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Landing gear noise is considered the dominant airframe noise source on aircraft during approach. Previous studies indicated the presence of a strong tonal sound on flyovers of several commercial aircraft types, and suggested that it was caused by the interaction of open cavities in the nose landing gear (NLG) system with the flow. Airframe noise prediction models, however, do not account for parasitic noise sources, such as cavities, which can lead to severe underpredictions of the noise levels generated by NLG systems. In this paper, a method to improve the well–known landing gear noise prediction methods of Fink and Guo is suggested. The study is based on aircraft flyover measurements performed with a microphone array which, together with acoustic imaging techniques, allows for the separation of the noise emissions coming from the NLG. Flyover recordings from several Airbus A320 aircraft under operational conditions are analyzed and, based on the tonal frequency observed, potential cavity dimensions are suggested. The sound pressure levels of the narrowband tones were found to scale with approximately the 9th power of the airspeed. A simple correction formula for accounting for this type of cavity noise in the prediction models, depending on the aircraft velocity, is proposed. By applying this correction, the overall noise level predictions of the updated noise models become more accurate, reducing their average difference with the experimental data from 5 dB to just 1 dB.

I. Introduction

Noise pollution is considered as Europe's second largest environmental health threat after air pollution by the World Health Organization (WHO) in their report of 2018 [1]. Aircraft noise is one of the main contributors and causes annoyance and complaints to millions of people living close to airports [2, 3], and even harmful long–term health effects, such as cardiovascular diseases or hearing problems [1, 4]. As a result, strict noise regulations limit the capacity of airports, even imposing night curfews, with the consequent substantial loss of revenue [5, 6]. Despite the significant reductions in the noise levels of individual aircraft in the last decades, the increasing demand for flights (with a growth of about 5% per year [7]) causes the volume of air traffic to approximately double every 15 years, considerably aggravating the situation. Therefore, achieving further reductions of the noise emissions [8] is one of the main challenges that the aeronautic industry has to face nowadays, especially with the ambitious goals set by some governmental organizations for the near future [9], such as those reflected in the *Flightpath 2050* project [10].

Whereas sound barriers are typically used to reduce the impact of other sources of community noise, such as road traffic or railway noise, there is no practical way to shield communities near airports from the noise emissions of low–flying aircraft [11]. Thus, most research efforts are being devoted to reducing the noise levels at the source, i.e. the aircraft. Over the last decades, engine noise levels have been considerably reduced compared to the older turbojet engines thanks to technologies such as high–bypass–ratio turbofan engines and acoustic liners [12]. This situation has increased the relative importance of airframe noise, especially during approach, which is considered as a potential lower bound to aircraft noise in the future [13]. Therefore, it is essential to identify the noisiest elements on board to further reduce the noise levels and

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annoyance caused by aircraft and to obtain accurate information on their characteristics for implementation in noise prediction models. Accurate parametric aircraft noise prediction models are essential for the design of future low–noise aircraft and effective noise reduction strategies for the current ones [14, 15].

The landing gear (LG) system is considered to be the dominant airframe noise source during the approach stage for modern commercial aircraft [14, 16]. It consists of complicated structures of bluff bodies (struts, links, wheels, fairings, etc.) of different sizes and (normally) not acoustically optimized [17], see Fig. 1a. Therefore, the sound generation mechanisms and noise emissions of this system are relatively complex. Landing gear noise is expected to be relatively more relevant for larger commercial aircraft since, for example, the main landing gear (MLG) of an Airbus A320 has only four wheels, whereas that of an Airbus A380 has twenty [14]. Even though the MLG structure is typically larger and more complicated than the nose landing gear (NLG) (i.e., it is expected to be louder), the local flow velocity V impinging the MLG system is approximately 20% lower than the freestream velocity V_∞ because of the recirculation of the flow underneath the wings where the MLG is usually located [14, 18]. In addition, the local flow velocity V just upstream of the NLG can be noticeably higher than V_∞ because of the flow acceleration when passing the nose of the fuselage. [19]. Therefore, due to the strong dependence between the noise levels of bluff bodies such the LG and the flow velocity [20], both LG systems often emit comparable noise levels [21].
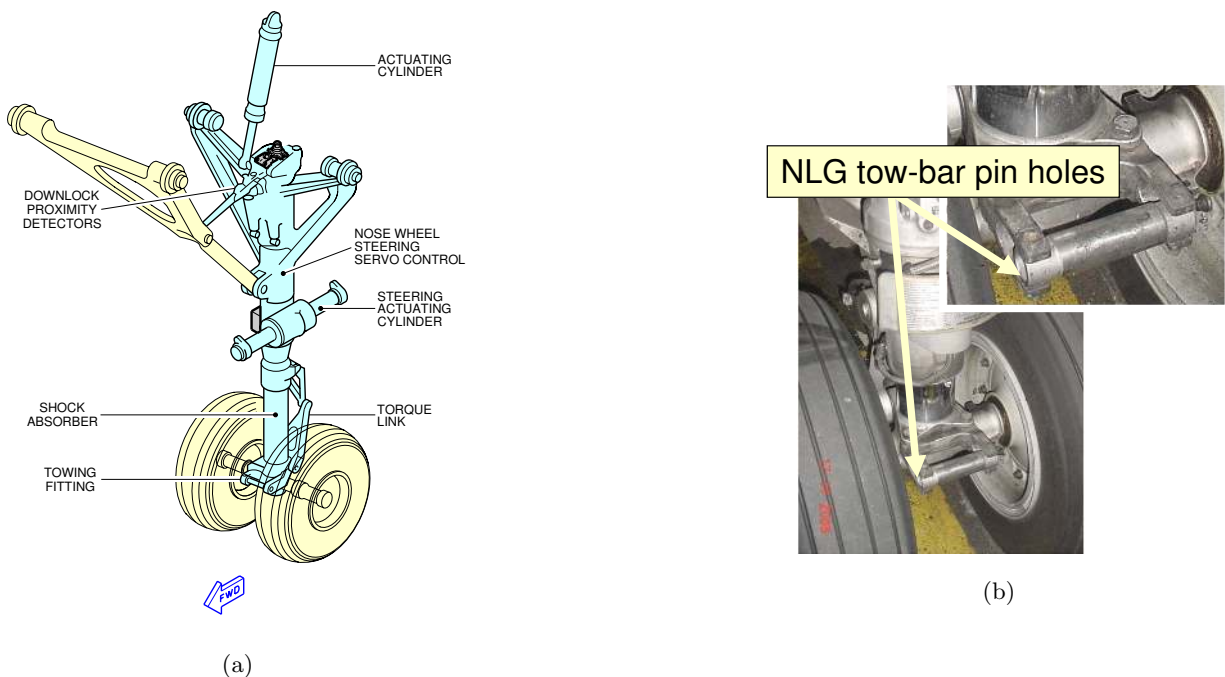

Figure 1: (a) Illustration of the nose landing gear (NLG) assembly of the Airbus A320–200. Adapted from [22]. (b) Photographs showing the towing fitting pin holes in the NLG. Adapted from [23].

