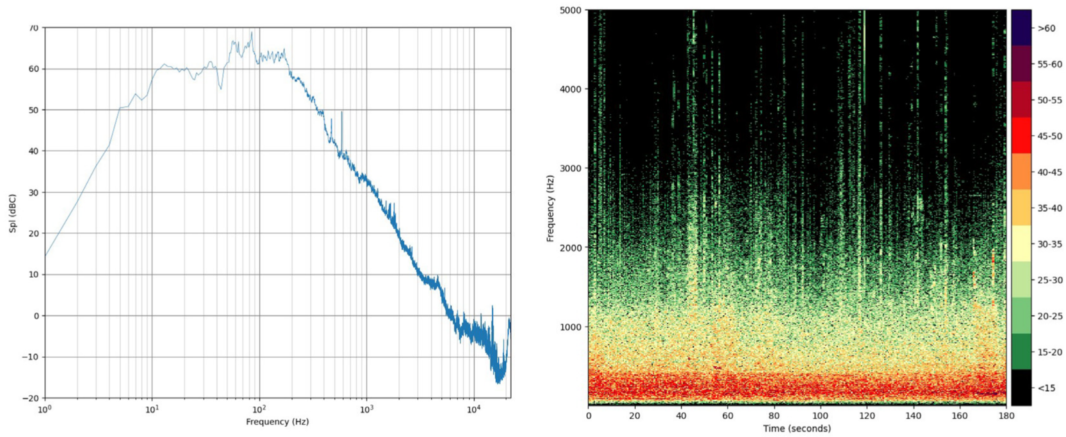

Fig. 3. Measured equivalent sound levels spectrum (left) and corresponding spectrogram (right) for C-weighted measurements for the aircraft A350-900 (segment 9 of Table 4) showed several dominating low-frequency peaks below 600 Hz.

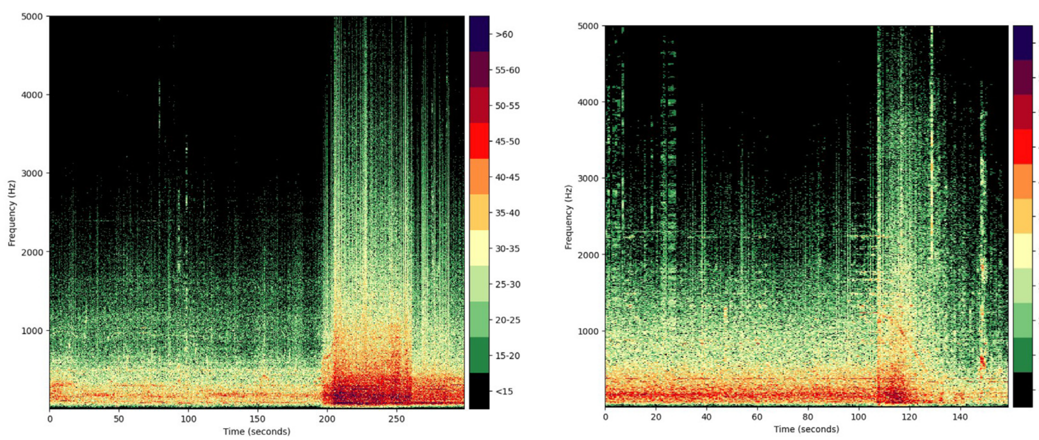

Fig. 4. The spectrogram of the noise was recorded during takeoff (segment 5) (left) and landing (segment 20) (right) for the aircraft A350-900 (Table 6) for A-weighted measurements. The C-weighted spectrograms showed a similar pattern with a more intense increase in noise level.

Table 8
Measured sound levels for the aircraft A380–800 (flight 1), total measurement duration 22 m 35 s, entire trip duration 9 h 51 m.

Segment	Duration (s)	L_{eq} [dB(A)]	L_{max} [dB(A)]	L_{eq} [dB(C)]	L_{max} [dB(C)]	Flight stage
1	331.0	65.4	69.1	84.4	90.7	Taxiing
2	305.2	69.8	76.8	90.8	100.1	Takeoff
3	216.8	70.8	72.6	84.8	86.6	Cruising
4	125.4	71.9	74.9	83.7	85.2	Cruising
5	74.3	70.2	70.9	83.5	84.8	Cruising
6	18.4	68.7	69.5	84.7	85.2	Cruising
7	144.5	69.0	69.9	83.1	84.8	Cruising
8	19.5	68.2	68.9	83.9	84.3	Cruising
9	120.0	68.0	68.9	85.1	86.1	Landing

Fig. 4. As shown, the takeoff event was dominated by increased noise levels across a wider frequency band below 1000 Hz. A burst of increased noise level also dominated the landing event.

