vibration

Review

Whole-Body Vibration Experienced by Pilots, Passengers and Crew in Fixed-Wing Aircraft: A State-of-the-Science Review

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Abstract: Before the coronavirus pandemic, there were 4.5 billion passenger movements by aircraft annually; this is expected to recover after the pandemic. Despite the large numbers of flights per year, there are few reports of whole-body vibration in fixed-wing aircraft. This paper reports a review of literature intended to collate reported data related to exposure to whole-body vibration. Following a filtering process to select relevant articles, a literature search elicited 26 papers reporting measurements of vibration. These included measurements made in the cockpit and cabin, and for pilots, crew and passengers. Aircraft included military, commercial and passenger aircraft, turboprops, jets and piston prop aircraft. There was a lack of consistency on measurement method and analysis, and few met the full requirements of ISO 2631-1. However, measurements showed significant components of vibration at frequencies largely attenuated by the ISO frequency weighting filters, but have been shown to be important in terms of human vibration perception. Propeller aircraft showed strong tonal components in vibration frequency spectra. There was also a significant effect of the flight phase in the vibration exposure. It is recommended that the body of literature related to human response to whole-body vibration on aircraft is augmented with further studies in order to understand in-flight experiences and to optimize human health, wellbeing, comfort and performance.

Keywords: aircraft; whole-body vibration; human response to vibration; turboprop; ComfDemo project; review

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1. Introduction

With globalization, there is an increasing desire for people to travel long distances, be it for business, family or leisure activities. Passenger numbers dropped from 4.5 bn in 2019 to 1.8 bn in 2020, but a rapid recovery in numbers is expected [1]. In addition to passengers, there are high numbers of pilots and crew flying regularly; for example, in the United States there are about 460,000 qualified and certified pilots, most of whom are commercial and airline [2], in addition to military personnel. In an aircraft, the human body is exposed to different oscillatory motions of seats and floors, resulting in whole-body vibration experienced by pilots, crew members and passengers [3,4]. Additionally, packaging (i.e., seat design and pitch) and environmental factors within the cabin, such as thermal, noise, air quality, and humidity could also affect human comfort perception in context to whole-body vibration [5–8]. Many studies have demonstrated that long-term sitting and exposure to whole-body vibration play a role in the development of back pain, neck pain and the overall perception of human comfort [9–11].

Whole-body vibration occurs when a person is supported by a vibrating surface. Vibration is transmitted to the body and will propagate through it. Whole-body vibration can adversely affect the comfort, performance, and health of the person, depending on the vibration magnitude, duration, waveform, and activity performed. The frequency range between 1–20 Hz is usually considered the dominant range where people are most sensitive to whole-body vibration [4]. However, studies have also shown important effects at higher frequencies, especially for low magnitude signals, that are important for motion perception, wellbeing, and assessment of quality [12].

Measurement and evaluation of whole-body vibration methods are specified in ISO 2631-1 [13]. This specifies methods to measure multi-axial vibration at the seat surface, backrest, and floor in the fore-aft (x), lateral (y), and vertical (z) directions, in addition to rotation around those axes: roll, pitch and yaw. However, rotational motion is rarely reported in the literature, due to difficulty in measurement, low magnitudes, and lack of requirement for assessment in order to comply with regulation [14]. ISO 2631-1 specifies the application of frequency weightings to acceleration signals in order to model the response of the human body. In horizontal directions weighting W_d is used to attenuate the signal at frequencies above 2 Hz; at 100 Hz, the attenuation is −37 dB, corresponding to a scaling factor of 1.4%. In the vertical direction weighting W_k is used to attenuate frequencies above 10 Hz; at 100 Hz, the attenuation is −21 dB, corresponding to a scaling factor of 8.9%.

Although air travel exposes many millions of passengers and crew to whole-body vibration daily, measurements of exposure are rarely reported. This review seeks to collate data reported on fixed-wing aircraft whole-body vibration exposure, and to identify where further research is needed in order to fill gaps in published data.