The noise emissions from a LG system are usually a combination of broadband noise, mainly caused by the interaction of the LG with turbulent flow, and tonal noise, generated by cavity resonances [24–26] and Aeolian tones due to flow separation and vortex shedding [27–29]. The contribution of the Aeolian tones to the overall noise levels, however, is typically negligible and their tonal frequencies are usually considerably lower (around 100 Hz) than those corresponding to cavity noise [30].

Several studies have investigated the noise levels generated by the LG system using wind–tunnel experiments [24, 27, 31–35], aircraft flyover measurements [13, 21, 36–38] and computational simulations [39–42]. Multi–approach studies [30, 43] showed that all these three methods have their respective benefits and disadvantages, and that hybrid investigations combining two or more approaches can offer an improved solution.

For example, numerous flyover measurements under operational conditions have reported that the NLG system of some commercial aircraft types emits a very prominent tonal component [13, 17, 21, 28, 30, 36, 43, 44], most likely due to the interaction of the grazing turbulent air flow over open pin hole cavities within the structure of the NLG [13, 27], see Fig. 1b. A remarkable example is the Airbus A320 NLG which emits tones at around 1700 Hz that protrude more than 10 dB from the surrounding broadband noise [21, 45].

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That tonal frequency indicates that the dimensions of the cavity generating that noise are relatively small [46]. Some computational studies considered relatively large cavities in the landing gear system, such as the landing gear bay wheel cavity [47–49] and the wheel rim cavity [39, 41]. Small cavities, however, are not reproduced in most dedicated wind–tunnel experiments and computational simulations, possibly due to the simplification of the complicated geometry performed by these approaches because of the lack of detail available in the models or to reduce the computational time required [30, 50]. Hence, it is doubtful how noise prediction methods based on such approaches can compare or be validated through aircraft flyover measurements [13]. Indeed, current noise prediction models, such as the methods by Fink [20] and Guo [51, 52], only provide the estimated broadband emissions of the landing gear, but do not consider parasitic noise sources, such as cavities. Previous research [43, 45] showed that prediction models can considerably underpredict the emissions of the NLG because of this fact, compared to aircraft flyover measurements under operational conditions.

In general, parasitic noise sources are present and relevant in other elements on board of commercial aircraft, such as the fuel overpressure ports (FOPP) located at the wings of the Airbus A320 family [13, 50, 53], anti–ice vents [54] or the landing gear bay wheel [48, 49]. The sound pressure levels (L_{p}) of these noise sources can dominate the overall airframe noise signature during landing [13] and even be perceived in cruise configuration [50]. In addition, sounds with a high tonality are perceived by the human ear as more annoying than a broadband sound with the same L_{p} [45, 55–57]. Moreover, the strong amplitudes of tonal cavity noise can cause acoustic fatigue, stability problems, drag increase and even damage in aircraft or ground vehicles [58].

The typical 3° glide slope adopted in descent operations forces aircraft to fly at low altitude for a relatively long distance [59]. Since the landing gear doors start opening at an horizontal distance of approximately 10 km to touchdown (corresponding to altitudes of about 500 m), the aforementioned NLG cavity noise can become audible at long distances from the runway [53, 59]. Moreover, in these situations the aircraft velocities are higher than when the aircraft is close to touchdown so, given its strong dependence with the flow velocity [60], cavity noise can become even more relevant.

The present paper tries to tackle this issue by investigating the tonal cavity noise of the NLG and the physical mechanisms behind it, and then proposing a simple implementation of cavity noise estimations in landing gear noise prediction models, in terms of a tone correction. In order to do so, experimental measurements of commercial aircraft flying under operational conditions were performed. A microphone array was employed, which, combined with acoustic imaging algorithms [61–66], allows for the visualization of sound and the separation of the noise emissions generated by different elements on board [61, 67]. This case study focuses on the Airbus A320 aircraft, which is a relevant example, given its popularity (at the moment of writing this manuscript, it is the world's best–selling airplane) and the aforementioned presence of a strong tonal component in the noise signature of its NLG system [21, 45].

The paper is structured as follows: A general overview of the cavity noise theory is provided in section II. The experimental setup is explained in section III. The acoustic imaging method employed, as well as the sound propagation model considered, are described in section IV. The landing gear noise prediction models of Fink and Guo are briefly introduced in section V. Finally, the obtained results are discussed in section VI and the main conclusions and recommendations for future work are stated in section VII.

II. Cavity noise

Cavity noise is a multi–faceted, complicated phenomenon, of which the details of the physical mechanisms are still not fully understood [60, 68–70]. Cavity noise emissions are normally characterized by strong tonal sound emissions, as well as broadband noise. For the last decades, numerous research publications [25, 26, 46, 59, 60, 68–80] aimed at identifying the governing sound generation mechanisms responsible for cavity noise and providing semi–empirical or analytical models for the prediction of the frequency and amplitude of the tonal noise. Good overviews of the suggested theories in these and more studies were provided by Komerath *et al.* [78] and in the lecture notes of Gloerfelt [70]. Henceforth, a simple cavity geometry with streamwise length L and depth D exposed to an incoming flow velocity V_{∞} is considered, see Fig. 2. In general, two principal sound generation mechanisms are typically considered as the main causes of tonal cavity noise [60, 79]:

- **Fluid–dynamic oscillation feedback loop**: The incoming flow over over the cavity opening finds an acoustic impedance discontinuity when it reaches the leading edge of the cavity. Then, a shear

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layer is formed between the outer freestream flow and the secondary cavity flow, where vortices are shed periodically from the upstream lip of the cavity [25]. These vortices convect downstream (at a fraction of the freestream flow velocity) along the cavity streamwise length L until they impinge at the trailing edge of the cavity, i.e. the downstream lip, see Fig. 2. This generates a fluctuating force at the downstream edge that causes acoustic waves (red curves in Fig. 2) that travel upstream to the upstream edge and stimulate and shed a new instability wave (a vortex), completing, thus, a feedback cycle, see Fig. 2. The theory of Rossiter [46] studies this mechanism and provides a semi–empirical formula for estimating the tone frequencies. The characteristic dimension conditioning this mechanism is the streamwise cavity length L. The Strouhal number corresponding to the tonal frequency based on L, $St = f_{\text{tone}} L/V_\infty$, varies slowly with M [76]. This sound generation mechanism is usually dominant for high–velocity flows ($M > 0.5$), for which a better agreement with Rositter's theory is found. This noise mechanism can be mitigated by shielding the upstream part of the cavity [50].