3.3. Airbus A380–800

The sound level measurements for Airbus A350-900 were conducted on two different flights. The results obtained from these flights are shown in Table 8 and Table 9.

The average values of A-weighted sound levels and C-weighted sound levels during cruising were 69.5 dB(A) and 83.7 dB(C), respectively. Airbus 380–800 was deemed to be among the quietest aircraft for cabin noise during cruising. The dominating low frequency for A-weight noise was close to 400 Hz. The frequency values of 200 Hz and 400 Hz were indeed the dominating low-frequency noise as reflected by the C-weight spectrum as shown in Fig. 5 (Segment 4 of Table 9). The average value of C-weighted L_{eq} was 14.2 dB higher than A-weighted L_{eq} during cruising. The spectrogram for A-weighted noise during takeoff and landing is presented in Fig. 6.

3.4. Boeing B787-900

The in-cabin noise measurements for Boeing B787-900 were conducted on five different flights. The results are shown in Table 10–13 to Table 14.

Table 9
Measured sound levels for the aircraft A380–800 (flight 2), total measurement duration 29 m 49 s, total trip duration 11 h 58 m.

Segment	Duration (s)	L_{eq} [dB(A)]	L_{max} [dB(A)]	L_{eq} [dB(C)]	L_{max} [dB(C)]	Flight stage
1	612.4	70.7	83.9	88.2	99.7	Takeoff
2	317.5	71.8	78.0	84.5	86.3	Cruising
3	3.2	68.2	68.6	82.4	82.6	Cruising
4	300.2	68.4	69.6	83.0	85.2	Cruising
5	2.2	67.9	68.2	84.3	84.5	Cruising
6	92.7	68.8	76.0	81.6	83.8	Cruising
7	186.7	69.6	84.4	85.1	89.9	Cruising
8	274.0	71.9	83.0	91.8	102.1	Landing

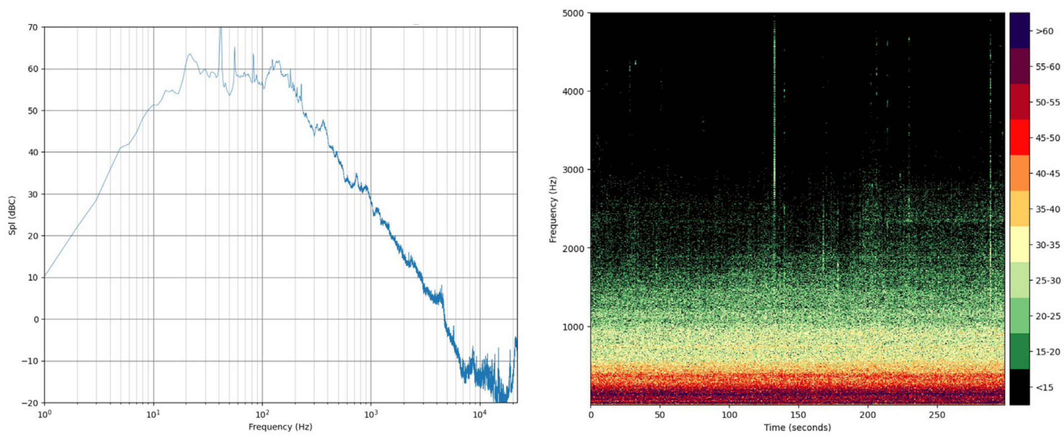

Fig. 5. Measured equivalent sound levels spectrum (left) and corresponding spectrogram (right) of the noise recorded for the aircraft A380–800 (flight 2; segment 4 of Table 9) for C-weighted measurements.

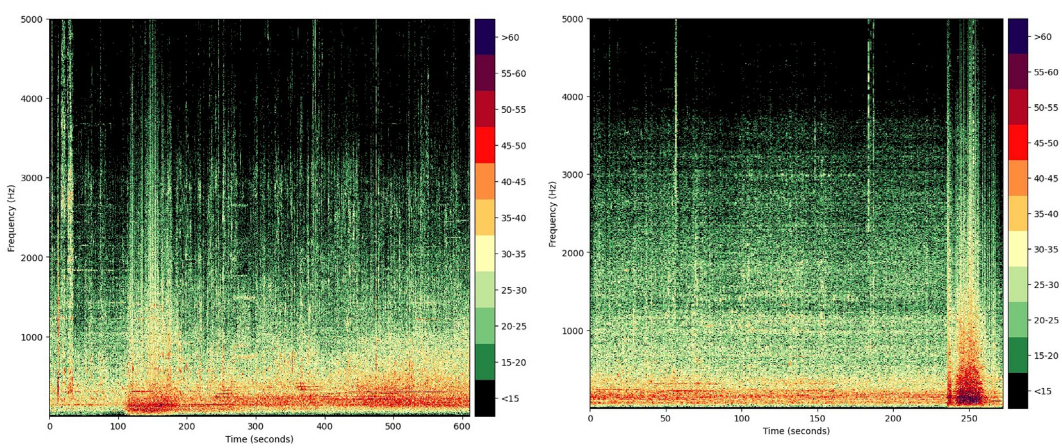

Fig. 6. The spectrogram of the noise was recorded during takeoff (left) (segment 1) and landing (right) (segment 8) for the aircraft A380–800 (Table 9) for A-weighted measurements.