2. Methods

Online databases SCOPUS, Web of Science, and Google Scholar were the primary sources of data. In addition, data was obtained from personal collections including conference papers. After an initial pilot study to test the specificity of terms, the search terms in Table 1 were used as selection criteria. Boolean operators were applied where appropriate, combining all combinations of Term 1, Term 2, and Term 3: e.g., aircraft AND human AND vibration. Relevant references cited in these papers were also used. Non-relevant papers were excluded based on title and abstract, and duplicates were removed (e.g., conference and journal papers reporting similar data). The database search was limited to papers post-2000; however, papers identified via citation were not restricted in publication date. Papers focusing on motion sickness were excluded from the shortlist.

Table 1. Search terms used in SCOPUS, Web of Science, and Google Scholar.

Term 1	Term 2	Term 3
Aircraft Airplane	Human Cabin Passenger Crew Pilot	Vibration Whole-Body Vibration WBV

3. Profile of Shortlisted Literature

From the initial search, 99 papers were selected. Of these, 36 were specifically relevant to rotary-winged aircraft only (helicopters), and therefore considered out of scope. A further 28 of the remaining 63 papers (44%) did not contain reports of human vibration data or response (e.g., focus on structural dynamics or acoustics). Four papers were identified by title but could not be sourced. One paper was eliminated due to errors identified in measurement technique, and 4 due to having insufficient detail to evaluate. Thereby, 26 papers were used as the focus for the remaining review. Additional papers providing context are included in this paper and references.

Twelve papers reported vibration data focusing on the cockpit; 16 reported data on vibration experienced in the cabin. Twelve reported data from jet aircraft (including one assumed to be jet from context); 16 reported data from propeller aircraft. Five papers reported data from commercial aircraft, 11 from military aircraft, and 10 from passenger aircraft. Several studies were reported across multiple papers, focusing on different aspects of the data reported.

The methods of measurement varied between studies. Most used accelerometers and a data acquisition system, but some used vibration meters. Data analysis was carried out on the stored vibration files post-hoc. The location of measurement also varied between studies. Several studies did not take measurements on the surface of the seat but at the seat mounting point, or adjacent to the seat surface. Whilst ISO 2631-1 [13] provided a method for the assessment of vibration using a '12-axis' method including vibration on the floor, seat and backrest, in addition to rotational components, there was no paper sourced that reported 12-axis data.

Papers included in the review are listed in Appendix A.

4. Sources of Vibration in Aircraft

Whole-body vibration in aircraft is sourced from the external environment, the propulsion system, and aircraft functions [15].

The external environment includes ground conditions when taxiing, taking off and landing [16–18], air turbulence [19], and the effects of wake from other aircraft [20]. Intentional 'surfing' the wake and wingtip vortices of a leading aircraft can increase lift of a trailing aircraft; therefore, this reduces fuel burn, resulting in improvements in range, economy, and emissions [21].

The type of power source for the aircraft affects the vibration environment. Turbofan jets ('jets') place a continuous thrust loading on the aircraft. Almost all propeller aircraft have propellers mounted at the front of the aircraft fuselage or wing, meaning that the airframe is continuously affected by the wake propagating from each propeller blade [22].

Vibration in the cabin can also be caused by aircraft functions, including the retraction and deployment of landing gear, operation of flaps, airbrakes, and other systems [15]. Passengers can also be disturbed by localized causes of vibration such as shake and rattle effects, and passengers operating seat-back trays and seat adjustment mechanisms [6].

5. Spectral Content of Vibration during Cruise Phase

During the cruise phase of flight, the spectral content of vibration in aircraft includes low-frequency components associated with turbulence, and higher frequency components associated with the engines [23]. Low-frequency components are primarily observed at frequencies below 10 Hz [19,24].