- **Acoustic resonance**: The incoming flow over the cavity opening can make the cavity behave as a complex oscillator by adding and removing fluid mass intermittently, like a piston [60]. The amplitude of these oscillations, however, is controlled by many factors, which makes its semi–empirical prediction very challenging [27, 59]. Two main types of acoustic resonance can occur: a volume–dependent Helmholtz oscillation [81] (in case the cavity opening has a neck, i.e. a high volume to opening area ratio) and a duct resonance [25, 26]. Depending on the geometry of the cavity, length–, width–, and/or depth–wise modes can be excited in this process. This mechanism is especially relevant for low–velocity flows ($M < 0.5$) and in deep cavities ($L/D < 1$) [73]. The Strouhal number corresponding to the tonal noise for this mechanism varies approximately as $1/M$ [76]. The explanatory diagram of Fig. 2 shows an example of depth–wise acoustic resonance modes as dashed blue lines.
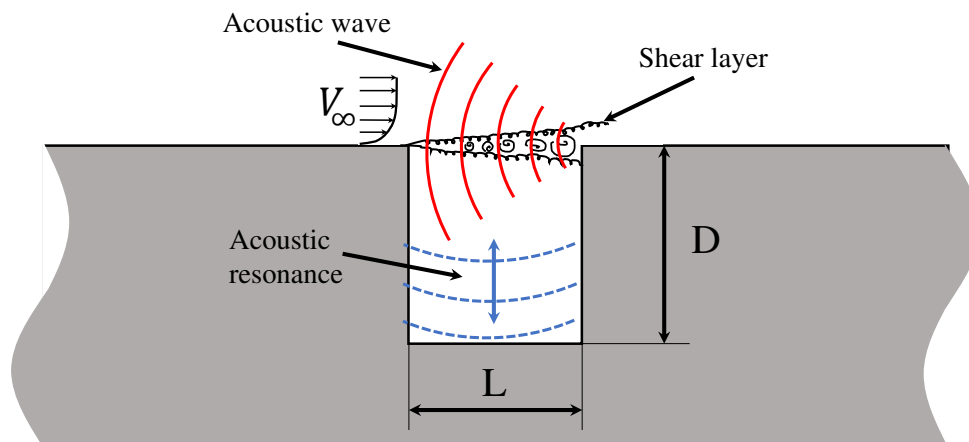

Figure 2: Diagram explaining the two main cavity noise generation mechanisms.

In case the tonal frequencies from both mechanisms have similar values, the flow provides the energy to excite the acoustic resonator, reinforcing the sound generation due to the acoustic coupling (also called *lock–on*) between both mechanisms, and very high amplitude tones can occur [60, 76]. Therefore, the amplitude of the oscillations strongly depends on the non–linear acoustic–vortical interaction [70], which complicates the prediction of this phenomenon.

Rossiter's theory provides satisfactory predictions in terms of the tonal frequency [60], especially at high subsonic flows, although it gives no indication on which oscillation modes will occur [54] and it disregards the influence of the cavity depth D. Block [76] proposed a way to account for the length to depth ratio L/D in the predictions based on experimental data for subsonic flow velocities and provided an expression for predicting the existence of acoustic coupling based on the cavity geometry. Despite the substantial effort devoted on cavity noise, a clear understanding of the dependence of the far–field amplitude of cavity noise on parameters, such as the cavity geometry and flow conditions, is seriously lacking. This is mostly due to the wide variety of possible configurations, as well as numerous primary and secondary parameters driving the cavity oscillation phenomenon [70], such as the strong dependence on the boundary layer (BL) characteristics of the incoming flow and the three–dimensionality characteristics of this phenomenon [60].

A thorough experimental investigation on cavity noise was performed by Ahuja and Mendoza [60] who assessed the influence of several cavity geometries, and flow velocities, temperatures and BL thicknesses of the incoming flow. That study measured the far–field noise emissions, as well as their directivity. Some of their main findings are listed below:

- In general, deep cavities ($L/D < 1$) produce louder noise levels because the acoustic coupling is much stronger [60, 70]. Thus, the depth–wise resonance can produce extremely high intensity tones, even for low flow velocities [72]. In addition, deep cavities can also present relatively strong higher harmonics. This situation is unlikely to happen for shallow cavities, because the depth–wise mode would resonate at higher frequencies and not match the frequency of the fluid–dynamic oscillation feedback loop. In general, increasing the L/D ratio increases the Strouhal number corresponding to the tonal frequency, for a given M [76].

- The acoustic coupling phenomenon is likely to be strongly dependent on the characteristics of the BL. Laminar BLs were found to produce louder tones than turbulent ones [25]. In addition, increasing the thickness of the BL seemed to reduce the cavity noise levels and eliminate the harmonics [54]. Sarohia [77] suggested that a critical minimum value of the parameter $\sqrt{Re_\theta}L/\theta \geq 800$ is required for the excitation of tones, where θ is the momentum thickness of the BL and Re_θ is the Reynolds number based on that parameter. In one of the cases tested by Ahuja and Mendoza [60], increasing the BL thickness twofold caused a noise reduction of 23 dB [60].

- The cavity noise levels have a strong dependence with the flow velocity. Whereas bluff bodies like a LG system scale with the 6th power of the Mach number ($M = V/c$, where c is the speed of sound) [30], cavity noise was found to scale with the 8th [60, 73] or even the 10th power [53] for low Mach numbers. Moreover, in most cavities there seems to be a threshold Mach number below which the resonance mechanisms are not activated and, hence, no tonal noise is generated [59].

- Deep cavities present a more directional sound emission pattern, although for $M < 0.4$ (such as for aircraft landings), all cavity geometries behaved as almost omnidirectional (especially at low frequencies).

Cavity noise research related to aircraft began with relatively shallow cavities ($L/D > 1$) and high–speed flows since the object of study was the weapon bay of military aircraft. The flow–induced oscillations caused about 30 % of the total drag of the plane [70]. On the other hand, cavities can be beneficial for reducing the fan noise of aircraft fan noise when used as acoustic liners [12, 70] and they can also be helpful for aeroacoustic measurements when used to recess and protect the microphones from the turbulent boundary layer pressure fluctuations in closed–section wind tunnels [11, 82–85].

The current research, however, can be considered as an inverse problem, since most literature on cavity noise aims at predicting the noise emissions for a given cavity geometry and flow conditions, whereas in this study the noise emissions are known but not the cavity geometry.

III.   Experimental setup

A microphone array featuring a single–arm logarithmic spiral distribution with a 1.7 m diameter was placed 1240 m away from the threshold of the Aalsmeerbaan runway (36R) at Amsterdam Airport Schiphol, see Fig. 3. With this setup, a total of 115 commercial aircraft flyovers were recorded during their landing stage [16, 37]. These recordings correspond to flights in operational conditions (i.e., real–life conditions) and had their turbofan engines operating at lower power settings compared with takeoffs [16, 86], which eases the identification of airframe noise sources like the NLG.