Table 10
Measured sound levels for the aircraft B787-900 (flight 1), total measurement duration 24 m 7 s, entire trip duration 6 h 5 m.

Segment	Duration (s)	L_{eq} [dB(A)]	L_{max} [dB(A)]	L_{eq} [dB(C)]	L_{max} [dB(C)]	Flight stage
1	55.7	67.0	69.7	82.5	85.8	Taxiing
2	121.1	66.5	69.0	84.0	91.0	Taxiing
3	403.7	73.5	81.2	92.0	101.5	Takeoff
4	107.7	70.8	71.6	86.4	87.6	Cruising
5	112.4	73.8	76.4	87.7	89.0	Cruising
6	107.0	71.1	72.0	85.1	86.0	Cruising
7	5.6	72.2	73.7	84.5	85.1	Cruising
8	63.9	71.9	72.5	84.4	85.1	Cruising
9	39.2	70.4	74.4	84.5	85.4	Cruising
10	119.3	69.4	71.2	85.6	87.0	Cruising
11	78.8	71.0	72.0	85.7	86.9	Landing

Table 11
Measured sound levels for the aircraft B787-900 (flight 2), total measurement duration 24 m 7 s, entire trip duration 6 h 12 m.

Segment	Duration (s)	L_{eq} [dB(A)]	L_{max} [dB(A)]	L_{eq} [dB(C)]	L_{max} [dB(C)]	Flight stage
1	45.0	68.0	70.1	85.9	90.0	Taxiing
2	158.3	76.2	82.0	94.7	101.0	Takeoff
3	148.4	72.7	77.1	87.9	91.9	Cruising
4	43.5	73.9	75.0	87.8	89.0	Cruising
5	70.2	72.5	73.2	87.1	88.4	Cruising
6	70.2	72.7	73.7	87.8	89.1	Cruising
7	73.2	71.9	72.4	87.7	88.9	Cruising
8	40.7	71.6	72.4	86.5	87.8	Cruising
9	46.6	73.0	74.1	86.5	87.3	Cruising
10	63.2	70.1	70.8	85.4	86.3	Cruising
11	79.3	76.9	79.9	94.0	97.7	Cruising
12	96.4	76.1	81.2	91.9	96.6	Cruising
13	60.2	74.6	75.5	90.6	92.6	Landing

Table 12
Measured sound levels for the aircraft B787-900 (flight 3), total measurement duration 39 m 27 s, entire trip duration 6 h 34 m.

Segment	Duration (s)	L_{eq} [dB(A)]	L_{max} [dB(A)]	L_{eq} [dB(C)]	L_{max} [dB(C)]	Flight stage
1	20.6	69.1	72.1	81.8	85.7	Taxiing
2	48.9	68.0	69.5	76.9	80.2	Taxiing
3	41.4	69.9	75.8	77.8	83.2	Taxiing
4	55.4	67.8	70.1	78.9	84.8	Taxiing
5	52.2	75.3	85.2	82.4	88.7	Taxiing
6	167.4	76.7	83.3	95.0	101.8	Takeoff
7	183.2	72.7	81.9	88.6	90.9	Cruising
8	110.3	74.4	84.5	87.9	91.7	Cruising
9	276.8	77.3	80.4	88.5	90.0	Cruising
10	66.3	77.7	79.1	88.7	89.9	Cruising
11	2.8	77.7	78.1	88.7	89.1	Cruising
12	135.4	78.9	79.8	89.4	91.0	Cruising
13	91.0	80.6	82.1	90.6	92.2	Cruising
14	95.9	79.3	80.4	90.0	91.3	Cruising
15	50.7	79.5	81.4	90.1	91.3	Cruising
16	84.3	78.7	80.0	89.3	90.8	Cruising
17	92.7	74.9	79.9	87.8	92.6	Cruising
18	110.2	75.5	78.7	91.3	92.9	Cruising
19	109.4	72.6	79.7	87.2	92.4	Cruising
20	144.3	70.7	79.5	85.0	91.2	Cruising
21	235.2	69.6	74.7	87.4	93.4	Landing

Table 13
Measured sound levels for the aircraft B787-900 (flight 4), total measurement duration 48 m 23 s, entire trip duration 3 h 17 m.

