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INSTRUMENTATION AND MEASUREMENT VALIDATION APPROACH FOR AN AERO-ACOUSTIC CIRCULAR TESTRIG BASED ON TEMPORAL, FREQUENCY, AND MODAL CRITERIA

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ABSTRACT

This paper presents the study of a multi-criteria approach for the instrumentation and measurement validation of an experimental testrig. The study case is an aircraft engine liner characterization bench (named CANNELLE) which is a 3m-long circular duct, based on higher-order modal generation and detection principles. This approach has been initiated for rigs with a large number of sensors, being in this case two arrays of a hundred flush mounted microphones, distributed in an optimized pseudo-random arrangement. Heavy experimental campaigns with associated large test matrices lead to huge datasets, which need to be rapidly validated after the recording, and before moving forward to the next testpoint. Therefore, the proposed validation is based on a multiple criteria approach, and aims at comparing them with target values and associated confidence intervals. Thus, the final objective is to identify potential anomalies in each measurement run among the three following categories: a priori validated data, with nominal criteria; the "should be ok" data, with barely nominal criteria, and little investigation to perform; and the data with severe defaults, which require further analysis. The proposed paper presents the outcomes of this study, exploring criteria on the temporal, frequency, and modal domains when applied to a fully rigid bench without aerodynamic excitation flow.

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1. INTRODUCTION

In the civil aircraft industry, the turbofan engines are the standard today for most of the mid- to long-range commercial flights. As the overall traffic is increasing and will continue to grow, the aircraft and engine manufacturers are more and more preparing their next products with a sustainable approach. Meanwhile, the latest international regulations, the ICAO chapter 14 [1] and the FAA stage 5 [2], are reinforcing the emission targets. For instance, they are imposing for the external noise a cumulative reduction of 7 EPNdB versus the previous version chapter 4 / stage 4, and further restrictions are expected for the next generation of aircraft. Therefore, it is of paramount importance to design and validate model of acoustic liner with efficiency and reliability. For that, testing is a key feature, especially when disruptive design are proposed, for which precise modeling and simulations are not mature or fast enough.

Research on liners is very abundant and diversified [3–12], as being at the crossroad of several disciplines, including for instance pure acoustics, aerodynamics, thermic coupling, or icing. Higher-order (also called transverse) acoustic modal content is a specific research field. Indeed, it is not that easy to set-up and measure, requiring several sources and microphones which quantities can be quite large, especially for turbofan engine experiments, whose number of blades is high, so that is the modal order. At the origin of the present paper, there are two testrigs developed at the acoustic testing laboratory of Airbus Commercial Aircraft (Toulouse, France), which are heavily instrumented, with more than 150 sensors: a rectangular cross-section bench and a circular one. The testcampaigns performed with these benches are often parametric, to have a deep understanding of the physics, which leads to large temporal datasets. During the testcampaign, it is mandatory to validate the running testpoint before moving to the next one, in order to ensure the quality of the data, as the testmatrix sequences are optimized depending on priorities and added value.

To do so, data validation must be specific to guide the experimenter towards the potential issues and facilitate their root cause analysis. The proposed strategy is to work both on the microphone temporal data, their frequency transforms, and finally the modal calculations, by computing criteria on these three datasets. To be more specific, each criterion is compared to a target value, and several thresholds are defined, allowing to classify the criterion into three categories: a priori validated data; the "should be ok" data; and the data with severe defaults. The criteria have been chosen to explore three domains: the instrumentation, the measurement and the experiment quality. This approach has been developed for the abovementioned rectangular cross-section bench called ModSquare [13, 14] at the Airbus acoustic lab, and its extension to the circular one named CANNELLE is proposed in this study.