Higher frequency components have been reported up to 1000 Hz. For measurements made at the seat mounting point (e.g., [25,26]) vibration data shows energy at all frequencies up to the highest frequency of measurement for measurements of vibration in jets (Figure 1). A tonal component between 80 and 110 Hz has been shown and associated with fan blade/rotational modes in the jet [19].

For turboprops, the vibration is highly tonal. It is dominated by harmonically rich signals with a first peak corresponding to the rotational speed of the engines and higher harmonics associated with the blade pass frequency [27]. This has been demonstrated in civilian and military aircraft. Smith [28] noted that vibration data measured on a twin engine four-blade EC2 Hawkeye tactical aircraft had a component at 18.5 Hz associated with the rotor, and 73.5 Hz associated with the blade pass frequency (BPF). Studies of the vibration measured on various versions of four engine C-130 Hercules aircraft [23] showed turbulence below 10 Hz, a tonal component at 17 Hz corresponding to the rotor speed. The four-bladed C-130H3 showed a higher frequency peak at 68 Hz, whereas the six-bladed WC/C-130 showed a peak at 102 Hz. Similar features have been reported for piston propeller aircraft [29].

Whilst higher frequencies are largely filtered out if human vibration frequency weightings are applied, perception of whole-body vibration up to 100 Hz has been shown to be underestimated by ISO 2631-1 [13] for low-magnitude signals, such as those measured in aircraft [12,26].

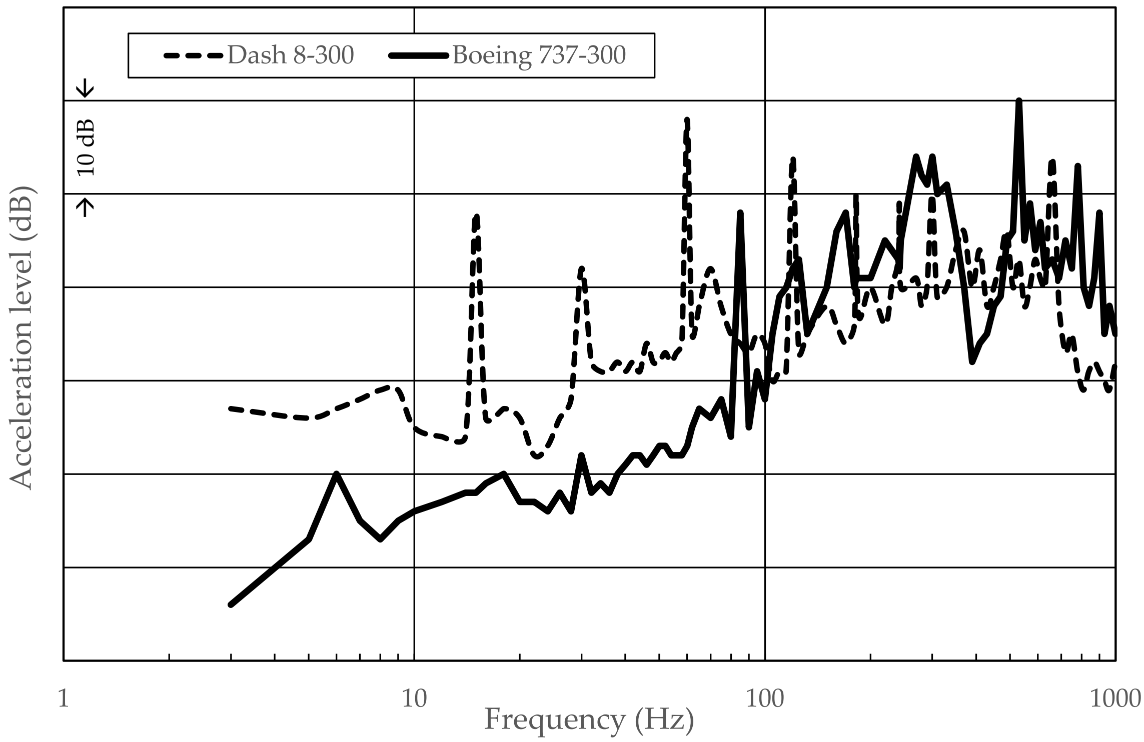

Figure 1. Typical vibration measured at the seat rail in the vertical direction for a turboprop (Dash 8) and jet aircraft (737) during the cruise phase (adapted from [25]). NB absolute values are not reported in the source.