Out of all measurements, only the recordings corresponding to seven flyovers of the Airbus A320 aircraft family were considered for this manuscript. This aircraft type was selected because its NLG system is known to be one of the dominant noise sources during landing [21, 44, 45], due to its strong tonal signature (see Figs. 4), which is most probably caused by the presence of open cavities, as mentioned in section I.

The array consisted of 32 PUI Audio POM–2735P–R analog condenser microphones [87], which have a sensitivity of -35 $\pm$ 2 dB (ref. 1 V/Pa) and a frequency range of 20 Hz to 25 kHz. The microphone array employed a sampling frequency of 40 kHz and a band–pass filter to obtain frequencies between 45 Hz and 11,200 Hz. An optical camera (Datavision UI-1220LE [88] with a Kowa LM4NCL lens recording with a

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sampling frequency of 30 Hz) was placed at the center of the array facing straight up from the ground, which provided video footage synchronized with the microphone data. The meteorological conditions during all the measurements were very similar and presented low wind speeds [86].
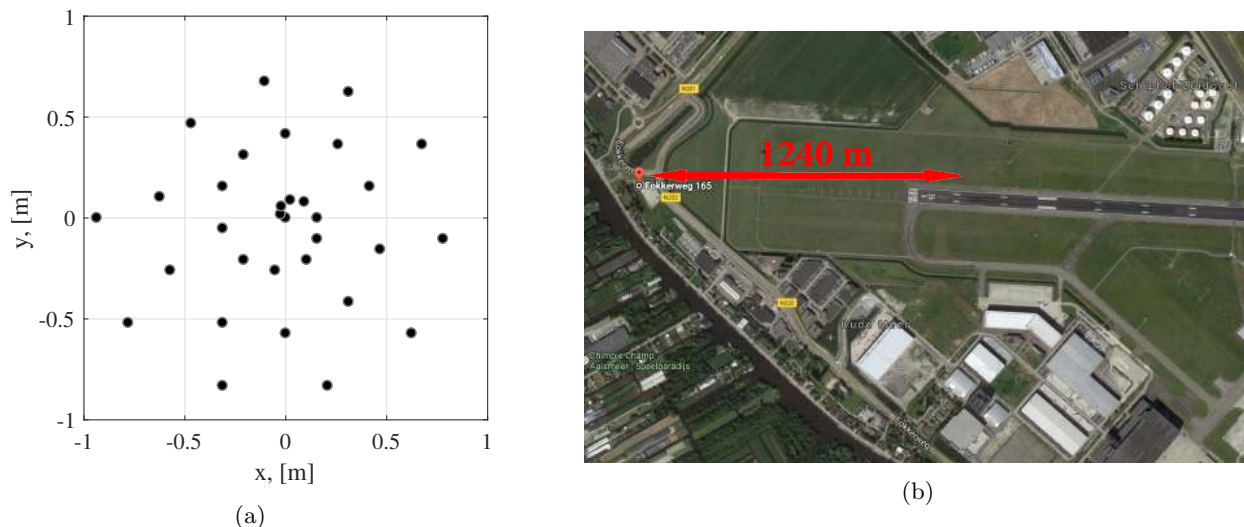

Figure 3: (a) Microphone distribution for the array used in the flyover measurements [5]. (b) Location of the microphone array with respect to the Aalsmeerbaan (36R) airport runway. The North is pointing to the right of the picture [17].

The aircraft trajectories were considered to account for the propagation effects from the source to the receiver, see section IV below. For determining the aircraft trajectories, data from three different sources [44] were used:

1. The Automatic Dependent Surveillance–Broadcast (ADS–B) (when available, sampled twice per second).

2. The radar from air traffic control (offered by Amsterdam Airport Schiphol, sampled once every four seconds).

3. The extrapolation of the images taken by the optical camera (sampled 30 times per second).

The three methods provided very similar results (with variations up to 4%), but the data from the optical camera were employed due to its higher availability, higher sampling rate and because it allows for an overlay the acoustic source maps to the pictures. The results from the other two methods were used as a validation. The average flight altitude and aircraft velocity above the array for the flyovers presented here were 65.3 m and 75 m/s the Airbus A320. Given the sampling frequency of the optical camera (30 Hz), the aircraft moves approximately 2.4 m between two consecutive images. Henceforth, true airspeeds V_∞ (considering the wind velocities obtained from the Royal Netherlands Meteorological Institute [89]) are employed in this paper. The true airspeeds values recorded ranged from 70.2 m/s to 81.1 m/s (i.e. $0.206 \leq M \leq 0.238$).

Moreover, only the sound emission angles corresponding to the aircraft overhead of the microphone array (i.e. a polar emission angle $\theta \approx 90°$, and an azimuthal sideline angle $\phi \approx 0°$) are considered because planar microphone arrays show their best performance in their perpendicular direction [90]. This limits the study of the directivity of the different sound sources on board of the aircraft, but landing gear noise [14, 31, 36] and cavity noise [60] emissions at low velocities are assumed to be almost omnidirectional in the polar direction (θ), so this limitation is not considered as important.

IV.   Acoustic imaging method and sound propagation

For each measurement, a time interval of 0.1024 s was considered, centered at the instant for which the NLG of the aircraft is approximately overhead of the microphone array center (polar emission angle of $\theta \approx 90°$). Some small deviations in the aircraft trajectories were observed in the lateral direction, with

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offsets up to 3 m, corresponding to azimuthal sideline angles (ϕ) of less than $2.5°$ with respect to the normal direction to the array plane. The averaged cross–spectral matrix (CSM) of the microphones' signals is computed using Welch's method [91] using data blocks of 2048 samples and Hanning windowing with 50% data overlap, obtaining a frequency resolution of approximately 20 Hz. This short time block was selected as a compromise between allowing some CSM averaging and having a relatively small aircraft displacement (about 7.5 m in this case) during the time block.

The frequency range analyzed spans from 1 kHz to 10 kHz, which is considered to be of interest for aircraft noise research [14]. The lower bound was selected for obtaining sufficient spatial resolution to separate the NLG and other noise sources on board, like the turbofan engines, which are located approximately 15 m apart. Spatial aliasing and the signal to noise ratio determined the highest frequency of study [5].

Functional beamforming [92, 93] was employed for processing the acoustic data recorded by the microphone array because it provides better dynamic range and array spatial resolution than conventional beamforming [11], and these characteristics are important for flyover measurements, due to the relatively large distance between source and observer [16, 37, 44]. Comparative studies [44, 62] with other acoustic imaging methods proved that functional beamforming provides better results when applied to flyover measurements. This technique raises the acoustic source map obtained with conventional beamforming to the power of an exponent parameter ν and the CSM to the inverse of this power $1/\nu$. The value of ν for this study was selected to be 8 after performing a sensitivity analysis [66].