Segment	Duration (s)	L_{eq} [dB(A)]	L_{max} [dB(A)]	L_{eq} [dB(C)]	L_{max} [dB(C)]	Flight stage
1	69.3	65.0	67.6	85.4	89.6	Taxiing
2	76.9	64.9	67.9	86.2	91.1	Taxiing
3	172.4	74.0	80.2	93.4	101.3	Takeoff
4	156.4	69.3	70.9	85.0	86.4	Cruising
5	184.6	74.9	76.4	88.2	90.2	Cruising
6	147.3	76.1	79.2	89.1	90.1	Cruising
7	81.4	74.8	75.4	87.8	89.0	Cruising
8	291.6	72.6	76.3	86.5	90.1	Cruising
9	178.7	71.8	72.7	85.5	86.5	Cruising
10	109.8	71.5	72.1	85.5	86.4	Cruising
11	165.5	71.7	73.0	85.2	86.2	Cruising
12	55.2	71.7	73.2	85.2	86.3	Cruising
13	108.7	72.6	75.9	85.2	86.6	Cruising
14	68.0	72.0	73.0	85.2	86.0	Cruising
15	72.6	72.4	73.0	86.0	87.0	Cruising
16	104.4	73.1	74.1	86.2	87.6	Cruising
17	37.7	70.2	71.1	84.2	85.1	Cruising
18	56.1	68.3	69.7	82.7	83.7	Cruising
19	2.8	68.7	69.2	81.3	81.8	Cruising
20	183.2	67.6	70.4	82.3	84.3	Cruising
21	200.6	67.6	69.6	82.0	84.2	Cruising
22	243.5	72.7	81.5	88.4	98.9	Cruising
23	81.9	71.1	74.7	86.3	87.7	Landing

Table 14
Measured sound levels for the aircraft B787-900 (flight 5), total measurement duration 51 m 40 s, entire trip duration 10 h 30 m.

Segment	Duration (s)	L_{eq} [dB(A)]	L_{max} [dB(A)]	L_{eq} [dB(C)]	L_{max} [dB(C)]	Flight stage
1	226.8	68.9	75.6	89.2	93.3	Taxiing
2	16.7	68.1	69.3	89.8	91.1	Taxiing
3	90.8	76.8	80.2	98.4	103.0	Takeoff
4	225.0	70.5	78.4	87.1	90.2	Cruising
5	302.6	73.3	74.4	88.4	90.3	Cruising
6	132.8	72.9	75.3	88.1	89.7	Cruising
7	99.2	69.6	70.4	84.5	86.5	Cruising
8	4.3	70.2	70.6	84.4	86.3	Cruising
9	179.3	69.8	76.8	84.6	86.4	Cruising
10	61.9	69.4	72.8	84.5	86.3	Cruising
11	72.8	69.4	71.2	84.1	85.8	Cruising
12	317.1	69.7	76.5	84.1	86.2	Cruising
13	153.6	69.7	74.0	84.1	85.5	Cruising
14	132.1	72.1	76.2	90.6	93.1	Cruising
15	343.3	70.2	75.4	87.3	92.3	Cruising
16	123.3	71.5	79.4	87.9	89.3	Cruising
17	98.3	72.5	74.7	91.6	93.4	Cruising
18	131.9	70.1	73.2	88.1	92.3	Cruising
19	190.6	70.7	75.7	88.7	94.3	Landing

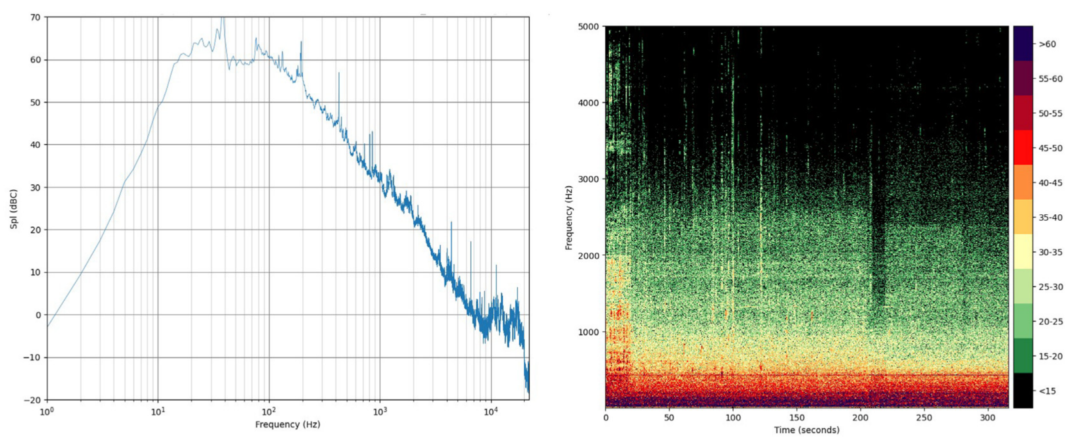

Fig. 7. The spectrum (left) and spectrogram (right) for C-weighted measurements for the aircraft B787-900 (flight 5; segment 9 of Table 14) showed several dominating low-frequency peaks below 600 Hz.