6. Magnitudes of WBV Measured in Fixed-Wing Aircraft

The magnitude of vibration reported is highly dependent on the methods used for data analysis. As previously shown, many aircraft show a peak in vibration close to 100 Hz. If analyses are carried out using the ISO 2631-1 weighting, this will be attenuated such that in horizontal directions it will be scaled by 0.014, and in the vertical direction scaled by 0.089. It is therefore essential that measurement and evaluation methods are reported in full. Care must be taken when comparing measurements that have been made, for example, on the floor/seat, weighted/unweighted, r.m.s./VDV. Due to the variety in methods used in published studies, it is not possible to provide collated summary data in this paper and each study must be considered on its own merits.

Most vehicle seats have a peak in transmissibility at less than 10 Hz, and attenuate at higher frequencies (e.g., [4]). However, there are no known papers that report the full transmissibility curve of aircraft seats up to 100 Hz. Vibration differs at the seat mounting points, seat frame, and on the seat surface, and therefore fully reporting the measurement location is also necessary. Ilic et al. [29] showed that for a piston propeller aircraft, vibration at the primary engine frequency on the surface of the seat was about 35% of that measured on the floor, indicating effective vibration attenuation.

Measurements at the pilot's seat on small agricultural piston propeller aircraft (Embraer EMB-201A, EMB-202) showed weighted vibration dose values (VDV) of 7.1, 10.0, and 8.9 $m/s^{1.75}$ per hour when crop spraying (data normalized to 1 h from reported results between 1 h 17 min and 1 h 36 min) [30]. These data included takeoff and landing that corresponded to peaks in the signal, and therefore were likely to dominate the VDV measurement. The same research team [31] extended this study to include two further agricultural piston propeller aircraft (Cessna A188B and Air Tractor AT402B). Frequency-weighted r.m.s. data measured on pilot seats were measured over repeated takeoff, work (spraying), and landing cycles. Data ranged from a mean of 0.376 m/s^2 r.m.s. (s.d. 0.022, 8 cycles) for the A188B to 0.520 m/s^2 r.m.s. (s.d. 0.142, 16 cycles) for the EMB-202. Data for the EMB-201A and AT402B were 0.492 m/s^2 r.m.s. (s.d. 0.127, 8 cycles) and 0.472 m/s^2

r.m.s. (s.d. 0.081, 6 cycles) respectively. Spectral analysis of vibration measured on a Lasta training aircraft showed a highest vibration in the y-direction of 1.04 m/s^2 r.m.s. at 90 Hz when cruising at full power [32].

Several studies have reported whole-body vibration data measured on various models of C-130 Hercules turboprop aircraft. Hopcroft et al. [33] collated data from several reports and reported frequency-weighted r.m.s. data in addition to measurements of the magnitudes of vibration in the 16 Hz and 100 Hz frequency bands. Frequency-weighted vibrations at the co-pilot seat (specific measurement location not identified) were 0.01, 0.02 and 0.06 m/s^2 r.m.s. in the x-, y- and z-directions, respectively. At the left passenger seat these were 0.12, 0.04 and 0.16 m/s^2 r.m.s. In the 16 Hz band the magnitude of vibration depended on the aircraft and the position in the aircraft. At the DSO (Defensive Systems Operator) station, one study showed vertical 16 Hz vibration between 4.75 and 9.44 m/s^2 r.m.s. All other studies showed data less than 10% of these values. The dominant direction of vibration was y- for the ARWO (Aerial Reconnaissance Weather Officer) station but x- for the passenger seats. This may be due to the aircraft configuration where passengers face sideways rather than forwards. Smith [34] also reported that the C-130J vibration magnitudes fell well below ISO 2631-1 thresholds for risk, but reported 1/3 octave data showing 16 Hz vibration above 0.1 (x-), 0.3 (y-) and 0.2 (z-) m/s^2 r.m.s. at the seat pan for the ARWO position, which was greatly reduced with propeller balancing [35].