The paper as proposed by the authors is organized in two main parts. The first one introduces some of the key features of the CANNELLE bench, including an overview of the test rig, its instrumentation, and post-processing. A focus is made on the bench specificities, based on modal generation and detection principles, with multiple sources arranged azimuthally, generating higher-order transverse modes in the duct. The second part presents the validation methodology of the generation, acquisition and test quality, based on experimental results, using temporal, frequency and modal data. Then, the chosen criteria are explained in detail. The proposed analysis is based on the canonical case of a purely rigid duct, without any aerodynamic excitation. Indeed, this configuration is used as a reference, and has been characterized several times during each campaign, for validation, repeatability and reproducibility purposes since the bench entry into service. Finally, the criteria results are discussed, as well as the thresholds and global outcomes of this analysis.

2. TESTRIG PRESENTATION

The following section presents the bench chosen for this paper, named CANNELLE. The main features of the testrig are presented, as well as its experimental set-up and operations.

2.1 Bench overview

The testrig chosen for this study is called CANNELLE, which stands in French for *Caractérisation des traitements Acoutiques Nacelle en eNvironnement et EcouLement réaListEsEs*. It has been developed in between the late 2000s and early to mid 2010s at the Airbus acoustic testing laboratory in Toulouse, with the motivation to validate modeling and numerical simulations with experimental data for impedance eduction, mainly applied to the liners of the engine's nacelles. It is a straight duct of about 3m-length, with a circular cross section of 350 mm diameter, whose walls are made of thick aluminum. The bench is based on higher-order modal generation and detection principles. The in-duct acoustic modal theory is not reminded in this paper, as already well documented in many publications and books [15, 16]. Fig. 1 proposes a picture of the CANNELLE bench when installed in "pure acoustic" configuration, meaning that there is no aerodynamic flow in the duct. The rig can be decomposed into several

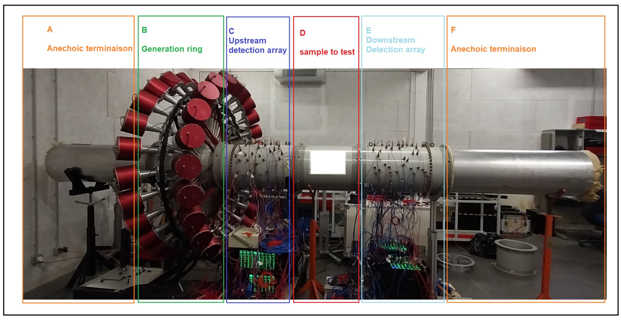

Figure 1. Picture of the CANNELLE bench in the Airbus acoustic laboratory, Toulouse (France).

sub-parts such as follow:

- the part [A], a first ending of about 1m, filled with glasswool;
- the part [B], the generation ring composed of 50 loudspeakers, used for modal excitation;
- the part [C], a first modal detection ring, consisting of an azimuthal array of 50 microphones equally

spaced, and an optimized pseudo-random array of 100 microphones;

- the part [D], the location for the sample to test;
- the part [E], the second modal detection ring, with the same arrangement than the part [C], except that sensor positions are symmetrical regarding the sample;
- the part [F], the second ending, as part [A].

The parts [A] and [F] are considered anechoic at the frequency and levels of interest, based on preliminary studies performed during the bench development phase. All parts are aligned with pins, ensuring a fair flushness into the bench. This aspect is very important because the bench can also be used in wind tunnels, in order to combine the aerodynamic flow to the acoustic excitation. In such a case, the parts [A] and [F] are removed, and the wind tunnel is connected on one side (let's say instead of part[A]), whereas a sonic throat of the Mach number of interest is plugged at the other end (instead of part [F]). There are three sonic throats built to this day, designed for Mach numbers 0.3, 0.45 and 0.6. The specificity of the CANNELLE bench is that the acoustic excitation could bemounted both for parallel or counter flows. Indeed, by moving the generation ring (part B) after the downstream detection array (part [E]), the acoustic excitation is traveling against the aerodynamic flow. If acoustic liners of an engine nacelle are tested in the bench, and the generation ring (part [B]) is simulating a fan, counter flow is representing the inlet configuration, whereas parallel flow aims for bypass or exhaust.