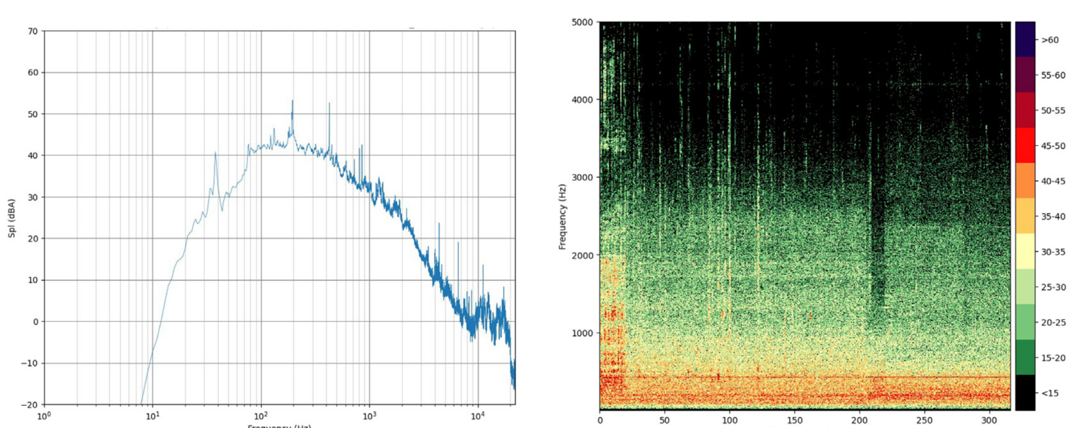

Fig. 8. The spectrum (left) and spectrogram (right) for A-weighted measurements for the aircraft B787-900 (flight 5; segment 9 of Table 14) showed several dominating low-frequency peaks below 600 Hz.

The average A-weighted L_{eq} for the five trips during cruising were 71.4, 73.1, 76.5, 71.6, and 70.7 dB, with an average value of A-weighted L_{eq} of 72.7 dB(A) for the five trips. The average C-weighted L_{eq} for the five trips during cruising were 85.5, 88.3, 88.8, 85.3, and 86.6 dB(C), with an average C-weight L_{eq} value of 86.9 dB(C) for the five trips. As a demonstration, the average C-weighted L_{eq} was, therefore, on average 14.2 dB higher than the A-weighted L_{eq}. The spectrum and spectrogram for C-weighted measurements for segment 12 of Table 14 are presented in Fig. 7. It showed several dominating low-frequency peaks below

Table 15
Measured sound levels for the aircraft B777-200ER, total measurement duration 31 m 51 s, entire trip duration nine h 49 m.

Segment	Duration (s)	L_{eq} [dB(A)]	L_{max} [dB(A)]	L_{eq} [dB(C)]	L_{max} [dB(C)]	Flight stage
1	374.7	73.4	82.2	93.2	103.7	Takeoff
2	131.0	75.3	76.2	89.8	90.4	Cruising
3	70.2	75.5	76.4	89.9	90.8	Cruising
4	39.2	75.6	76.2	89.8	90.3	Cruising
5	64.1	73.6	74.4	87.1	87.8	Cruising
6	69.3	73.9	77.0	85.8	86.9	Cruising
7	123.7	71.9	72.6	85.7	86.6	Cruising
8	185.9	70.3	72.3	86.0	87.6	Cruising
9	212.0	70.1	73.7	84.8	88.0	Cruising
10	33.8	71.0	72.4	83.2	83.9	Cruising
11	82.7	73.0	87.5	82.9	90.8	Cruising
12	118.3	68.3	71.0	82.9	92.6	Cruising
13	266.3	73.9	80.9	89.0	97.9	Landing