Vibrations measured aboard an EC2 Hawkeye [23,28], had a weighted vibration of between 0.1 and 0.3 m/s^2 r.m.s. (total value) when tested with a range of seat cushions and assessed using ISO 2631-1. On the seat pan, in the 20 Hz (propeller rotation frequency) and 80 Hz (blade pass frequency) 1/3 octave bands, weighted values were greatest in the vertical direction, with values of approximately 1.5 m/s^2 r.m.s. Unweighted vibration total values at the seat pan were approximately 5 m/s^2 r.m.s. Measurements of relative magnitudes of vibration in civilian Dash 8 aircraft have been reported by Bellman et al. [25,26], but the absolute values are not reported (Figure 1).

During cruise, the vibration magnitudes reported based on laboratory reproduction of vibration measured on an unspecified jet flying through turbulence were 0.48 to 0.61 m/s^2 r.m.s. (frequency-weighted [19]). During calm flight, a weighted vibration dose value equivalent to 1.07 m/s$^{1.75}$ per hour (data normalized to 1 h from reported results for a 10 h flight), measured at the seat mounting point was reported for a NASA Gulfstream G-111 test aircraft. This increased to 1.57 m/s$^{1.75}$ per hour when flying in turbulent air [21]. Modelled data predicting the vibration at the seat base for an Airbus A320 reported values from 0.11 m/s^2 r.m.s. to 1.91 m/s^2 r.m.s., depending on the level of turbulence (from 0.2 to 3.0 m/s), and whether the aircraft was flying solo or in close proximity to other aircraft [20]. Measurement of vertical vibration made at multiple unspecified positions during flight of an Airbus A330 and A340 flying for 8 and 12 h showed that there was more vibration measured in the economy cabin (rear) than in business or the cockpit (front) [36]. The greatest magnitudes of vibration were approximately 0.1 m/s^2 r.m.s. in the economy cabin of the A340, and slightly higher in the rear galley of the A330.

7. Effect of Flight Phase on WBV Measured in Fixed-Wing Aircraft

Several studies have demonstrated that the whole-body vibration experienced in aircraft is affected by the flight phase. Flights have been broadly categorized into five phases: on ground/taxi, takeoff, cruise (calm), cruise (turbulent) and landing.

Burström et al. [16] took measurements on the crew seats of a Boeing 737–800 whilst landing. This showed pre-landing maneuvers comprising low-frequency signal, and the shock from the initial contact with the runway followed by 20 s of higher vibration before reaching the taxi phase. Vertical acceleration data showed peak shock close to 1 g. The vibration was greater in the rear crew seat than the front (Table 2).

Burström et al.'s data are slightly higher than those simulated by Ciloglu et al. [19], who predicted overall vibration magnitudes between 0.65 and 0.83 m/s^2 r.m.s. during landing and 0.78 to 0.96 m/s^2 r.m.s. during takeoff.

Table 2. Mean acceleration data recorded during 3 landings measured at crew seats on a Boeing 737-800. Data show unweighted and weighted r.m.s. acceleration (m/s^2) and vibration dose values (VDV, m/s$^{1.75}$) calculated over 45 s. Data from [16].