2.2 Instrumentation and operations

During the bench design and development phases, a compromise has been made between the maximal modal order, the maximal frequency and the generation (the number of loudspeakers) and instrumentation size (the number of microphones), leading to approximately 40 cut-on modes at 5000 Hz, linked to the duct diameter. The generation signal is a sinusoidal pure tone, sent to all loudspeakers with the appropriate phase delays, in order to directly generate the desired azimuthal mode shape. As loudspeakers only control the pressure on the duct wall, selecting a specific radial mode is not possible. Thus, all cut-on radial modes are excited simultaneously. The gain is adjusted to reach the expected level based on the acoustic pressure level, once averaged over all the microphones of the upstream acoustic array (part [B] in Fig. 1). The MaxMSP software is used to master the generation. A digital signal is sent encoded into MADI (Multichannel Audio Digital Interface) format towards two chained digital-to-analog RME M-32 DA converters, which output are the 50 analog lines sent to the 25 double channel QSC Audio RMX 2450 amplifiers. Finally, the amplified signals are sent to the 50 BMS 4599 compression drivers.

When used in the Airbus acoustic lab, the bench is in a "pure acoustic" configuration, meaning there is no aerodynamic flow. A temperature sensor (PT100) is installed flush mounted at the end of the bench, and recorded simultaneously with the microphones. The atmospheric pressure is manually entered in the testcampaign log, allowing to compute the sound wave celerity combined with the temperature. Only the 100 optimized pseudo-random microphones of each detection array (parts [C] and [E]) are used. These 200 sensors are 1/4 inch pressure field microphones with front-vented cartridges, mounted flush without their protection grids. To record, Brüel and Kjær 6-channel Lan-xi acquisition systems are used, powered and mounted on rack frames. The clock synchronization is managed by a B&K layer using PTP (Precision Time Protocol), with a classical master-slave architecture. A local network is connecting all the rack frames, the generation and acquisition computers using a network switch.

A record for one given frequency and modal configuration lasts 5 seconds, using a 7 seconds generation that includes a fade-in and a fade-out. A trigger signal sent from the MaxMSP patch is used to synchronize the acquisition. There is no feedback control loop or enslavement: indeed, the gain adjustment is done separately, at the beginning of the campaign. As already mentioned, the target is to reach a level on the average of the upstream detection array, when the bench is fully rigid, meaning that there is no liner installed. The usual target is around 120 or 130 dB for linear regime, and between 140 and 150 dB to reach non linearity. Parallel to the record, a "perfo" file is created, logging data such as the absolute and unique number of the run, the generation frequency, the targeted mode, and the atmospheric pressure for instance. All the frequency data (auto and inter-spectra, transfer function and coherence) are computed from the temporal raw data file, using B&K Connect version v26.0.0.241. Finally, the modal amplitudes and intensities are computed from the frequency data using an in-house code called MoDe, which has been validated on canonical cases with Actran FEM simulations in 2013 [17]. The transmission loss can be calculated by computing the modal difference between the two detection arrays, providing a direct evaluation of the acoustic sample efficiency.

3. CRITERIA METHODOLOGY AND APPLICATION

This chapter presents the validation methodology developed from the experimental results, and based on temporal, frequency and modal data. The chosen criteria are detailed, with their expected targeted values based on experience from the past campaigns, and on engineering judgment. They are applied to the purely rigid duct measurements in the CANNELLE bench without aerodynamic flow, which is considered as a reference measurement. To ease the presentation, a given testpoint, called α chosen randomly, is used in this chapter. A testpoint is the triplet combination of a target frequency, its associated level, and the azimuthal order of the mode to generate.