The movement of the aircraft was taken into account in the beamforming formulation [5, 44, 61, 94]. The spherical spreading and the atmospheric absorption of sound were also accounted for to obtain the L_p at 1 m from the source location [12, 16]. The atmospheric absorption coefficient α was calculated considering the measured ambient temperature, relative humidity and sound frequency, as stated in [95]. Since the wind speeds and background noise levels were relatively low [43], it was decided to use the full CSM for the calculations, i.e., without removing its main diagonal, because functional beamforming is relatively sensitive to this approach [96].

The obtained acoustic source maps were integrated over a region of integration (ROI) [63, 65, 97] covering the NLG position in order to isolate the sound signal emitted by this component. The ROI was centered at the approximate position of the center of the NLG's axis and was 10 m long in the flight direction y and 8 m long in the lateral x direction, see Fig. 4b. An integration technique called functional projection beamforming (FPB) [97, 98] was employed to yield the sound levels emitted by the NLG. This method characterizes the ROI as a subspace in the array steering vector space, projecting the array's CSM onto this subspace and taking the average of the diagonal elements of the outcome. A recent benchmark study [98] showed that FPB provides more accurate quantitative results for distributed sound sources, compared to other well–known acoustic imaging methods, such as the source power integration (SPI) technique [63, 65, 99].

V.   Noise prediction models

Two of the most frequently used models for predicting landing gear noise, those of Fink [20] and Guo [51, 52], are briefly explained here. These are semi–empirical and semi–analytical noise models typically used for fast estimation of airframe noise during design and parametric sensitivity studies, to quantify changes in noise impact due to changes to the aircraft geometry. The detailed formulas for these methods and comparisons with experimental data can be found in [30, 100].

V.A.   Fink's method

Fink's method [20] was developed for the US Federal Aviation Agency (FAA) and has been implemented in NASA's Aircraft Noise Prediction Program (ANOPP) framework [101, 102]. Fink assumes that there are two primary noise sources on the LG: the strut of the gear and the wheels, based on experimental data from flyover measurements of several aircraft (mostly from the Boeing company) [24]. The input parameters required for this method are simply the mean flow velocity, the number of wheels, the wheel diameter and the strut length. The various interaction effects of the wheels and strut with each other, as well as with other airframe components, are only accounted for by the use of empirical fitting factors. The convective amplification due to the movement of the source is taken into account. Different polar (θ) and azimuthal sideline (ϕ) emission angles can be calculated, but for this study the direction directly under the landing gear ($\theta = 90°$ and $\phi = 0°$) was studied. For these emission angles, the modeled contribution of the strut to

the overall noise emissions is expected to be negligible [43, 100].

V.B.   Guo's method

Guo's method [51, 52], also known as the *"Boeing"* method, is based on fundamental aerodynamic noise theory and scaling laws adjusted to fit full–scale LG aeroacoustic tests mostly from Boeing aircraft [100]. This model divides the landing gear components into three different types depending on their size, each of them contributing in a different frequency range:

1. Large–scale structures, such as the wheels, contributing to the low–frequency noise.

2. Mid–scale structures, such as the main struts, contributing to the mid–frequency noise.

3. Small–scale structures, such as the hydraulic lines and LG dressings, contributing to the high–frequency noise.

These three components are considered separately, each with a different spectral shape and directivity. Consequently, more detailed geometrical inputs are required for this method compared to Fink's method. Hence, Guo's method is expected to provide higher–fidelity noise predictions.

Moreover, the installation effects of the landing gear, such as the presence of the wing and fuselage causing reflections and diffraction, are also considered [52]. As for Fink's method, the emissions for different polar and azimuthal angles can be estimated, but the same aforementioned conditions ($\theta = 90°$ and $\phi = 0°$) were employed in this study.

VI.   Results and discussion

VI.A.   Acoustic source map analysis

Figure 4a depicts the narrowband frequency spectrum ($\Delta f = 20$ Hz) of an Airbus A320 flyover with $V_\infty = 81.1$ m/s at 1 m from the source. A strong tonal component is observed at a frequency $f_{\text{tone}} = 1660$ Hz with a tone protrusion ΔL_{p} of more than 10 dB with respect to the surrounding broadband noise, which makes it clearly perceivable by the human ear [55]. Even larger ΔL_{p} values are observed when considering the spectrum of the isolated NLG, since there are lower broadband noise levels to mask the tone.

The functional beamforming source map corresponding to that single frequency (1660 Hz) is depicted in Fig. 4b, which confirms that the strong tonal noise is indeed generated at the NLG. The dashed rectangle in this figure denotes the ROI employed for integrating the noise emissions of the NLG, whereas the small white square indicates the actual position of the center of the NLG. In this example, a black–line contour of the aircraft was manually added to the source map instead of using the image provided by the optical camera of the array because due to the fast motion of the source and the relatively low sampling frequency of the camera, it was not possible to obtain a picture frame where the NLG was exactly overhead.

VI.B.   Investigation of the tonal noise

Despite their different flight velocities, all seven Airbus A320 flyovers presented a similar tone at approximately the same frequency f_{tone} (1660 Hz or 1680 Hz). The relatively low frequency resolution $\Delta f \approx 20$ Hz, caused by the fast movement of the aircraft and, hence, the small period of time available with the NLG overhead, prevents a more detailed study of the exact frequency of this phenomenon. However, the tones are assumed to be almost pure, except for the poor frequency resolution and any potential spectral broadening due to the turbulence present in the atmosphere [62].

One potential cause for tonal noise emitted by an bluff body interacting with an airflow could be vortex shedding. The Strouhal number $St = f_{\text{tone}} d/V_\infty$ corresponding to the tonal peak due to vortex shedding is typically assumed to be around 0.2 [29]. Here, d is the characteristic length (such as the diameter of the wheel or main strut) and V is the true airspeed. For typical diameters of a wheel and main strut of a NLG (0.8 m and 0.15 m, respectively) and for the average velocity of 75 m/s in this experiment, the expected tonal frequency would be around 20 Hz for the wheel and 100 Hz for the main strut, which are considerably lower than the ones observed in the present study. Moreover, the fact that the values of f_{tone} recorded do not scale with the flow velocity also indicates that the physical mechanism generating the tones is not vortex shedding [28].