	Crew Seat Front			Crew Seat Rear		
Direction	x-	y-	z-	x-	y-	z-
Acceleration (unweighted)	0.6	0.4	0.9	0.5	0.9	1.4
Acceleration (weighted)	0.3	0.1	0.6	0.2	0.4	0.9
VDV (45 s)	2.6	1.8	3.2	2.1	3.4	5.2

Extreme military takeoff vibration exposures were measured in an F/A-18C Hornet being catapult launched from an aircraft carrier [17,37]. The study also reported data from touch-and-go maneuvers and arrested 'TRAP' landings; measurements were taken at the seat base and the helmet. During catapult launches, constant acceleration pulses were inversely proportional to the duration (due to fixed launch runway length). Acceleration in the x-direction was typically 2 to 3 g for 2 to 3 s, corresponding to takeoff speeds in excess of 200 km/h. Vertical acceleration showed a decaying vertical oscillation at about 3 Hz with a peak at 2 g, culminating in 2 to 3 g 0.1 s pulse at launch. During touch-and-go, an initial shock was reported on initial runway contact, followed by a vertical 1 Hz oscillation with minimal features observable as the aircraft becomes airborne again. TRAP landing had a peak x-direction deceleration of about 3 g with a deceleration duration of about 3 s. In the vertical direction, initial runway contact caused a shock similar to that experienced in the touch-and-go, but followed by a 1 g peak oscillation at about 2 Hz for 2 to 3 s.

Zanatta et al. [30] showed profiles of vibration exposure during repeated piston propeller agricultural flights, and showed peaks in the vibration during takeoff and landing. Detailed analysis of flight stages showed slightly higher vibration dose values during landing than takeoff, but these were significantly higher than the work (spraying) phase [38]. It was also shown that the roughness of the runway affects the vibration experienced by the pilots, and therefore improved runway maintenance could be an effective method of managing the vibration exposure. In these studies, runways were unpaved airfields.

As discussed in the previous section, vibration exposure during the cruise phase of flight depends on the presence or absence of turbulence.

Integration of multiple measurements can be completed in order to generate an overall value for comparison and interpretation, based on expected flight/mission profiles (e.g., [38,39]). This requires a combination of predicted vibration exposure magnitudes and vibration exposure times, and can be used to prioritize flight phases that dominate the vibration exposure of the pilot/crew/passengers.

8. Characterization of the Aircraft Vibration Environment

In order to obtain an understanding of the vibration exposure in aircraft, several parameters need to be defined. This review has shown that there is no single 'correct' method, but decisions need to be taken by the experimenter to gather the most useful data for their application; data obtained for one application might not be suitable for or transferrable to another application. In all cases, appropriate instrumentation and training are required (outside the scope of this review: see ISO 8041-1 [40]). When measurements of WBV are reported, it is recommended that information is provided as listed in Table 3.

Table 3. Parameters identified as potentially important variables when characterizing WBV in aircraft on the basis of this review. Some applications might require more detail for interpretation.

Parameter Type	Details
Aircraft	Type Model Configuration Maintenance Mission/flight plan Pilot skill
Subject of measurement	Pilot/aircrew Cabin crew Passengers Activity/tasks to be completed
Human response	Health risk assessment Biomechanical response Perception and comfort Physical/motor/cognitive performance
Measurement site	Longitudinal position in aircraft Lateral position in aircraft Relative position to engines/wing
Accelerometer location	Floor/seat mounting point Seat surface Seat backrest Clothing/helmet/armor -mounted
Timing of measurement	Flight phase Duration of data collection
External vibration sources	Ground conditions runway/taxiway/apron Launch/arrest systems Air turbulence Formation flying wake
Data analysis	Unweighted/bandlimited acceleration Frequency-weighted acceleration Time domain analysis Spectral analysis 1/3 or 1/1 octave band analysis Analysis at discrete frequencies of interest Modal analysis Criteria and critical values

9. Future Developments in Aircraft Design and Implication on Whole-Body Vibration Exposure

Civilian air travel has continued to grow in terms of passenger numbers and air traffic movements, with a peak in 2019 (pre-pandemic) of over 4.5 bn passengers [41–43]. In parallel, there is demand for improvements in air travel sustainability in order to slow down climate change. Future aircraft propulsion technologies include increased use of open rotors (e.g., turboprops), electric and hybrid systems, and finding alternative liquid fuels [42]. Demonstrators have been flown (e.g., Rolls Royce 'Spirit of Innovation', 2021 [44]) and specialist companies are expected to offer small passenger electric aircraft by 2035. An open rotor motor will generate a thrust wake that will inevitably stimulate vibration in the aircraft, and therefore there is likely an increased need for the mitigation of whole-body vibration in future.