3.1 Validation based on criterion in the time domain

It is firstly proposed to simply compute the overall sound pressure level (OASPL) as a function of time, and to verify that it is somehow constant / stable during the acquisition. To save some computation time, it has been chosen to compute it on one microphone only. Indeed, the purpose here is to verify that the generation is stable, not the microphones during a record, so that it is assumed here that the acquisition chain is behaving as expected (this aspect is detailed later in this paper). The first microphone of the upstream detection array (part [C] in Fig. 1) has been chosen, as also being used for the cross-spectral computation as the reference for this detection barrel. The criterion C1 is the OASPL computed with a time integration step of 0.25s, and compared the the target level during the 5 second of record. The chosen thresholds are summarized in Table 1, and the data are considered such as validated if the OASPL lies within a range of +/- 1dB around the target level.

Table 1. Criterion C1: OASPL VS time.

C1 $\in$ target +/- 1dB	Validated data
C1 $\ni$ target +/- 1dB	Defaults

This criterion is not intended to evaluate in detail the issues that could appear at different steps, such as:

- problems in the generation chain itself (from the generation computer, the digital to analog conversion, or from the amplification);
- issues due to the loudspeakers distortion;
- unknown effects during the propagation of the acoustic waves inside the duct;
- noise pollution linked to the acoustic background noise of the lab;
- issues in the acquisition chain (electrical noise, grounding issues, etc.).

Several of these points are addressed in the next section.

3.2 Validation based on criteria in the frequency domain

As described in section 2.1, there are two microphone arrays in the bench, one upstream and one downstream of the sample, with 100 pseudo-randomly distributed microphones each. It is proposed to compute the "mean auto-spectrum" for each array, which corresponds to the mean of all the microphone auto-spectra over the 5-second record. This quantity gives an overview of the sensors and signals behaviors in each array. The next six criteria are all based on this mean auto-spectrum for the upstream microphone array, the one between the source and the sample, as the example of Fig. 2.

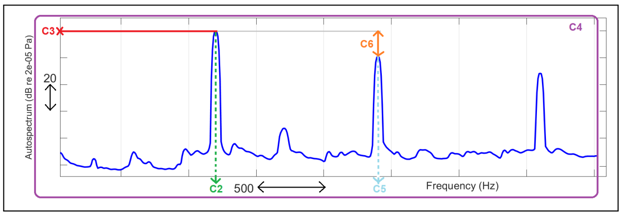

Figure 2. Mean auto-spectrum and schematic criteria representation for the testpoint α.

First, in order to ensure that the generated frequency is indeed the targeted one, the maximum peak frequency is detected in the mean auto-spectrum, and the difference with targeted frequency is computed, sketched as the criterion C2 in Fig 2. Any deviation would discard the testpoint, and a root cause analysis must follow.

Table 2. Criterion C2: max frequency identification.

$C2 = 0$	Validated data
$C2 \neq 0$	Severe defaults

The chosen thresholds are summarized in Table 2, and the data are considered as validated if there is no difference between the maximal frequency of the mean auto-spectrum, and the target frequency. This of course assumes that the generation frequency is piloted in accordance with the frequency step of the delta f used in the spectrum computations.

Directly after, the level of this maximum peak, identified as criterion C3, is compared to the generation target, ensuring proper correspondence. As above mentioned, all the generation gains are adjusted in the campaign preparation phase, and there is no enslavement or feedback control loop during a record. Any discrepancy in the productive tests has to be identified and investigated. A threshold value of 2dB is proposed, as presented in Table 3.

Table 3. Criterion C3: max level identification.

C3 $\in$ target +/- 2dB	Validated data
C3 $\ni$ target +/- 2dB	Defaults

It has to be noted that the gains are derived for the fully rigid sample, and applied then for all samples to be tested. Due to their impedance, or the quality of the mechanical flushness of the tested sample, the reflected energy will change, and can affect then the levels on the upstream array.