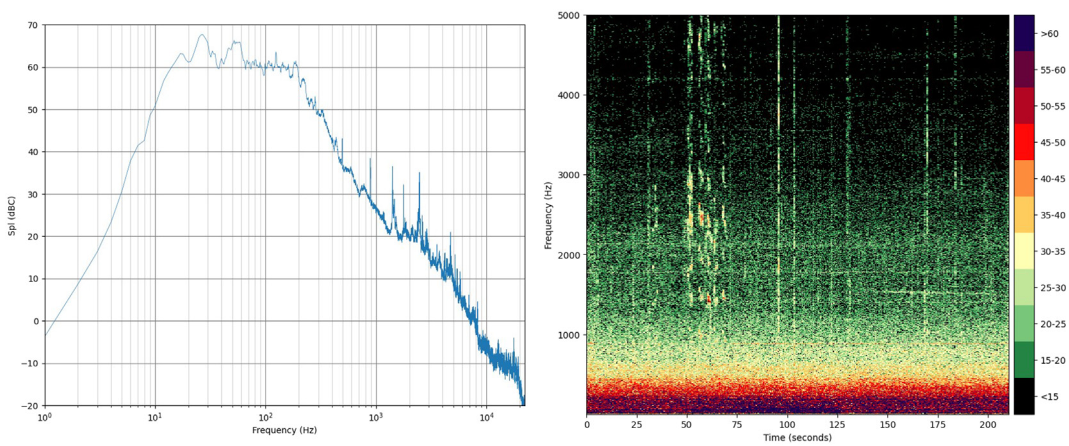

Fig. 9. The spectrum (left) and spectrogram (right) of the noise recorded for the aircraft B777-200ER (segment 9, Table 15) for C-weighted measurements.

Table 16
Measured sound levels for the aircraft B777-300ER, total measurement duration 45 m 51 s, total trip duration 11 h 29 m.

Segment	Duration (s)	L_{eq} [dB(A)]	L_{max} [dB(A)]	L_{eq} [dB(C)]	L_{max} [dB(C)]	Flight stage
1	301.7	78.5	86.8	96.6	104.7	Takeoff
2	303.0	76.1	85.8	89.7	92.0	Cruising
3	200.1	77.6	81.8	89.9	90.9	Cruising
4	134.9	82.0	83.4	93.0	93.9	Cruising
5	289.0	75.5	80.0	87.2	91.7	Cruising
6	109.8	75.3	78.2	87.5	88.5	Cruising
7	98.1	76.5	77.3	87.6	88.7	Cruising
8	199.7	75.5	77.1	86.3	87.2	Cruising
9	149.9	74.8	76.3	86.5	87.2	Cruising
10	130.0	72.8	73.7	84.8	86.0	Cruising
11	158.3	69.0	76.5	81.3	85.0	Cruising
12	266.0	67.2	72.3	81.9	84.3	Cruising
13	130.8	66.3	68.7	84.4	85.8	Cruising
14	279.9	70.4	79.7	91.9	101.4	Landing

400 Hz. For dBA, the same results are presented in Fig. 8. Several low-frequency peaks were found to be diminishing if given in dB (A).

3.5. Boeing B777-200 ER

The in-cabin noise measurements for Boeing B777-200ER were conducted on a single flight. The measured sound pressure level values are shown in Table 15.

For Boeing B777-200ER, the average value of A-weighted L_{eq} and C-weighted L_{eq} was 73.0 dB and 86.5 dB, respectively, during cruising. The C-weighted average L_{eq} of 86.5 dB was 13.5 dB higher than the average A-weighted L_{eq} during cruising. As an illustration, the spectrum and spectrogram, as shown in Fig. 9 for C-weighted measurements for segment nine of Table 15, showed several dominating low-frequency peaks below 600 Hz. As a result, the B777-200ER had a slightly higher A-weighted L_{eq} and C-weighted L_{eq} than the corresponding values for A330-300ER and comparable to A350 and B787.

3.6. Boeing B777-300 ER

The in-cabin noise measurements for Boeing B777-300ER were conducted on a single flight. The measured sound pressure level values are shown in Table 16.

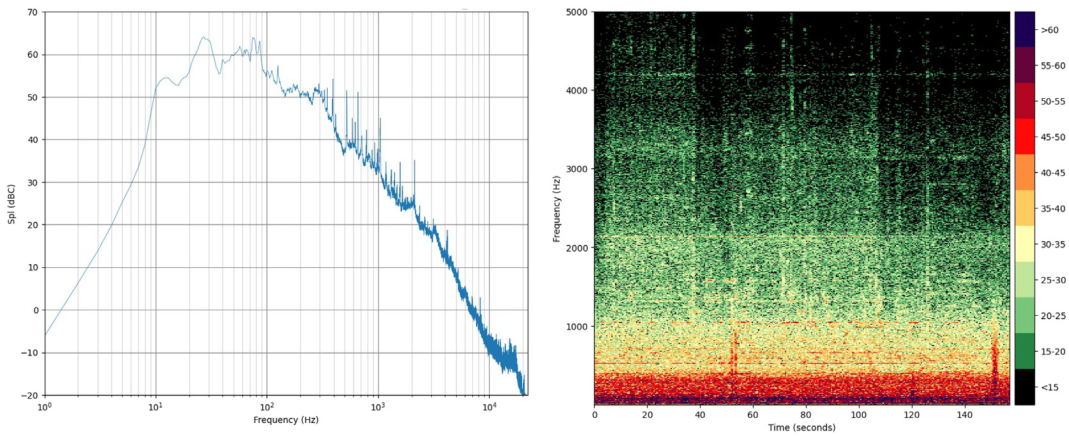

Fig. 10. The spectrum (left) and spectrogram (right) of the noise recorded for the aircraft B777-300ER (segment 11, Table 16) for C-weighted measurements.