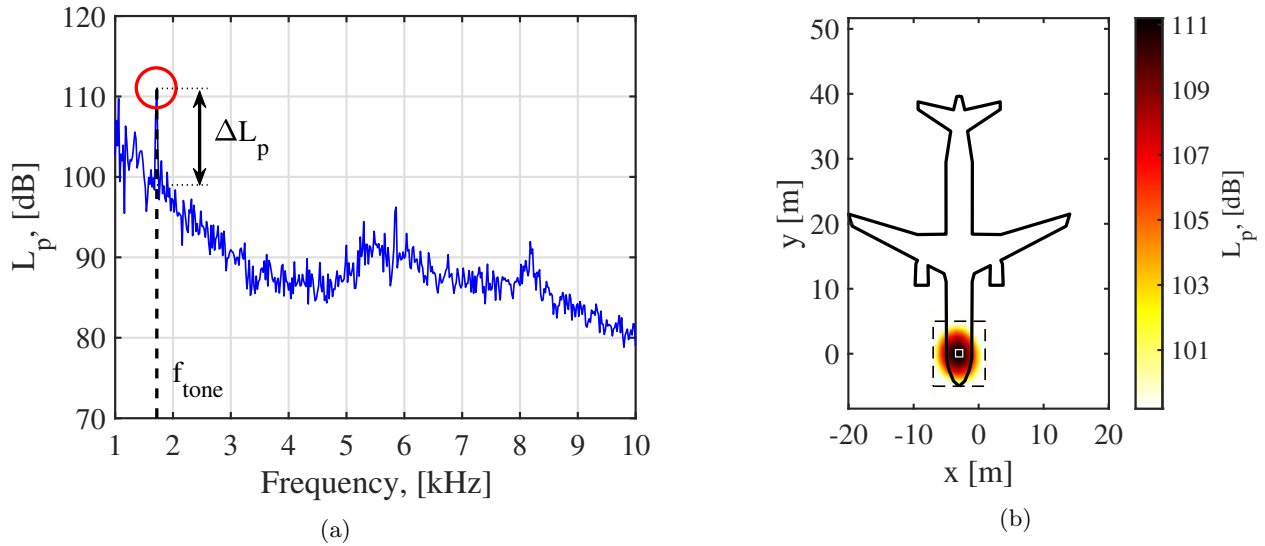American Institute of Aeronautics and Astronautics

Figure 4: (a) Narrowband frequency spectrum ($\Delta f = 20$ Hz) of an Airbus A320 flyover at 1 m from the source ($V_\infty = 81.1$ m/s). (b) Functional beamforming (with $\nu = 8$) source map for the same flyover at 1660 Hz.

Hence, these tones are most likely caused by the interaction of the flow with open cavities in the NLG system. Previous research [48, 49, 59] showed that the bay cavity, which hosts the NLG during cruise flight, can generate tonal noise, but at considerably lower frequencies (around 250 Hz). Therefore, the open cavities generating the tonal noise examined in this paper should be located in the structure of the NLG itself, e.g. in the axles or struts. Unfortunately, due to the large distance between the aircraft and the observer for this study (roughly 65 m), the spatial resolution of the microphone array is insufficient for determining the precise location of the cavities within the NLG system [103].

The theory of Rossiter [46] provides an estimation of the Strouhal number corresponding to the frequency of the tone $St = f_{\text{tone}} L/V_\infty$, based on the length of the cavity L and the local flow velocity V, for different Mach numbers. For $M \approx 0.23$ like in this experiment would be around, the expected Strouhal number for the cavity tonal noise (considering the first resonant mode, $n = 1$) is approximately 0.5 [76], which corresponds to a cavity length L of 25 mm. In case of a circular cavity, the cavity diameter is about 13% larger [54], which would correspond to a cavity diameter around 28 mm. A potential cavity with a similar geometry is the pinhole in the towing fitting, see Fig. 1b [22]. Moreover, the tonal frequency and cavity length suggested are in agreement with the cases of the FOPP cavity of the Airbus A320 family and the anti–icing vent of the Boeing 777 [54], mentioned in section I.

Unfortunately, a detailed description of all the components of the NLG system of the A320 publicly available and, thus, it is not possible to confirm the exact cavity location or which cavity noise generation mechanisms are dominant. Other parameters, such as the ratio between the length L and depth D of the cavity, remain unknown, although deep cavities ($L/D < 1$) seem to be more likely to generate such high tonal noise levels [60, 70], especially those with depths close to one quarter of the acoustic wavelength [54] (in this case that would correspond to $D \approx 50$ mm, i.e. $L/D \approx 0.5$). It is also unknown, whether this tone is caused by higher resonant modes ($n > 1$) and, hence, larger cavity sizes, or whether the cavity causing this tone is open on both sides. Therefore, a careful search for potential cavities matching any of these characteristics in a detailed NLG model is strongly recommended.

Therefore, this manuscript aims at providing a simple implementation of tonal cavity noise estimations in the LG noise prediction models of Fink and Guo, in terms of a tone correction, similar as the one typically used in the Effective Perceived Noise Level (EPNL) metric [12]. For that purpose, three parameters are analyzed:

1. The tone frequency f_{tone}: As aforementioned, the tonal frequencies observed in this experimental study were almost constant for all flyovers presenting only two different values: 1660 Hz or 1680 Hz. This could be due to the relatively small range of airspeeds, although the absence of a linear variation of

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f_{tone} with V_∞ indicates that the cavity is passive and that the driving mechanism is most likely acoustic resonance [54], or that acoustic coupling occurs [70].

2. The sound pressure level of the tone $L_{\text{p,tone}}$: Figure 5a presents the correlation analysis between $L_{\text{p,tone}}$ and V_∞ for the seven Airbus A320 flyovers. A scaling law with an exponent of 9.3 of V_∞ was observed to provide a very close match to the data (correlation coefficient $\rho = 0.96$, coefficient of determination $\rho^2 = 0.92$, and p–value of 6.4×10^{-4}). This value is in agreement with those reported in the literature [13, 53, 60, 73].

3. The tone protrusion ΔL_{p} (in decibels) with respect to the surrounding broadband noise (see Fig. 4a): This magnitude strongly conditions the perception and annoyance of a tone [55]. Figure 5b depicts the ΔL_{p} values observed for the integrated narrowband spectra corresponding to the ROIs covering the NLG, see Fig. 4b (and hence relatively more prominent than when considering the whole aircraft as in Fig. 4a). High values of ΔL_{p} of almost 20 dB are reported for the highest airspeeds. The data seems to closely follow a scaling law with an exponent of 4.6 of V_∞ ($\rho = 0.98$, coefficient of determination $\rho^2 = 0.96$, and p–value of 1.4×10^{-4}). The lower exponent value compared to the case of $L_{\text{p,tone}}$ is due to the scaling of the broadband landing gear noise surrounding the tone with an exponent of about 6 [30].