Alternative fuels are being tested and these could require radical new aircraft designs, such as the 2021 Embraer concept with aft-mounted propeller engines [45]. This is designed to reduce wing-transmitted vibration and to allow for flexibility in order to use hydrocarbon fuels, liquid hydrogen, or electric power options. Other aircraft designs include several blended-wing aircraft designed to increase capacity and efficiency, both in flight and at airports. Prototypes have included windowless designs, and non-forward-facing passenger configurations. It is unclear at this stage whether blended wings would change occupant vulnerability to turbulence. This is also true for extended wings and strut-braced concepts that improve lift but also increase aircraft size.

Reducing fuel burn on the ground can be achieved through switching from aircraft engines to other power sources. For example, in-wheel motors could be fitted to enable electrically powered ground movements [42]. This has the potential to reduce engine-induced vibration and noise in aircraft and at airports.

10. Recommendations

10.1. Standardize Reporting of Whole-Body Vibration Measurements Made in Aircraft

This review has highlighted the difficulty in interpreting reported whole-body vibration metrics due to the differences in measurement and analysis methods. It is recommended that measurement condition is fully reported, for example by using the framework in Table 3.

10.2. Extend Database of Whole-Body Vibration Measurements in Civilian Passenger Aircraft

Considering that there are over 4 billion air passenger movements per year, there are few published reports of whole-body vibration exposure in relevant aircraft. A minority of studies in the review addressed vibration in civilian passenger aircraft. Of those that did, only [16] used ISO 2631-1 [13] with measurements made on the seat surface, and that study focused on the exposure of cabin crew to discrete landing events, rather than during other flight phases. It is therefore recommended that further measurements are made in order to benchmark the current fleet including narrow and wide-body jets and turboprops during all flight phases.

10.3. Extend Scope of Whole-Body Vibration Metrics Reported in the Literature

Laboratory studies have shown that the human body is more sensitive to low magnitude high-frequency vibration than is indicated by analysis according to ISO 2631-1. Assessments of vibration comfort and perception could therefore be misleading due to the high frequency signals associated with jet fan rotation and turbojets. It is recommended that future measurements should include data measured on the seat surface, include weighted and unweighted data, and report spectral content. Weighted data would enable standardized assessments relevant to health during turbulence, takeoff, landing and taxiing, whilst unweighted data would enable assessment of those higher frequency components attenuated by frequency weightings, and relevant to perception.

10.4. Ensure Future Aircraft Technologies Are Optimized to Minimize Whole-Body Vibration

Many potential future technologies for future flight are likely to increase vibration exposure due to the growth in the number of propeller-based engines, and increased vulnerability to turbulence. If there is a reduction in comfort and perceived quality of the flight experience with these technologies, there is a risk that passengers will not accept future concept aircraft. It is recommended that an improved understanding of the human perception of passengers and crew in such environments is obtained, and that aircraft interiors (e.g., seating) are matched to passenger needs and aircraft environment.

10.5. Assess Performance and Wellbeing on Aircraft Crew in Response to Whole-Body Vibration

There were no studies found that focused on performance and wellbeing due to exposure to whole-body vibration in aircraft. Many crew tasks involve periods of walking in the aircraft cabin; ISO 2631-1 does not provide guidance on the evaluation of whole-body vibration on walking. Cabin crew are required to work in a moving environment, and are at risk of motion-induced interruptions, as has been reported in marine environments [46]. These interruptions have also been associated with cognitive impairment [47], whereby there is both a direct and indirect effect on cognitive performance. It is known that vibration can affect both performance and workload [48,49]; the effect of high-frequency (turboprop) vibration should be assessed, for personnel are required to conduct complex vigilance tasks whilst flying (e.g., military, search and rescue, scientific operations).