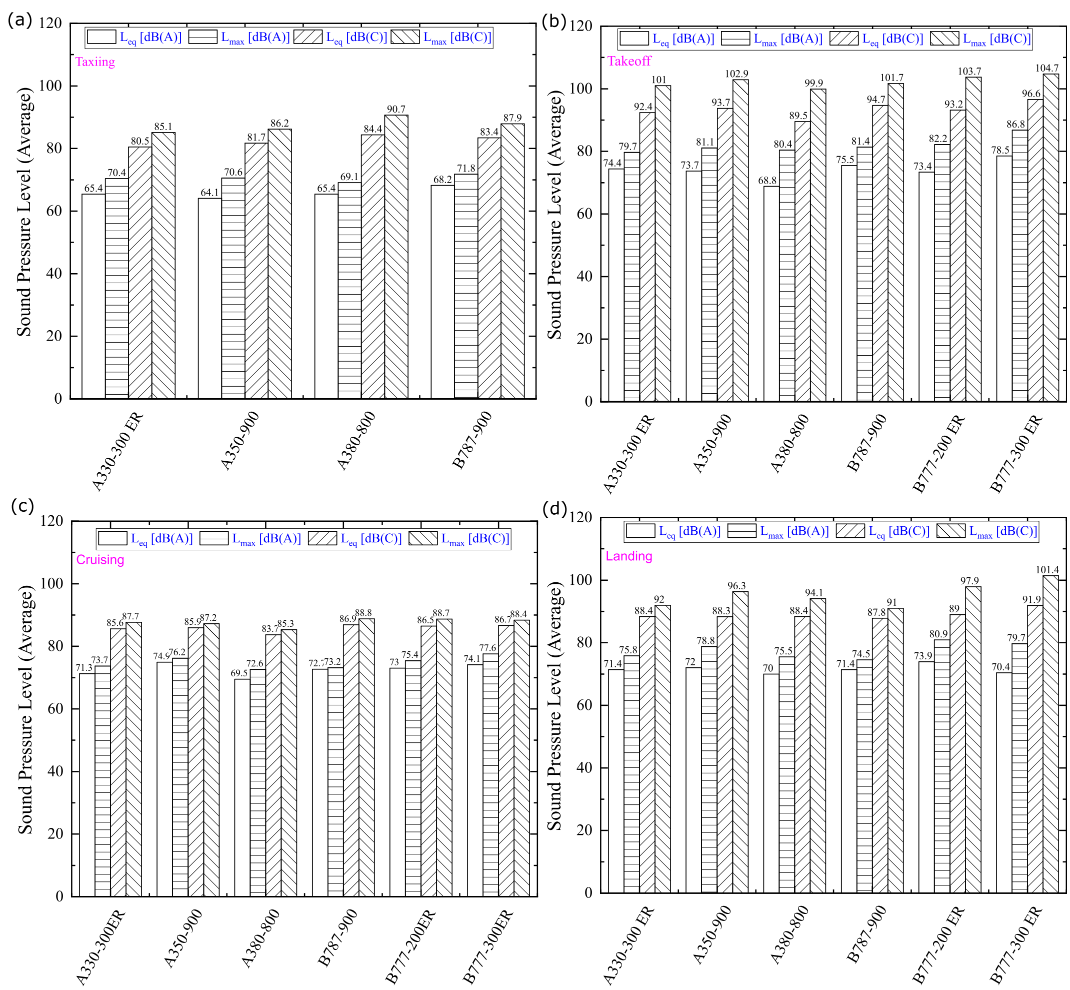

Fig. 11. Measured average sound pressure level values of six aircraft models in operation at various stages (a) taxiing, (b) takeoff, (c) cruising, and (d) landing.

For Boeing B777-300ER, the average value of A-weighted L_{eq} and C-weighted L_{eq} was 74.1 dB(A) and 86.7 dB(C), respectively. For illustration, the sound pressure level spectrum and corresponding spectrogram for C-weighted measurements for segment 11 of Table 16 are shown in Fig. 10. The A-weight L_{eq} and C-weighted L_{eq} were slightly higher than the corresponding values for its shorter counterpart of B777-200ER. The cabin noise was also comparable to that of A350 and B787.