It should be noted that these results are based on a limited number of measurements (only seven flyovers) within a limited envelope of true airspeeds ($0.206 \leq M \leq 0.238$). In fact, given the strong influence of the incoming boundary layer and flow direction on cavity noise [27, 60], small variations on the local flow characteristics (such as cross wind) due to the aircraft operational conditions may play an important role in the far–field cavity noise emissions and even define whether such resonances are excited or not [54].
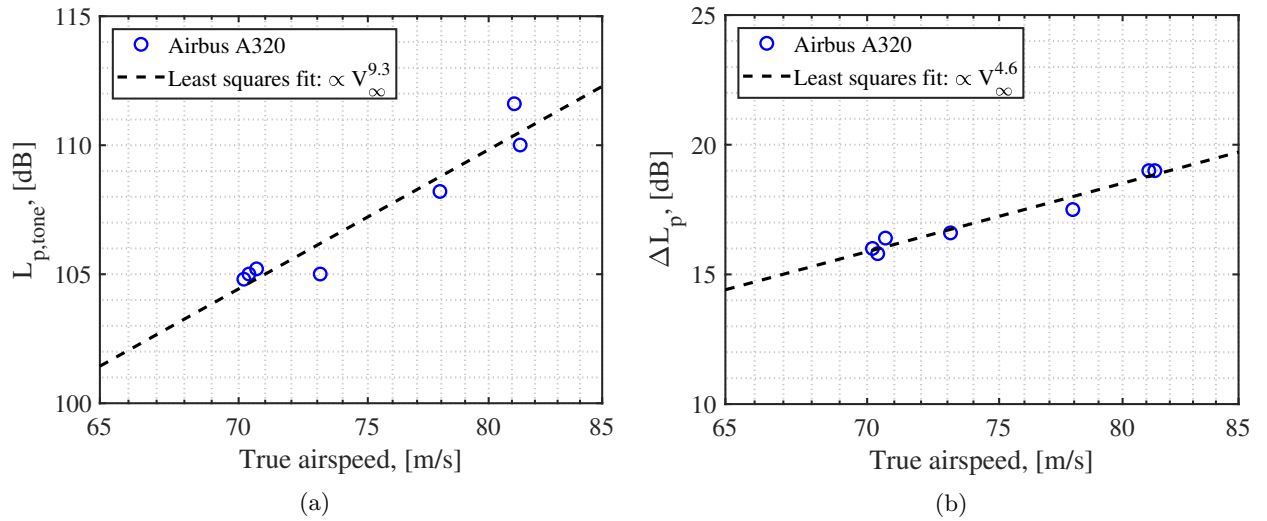

Figure 5: Correlation analysis of the influence of the true airspeed V_∞ on: (a) the tone sound pressure level $L_{\text{p,tone}}$ and (b) the tone protrusion ΔL_{p} with a frequency resolution of $\Delta f = 20$ Hz. Note the logarithmic scale in the x axes.

VI.C. Comparison with airframe noise prediction models

This section presents the comparison of the experimental data with the predictions of the LG noise prediction models of Fink and Guo, see section V. One–third–octave band spectra are employed for the comparison since the output of the prediction models is in that format. Even if one–third–octave band spectra are less accurate for describing the presence of narrowband tones, metrics such as the EPNL use this format to calculate their tonality correction. Hence, the tonal correction suggested in section VI.B is adapted here to one–third–octave bands.

Figure 6 contains the comparisons of the NLG spectra for the cases with the highest (81.1 m/s) and lowest (70.2 m/s) true airspeeds available. The overall sound pressure levels for the frequency range of interest,

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$L_{\mathrm{p,overall}}$ are presented in the legend. As expected, the tonal noise occurring in the 1600 Hz band is not considered by any of the models, causing underpredictions of up to 15 dB for the L_{p} at that band. Fink's method underpredicts the $L_{\mathrm{p,overall}}$ by 5 dB and 3 dB for the higher and lower velocity cases, respectively, whereas Guo's method offers predictions about 7 dB lower in both cases. In general, Guo's method provides estimations about 4 dB lower than Fink's throughout the whole frequency range considered.
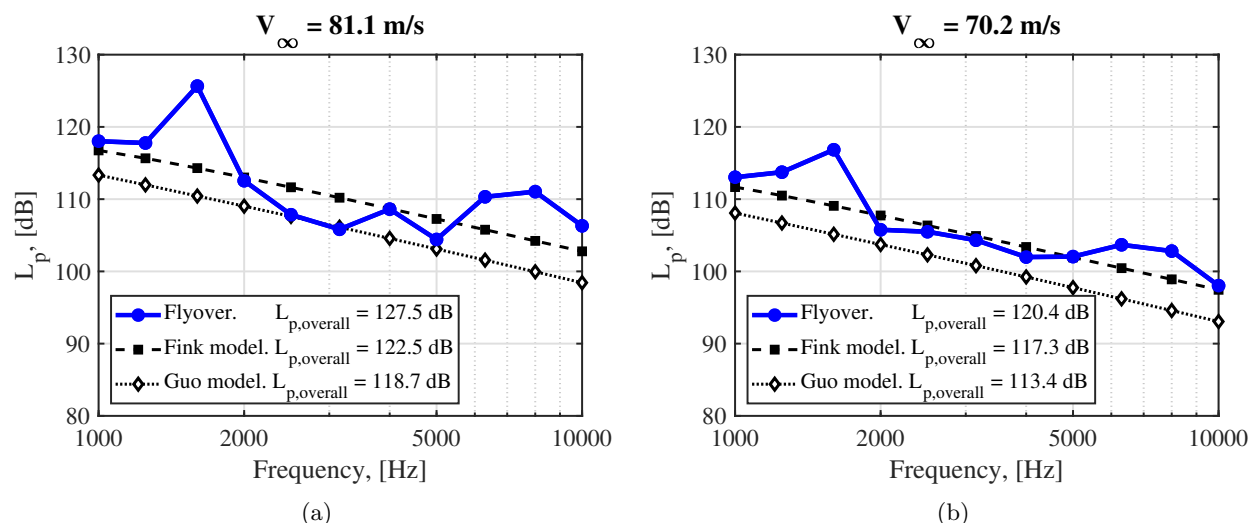

Figure 6: One–third–octave band frequency spectra of the NLG of Airbus A320 flyovers compared with the predictions of the (default) methods of Fink and Guo. (a) $V_{\infty} = 81.1$ m/s, (b) $V_{\infty} = 70.2$ m/s.

For the rest of the frequency range, the prediction models provide relatively good L_{p} estimations, especially between 2 kHz and 5 kHz. The high–frequency hump in the spectrum after 5 kHz observed in the experimental data is not accounted for in the prediction models either. Recent publications [30, 43] stated that the high–frequency noise generated by the NLG scales in a better way with the flow velocity using a 7th power law, instead of the conventional 6th power law usually considered for this noise source [104]. It was suggested that this higher influence of the flow velocity in the high–frequency noise levels is due to the turbulent flow surrounding the small features of the NLG, instead of the surface pressure fluctuations, like in the lower frequency range [30, 43]. On the other hand, frequencies higher than 5 kHz have a smaller impact in aircraft community noise, since for typical distances between aircraft and noise sensitive areas, these frequencies are heavily attenuated due to the atmospheric absorption [14]

The narrowband tone protrusion relation with the flow velocity found in section VI.B is adapted to one–third–octave bands ($\Delta L_{\mathrm{p,TOB}}$). This is done by considering the increment in L_{p} that the tone causes in the 1600 Hz band with respect to the expected value without tone. Considering the monotonically decreasing shape of the spectra modeled by Fink's and Guo's methods in this frequency range, the L_{p} values without tone are estimated as the arithmetic average of levels of the two neighbouring bands: 1250 Hz and 2000 Hz. With those assumptions, the tone correction for the 1600 Hz one–third–octave band for the Airbus A320 NLG cavity can be approximated as:

$$\Delta L_{\mathrm{p,TOB}} = 55 \, \log\left(\frac{V_{\infty}}{V_{\mathrm{ref}}}\right) - 94.5 \tag{1}$$

where V_{ref} is a reference airspeed of 1 m/s.