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Appendix A

Table A1. Summary of Papers Reviewed after Online Database Search and Screening Review Including Aircraft Type, Measurement Location, Flight Phase, Reported Data, and Aircraft Typical Usage.

Authors	Year of Publication	Aircraft Types (tp: Turboprop, pp: Piston Prop, j: Jet)	Cockpit	Cabin	Commercial (C), Military (M), Passenger (P)	Unweighted (U), Weighted (W), Spectral (S)	Taxi (TX), Takeoff (TO), Cruise (CR), Landing (LA)
Bagherzadeh and Salehi [50]	2021	52 seat (tp)		*	P	S	CR
Bellmann and Remmers [25]	2003	Dash 8 (tp), 737-100 (j), 737-300 (j), 737-400 (j), A320-200 (j), A320-232 (j)		*	P	S	CR
Bellmann and Remmers [26]	2004	Dash 8 (tp), 737-400 (j), A320-232 (j)		*	P	S	CR
Burström, Lindberg and Lindgren [16]	2006	737-800 (j)		*	P	U, W, S	LA
Carbaugh [15]	2001	not specified		*	P		
Ciloglu, Alziadeh, Mohany and Kishawy [19]	2015	Passenger jet (j)		*	P	W, S	TO, LA, CR
Dunno [27]	2008	690B AC90 (tp)	*		C	S	TO, LA, CR
Dunno and Batt [22]	2009	690B AC90 (tp)	*		C	S	TO, LA, CR
Hanson, Andrade and Pahle [21]	2018	Gulfstream G-111 (j)		*	P	S	CR
Hopcroft and Skinner [33]	2005	C-130J (tp), C-130H (tp)	*	*	M	W, S	CR
Ilić, Rašuo, Jovanović, Jovičić, Tomić, Janković and Petrašinović [29]	2017	Lasta (pp)	*		M	S	TO, CR
Ilić, Rašuo, Jovanović, Pekmezović, Bengin and Dinulović [32]	2014	Lasta (pp)	*		M	S	TO, CR
Liu [20]	2020	A320 (j)		*	P	W	CR
Mellert, Baumann, Freese and Weber [36]	2008	A330 (j), A340 (j)		*	P	W	CR
Smith [51]	2002	not specified		*	M		
Smith [34]	2002	WC-130J (tp), C-130J (tp)	*	*	M	S	CR
Smith [17]	2004	F/A-18C Hornet (j)	*		M	S	TO, LA
Smith [23]	2006	WC-130J (tp), C-130J (tp), C-130H3 (tp), E2C Hawkeye (tp)		*	M	U, W	CR
Smith [28]	2008	EC2 Hawkeye (tp)		*	M	S, W	CR
Smith and Smith [35]	2005	C-130J (tp)		*	M	S, U, W	CR
Smith and Smith [37]	2006	F/A-18C Hornet (j)	*		M	S	CR
Stephens [24]	1979	727 (j), DC-9 (j), 747 (j), 737 (j)		*	P	W	CR
Zanatta, Amaral and da Silva [30]	2015	EMB-201A (pp), EMB-202 (pp)	*		C	W	TX, TO, CR, LA
Zanatta, Amaral and Giacomello [38]	2021	EMB-201A (pp), EMB-202 (pp), Cessna A188B (pp), Air Tractor AT402B (pp)	*		C	W	TX, TO, CR, LA
Zanatta, Amaral and Vidor [31]	2019	EMB-201A (pp), EMB-202 (pp), Cessna A188B (pp), Air Tractor AT402B (pp)	*		C	W	TX, TO, CR, LA
Zhou, Zhang, and Yan [18]	2011	Military (j)	*		M	S	TX, CR

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