4. Discussion

Fig. 11 (a-d) summarized the average equivalent sound pressure level values obtained from these aircraft models at various stages of operation. As shown, for all models, the sound level values on the A-weighted scale were lower than those on the C-weighted scale. Furthermore, the average sound pressure level inside the cabin during the takeoff operation was highest on both dB(A) and dB(C) scales. Moreover, during the landing operation, cabin noise was second most loud, followed by cruising and taxiing.

Moreover, on comparison between different aircraft models, it was noted that the average A-weight L_{eq} and C-weighted L_{eq} measured values for the A330-300ER cabin were lower than the corresponding values for A350 and B787. It should be noted that the cruising speed of A330 was lower than the cruising speeds of A350 and B787. It could be the reason for the lower cabin noise for A330. In addition, the B777-200ER had a slightly higher A-weighted L_{eq} and C-weighted L_{eq} than the corresponding values for A330-300ER and comparable to A350-900 and B787-900. Furthermore, the A-weighted L_{eq} and C-weighted L_{eq} of Boeing B777-300ER were slightly higher than the corresponding values for its shorter counterpart of B777-200ER. The cabin noise was also comparable to that of A350-900 and B787-900. However, both A350 and B787 are new-generation aircraft with significant improvements in composite components. As per measured data, the sound pressure levels of Airbus 380–800 were lowest among selected models, while maximum equivalent cabin noise was measured in the Airbus A350-900 model. However, the difference in decibel levels between the aircraft is minimal as it is within 3 dB. The Airbus A380 is powered by Engine Alliance GP7200 engines from the European Aviation Safety Agency (EASA) and the Federal Aviation Administration (FAA). The minimum cabin noise values confirm it is by far the quietest long-haul aircraft in the skies.

The Occupational Safety and Health Administration (OSHA) has set a permissible limit of noise exposure to the human. The permitted noise exposure limit varies from 90 dB(A) for 8 h to a maximum exposure of 115 dB(A) for less than 15 min [9]. Also, the National Institute for Occupational Safety & Health (NIOSH) has recommended an exposure limit of 85 A-weighted decibels as an 8-h time-weighted average sound level (TWA) [10]. However, our measured data set revealed that the average A-weighted sound pressure level values for all the aircraft were within the safe limit for noise exposure. So, technically the cabin noise was safe for crew members and passengers. However, human comfort could be affected by aircraft-cabin noise [12,13]. The high sound levels could directly or indirectly result in potential health-related consequences like hypertension, annoyance, mental tension, sleep disturbance, Increased risk of stroke, ischemic heart disease (IHD), unpleasantness, and speech disturbance [14–20]. Also, Phun et al. [21] examined the aircraft noise tolerability level depends on individuals up to a certain extent. Because the noise perceived by the individuals is also a subjective matter, Hence, the in-cabin noise effect may vary among person-to-person.

The noise generated by an aircraft flight is quite complex. As indicated earlier, the primary sources of aircraft noise are airflow noise, engine, and air-conditioning systems [22,1]. The engine noise due to turbomachinery noise has been reduced significantly for the new generations of turbine engines. However, the aerodynamic noise caused by high-speed turbulent flow over an aircraft fuselage and control surfaces may remain the primary noise source on future aircraft [2]. Thus, there is a potential risk of excessive noise exposure on crew and passengers for long-haul flights with a long flight time.

5. Conclusion

In this paper, the cabin noise of six major wide-body aircraft, namely Airbus A330, A380, A350, and Boeing B777 (2 variants) and B787, was recorded using a calibrated in-house developed software for smartphones regular commercial long-haul flights. The noise level measured by the app for the Samsung smartphones used in the study had been calibrated against a typical type 1 sound level meter. In terms of cabin noise, Airbus A350-900 was found to have a slightly higher average L_{eq} (Equivalent continuous sound pressure level) of 74.9 dB(A) and 87.9 dB(C) compared to that of Boeing B787 of 72.7 dB(A) and 86.9 dB(C), respectively. The difference was deemed to be minimal as the difference was within 1 to 3 dB. Airbus A380 was found to have the lowest cabin noise with average values during cruising 69.5 dB(A) and 83.7 dB (C), confirming the typical news report among the quietest aircraft.

The findings did confirm that the cabin noise in terms of dB(A) had improved significantly compared to the noise levels reported in earlier studies in the late 90s contributed by improved engine performance and innovation in aircraft designs. For example, the noise levels for the two modern aircrafts A350-900 and B787-900, were about 75 dB during the long duration of cruising, and therefore there was no risk of violating the 8-h TWA. However, the present study highlighted the significant presence of low-frequency noise which was the leading cause for the L_{eq} in terms of dB(C) to be more than 10 dB higher than the L_{eq} in dB(A). The reported studies on the health effect of low-frequency noise on crew and passengers were minimal. Such detailed studies would be required for crew and passengers soon.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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