Extrapolating Eq. (1), it seems that this tone would not protrude (i.e. $\Delta L_{\mathrm{p,TOB}} = 0$ dB) for an airspeed of about 52 m/s ($M \approx 0.15$), which is considerably lower than typical approach velocities for aircraft.

The predictions of the methods of Fink and Guo were updated with the tonal correction of Eq. (1) to provide a closer agreement to the experimental data. Figure 7 illustrates the effect of that correction for the same two flyovers considered in Fig. 6. For both airspeeds, Fink's predictions are now almost coincident with the experimental data for the 1600 Hz band, whereas the values of Guo's method remain about 4 dB lower, as aforementioned. The differences in $L_{\mathrm{p,overall}}$ are reduced now to only 1 dB for Fink's method and to less than 5 dB for Guo's method. Similar improvements were observed when applying Eq. (1) to the rest of the flyovers, but are not presented here for conciseness.
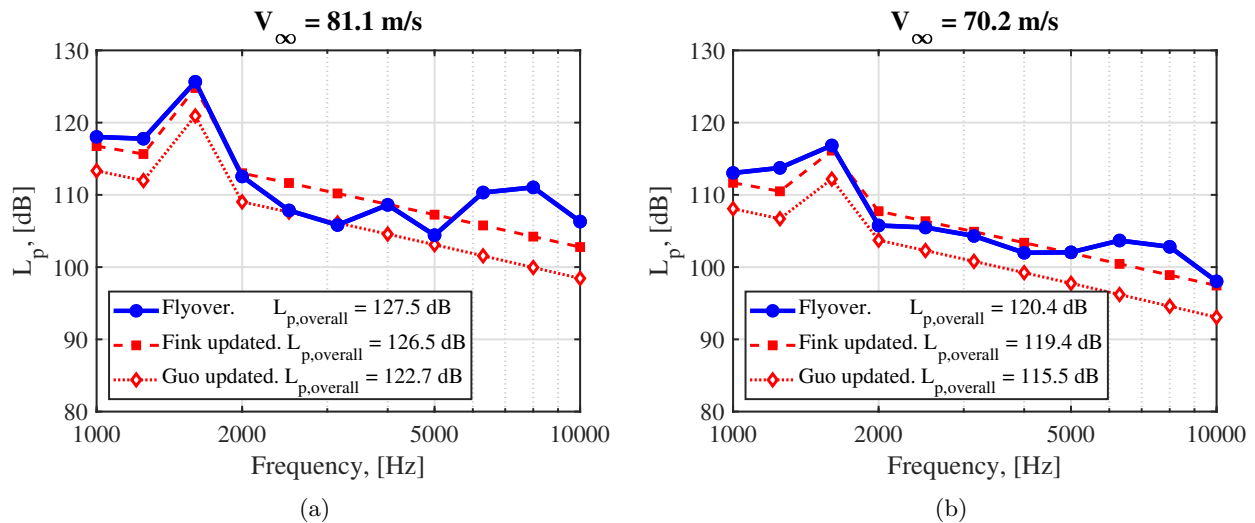
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Figure 7: One–third–octave band frequency spectra of the NLG of Airbus A320 flyovers compared with the predictions of the updated methods of Fink and Guo. (a) $V_\infty = 81.1$ m/s, (b) $V_\infty = 70.2$ m/s.

VII. Conclusions and outlook

This paper deals with the issue of tonal cavity noise in the nose landing gear (NLG) system of commercial aircraft. This phenomenon can dominate the acoustic signature of this aircraft element but is typically not accounted for in airframe noise prediction models, causing severe underprediction of its noise levels. The study is based on field experiments featuring a microphone array and commercial aircraft flying under operational conditions. In this preliminary research, the noise emissions of the NLG of seven Airbus A320 flyovers were isolated by applying acoustic imaging.

An analysis of the tones for different true airspeeds showed that the tone frequency was basically constant for all cases (about 1660 Hz). For the flow conditions present, cavity noise theory indicates that the cause for this tonal noise could be the presence of a cavity of approximately 25 mm length. However, further investigations are required with a detailed NLG model.

The sound pressure level (L_p) of the narrowband tones were found to scale approximately with the 9th power of the flow velocity, whereas the tone protrusion (ΔL_p) with respect to the surrounding background noise scales with an exponent of 4.6. Given this strong dependence of the tonal noise with the flow velocity, an obvious recommendation is to reduce the aircraft velocity to a minimum, while keeping the safety standards and keeping in mind the high–lift devices, which generate additional lift in low–speed conditions and, hence, higher noise levels.

Based on these findings, a tone correction was proposed to account for cavity noise in the one–third–octave band spectra estimations of the noise prediction models of Fink and Guo. The scaling of the correction with the airspeed follows a power law with an exponent of 5.5. By implementing this tonal correction, the differences between the airframe noise prediction models and the experimental data decreased considerably from 5 dB to 1 dB.

VII.A. Recommendations for future work

Future work should include a larger number of aircraft flyovers for increasing the statistical relevance of the study, and more aircraft types for studying the behaviour of different cavity geometries.

The search for the actual cavity location within the NLG geometry of the Airbus A320 (and in other aircraft types) is of course of high interest. Careful visual inspections (looking for cavity geometries like the ones suggested in this paper) and dedicated wind–tunnel measurements with an exact full–scale NLG model and the application of 3D–beamforming [105] could be an effective approach.

Once identified, the tonal cavity noise emissions can be reduced (or even eliminated) by a detailed design of noise reduction measures. An obvious solution might be to close the cavities with pinhole caps [13], but in case that is not possible other approaches that disturb the flow upstream of the cavity, like passive spoilers

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that thicken the boundary layer [54], vortex generators (as in the FOPP [13, 50]), or air curtains [58, 106] can be effective options, provided that they do not incur important drag penalties or installation costs. Changing the shape of the cavity while maintaining the open area constant is also an effective way to eliminate the tone emissions [54].

The high–frequency hump observed in the experimental data but not in the predictions should be researched and included in future improvements of the models, perhaps by having a larger scaling with the flow velocity for high frequencies.

Lastly, the noise emissions of the main landing gear (MLG) should also be investigated in search of tones, although, due to the bigger size of the MLG compared with the NLG, the potential tone frequencies would be lower. Thus, the use of larger microphone array is recommended for achieving a better spatial resolution.

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