In a third step, the next criterion compares the target level at the targeted frequency with the global OASPL, in order to detect any significant perturbations. Indeed, most of the energy should be carried by the targeted frequency in a laboratory environment such as the CANNELLE one. The C4 criterion is the absolute value of the difference between the max SPL at the targeted frequency with the OASPL averaged of the 100 microphones of the mean auto-spectrum, both on the upstream array. Based on the past experiences, and expectations of such a set-up, it has been decided to build two thresholds values, leading to the three categories mentioned in Table 4.

Table 4. Criterion C4: max level and OASPL difference

C4 $\leq$ 0.1	Validated data
0.1 $>$ C4 $\leq$ 0.5	Should be ok data
C4 $>$ 0.5	Severe defaults

Considering the high levels injected in the bench, the harmonics of targeted frequency are often generated by the compression drivers. If harmonic distortion occurs, the second highest level of the mean auto-spectrum might probably be a peak, and the first harmonic of the targeted frequency. For that, the second highest level is detected, and the ratio between the first and second max level frequencies is computed, to validate if it is indeed a harmonic. For the search of the second maximum, it is proposed to explore all the rest of the spectrum. However, a certain distance to the first peak has been set. Working with a delta f of 4 Hz, several values have been tested, and the selected distance is further than 20Hz (so 5 spectral lines) on each side of the first maximum. As summarized in Table 5, this is an all-or-nothing criterion. When it is different of two, so not an harmonic, it could have several root causes, like the generation chain (digital to analog conversion, the amplification), the loudspeakers distortion, the lab acoustic background noise, or the acquisition chain (electrical noise, grounding issues, etc.).

Table 5. Criterion C5: 2^{nd} and 1^{st} max level frequencies ratio.

C5 $=$ 2	Validated data
C5 $\neq$ 2	Defaults

Immediately after, if the second peak is indeed the first harmonic, it is proposed to compare it to the first maximum. The difference of the two is computed, leading to criterion C6. This is mainly providing information on the compression drivers health. The threshold of this criterion are difficult to set, mainly because it is directly linked to the targeted level. Indeed, if for instance, 130 dB is expected, the distortion is reasonable, and the C6 can be up to 20 dB when there is no default on the generation. However, if the target is 140 or 150 dB, then C6 criterion can easily be 5 dB or less, even when the compression drivers are working properly. Table 6 summarizes the threshold values for the C6 criterion.

The last criterion in the frequency domain is based on

Table 6. Criterion C6: difference between 1^{st} and 2^{nd} max levels.

C6 $>$ 20dB	Validated data
C6 $\in$ [10 ; 20] dB	Should be ok data
C6 $<$ 10dB	Defaults

coherence. It is quite straightforward in order to detect any issue linked to one or several microphones. Fo that, the coherence is computed for all microphones of both upstream and downstream arrays, with the reference sensor being the first microphone of each array. The criterion C7 is computed by extracting the coherence values at the generated frequency, as shown in Fig 3.

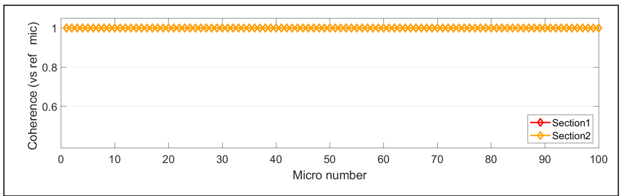

Figure 3. Coherences at the excitation frequency of all microphones of the two detection arrays for the testpoint α.

Table 7 summarizes the thresholds values for this criterion.

Table 7. Criterion C7: coherence values at the target frequency.

C7 $>$ 0.99	Validated data
C7 $\in$ [0.9 ; 0.99] dB	Should be ok data
C7 $<$ 0.9	Defaults

As the CANNELLE set-up is in a lab environment, the coherence is expected to be very close to 1, considering that there is no flow, and that all the microphones are in the same waveguide. A lower coherence might indicate a defect on the SPL at targeted frequency, a mic issue, or the presence of parasitic noise, either acoustic background or electrical noise. A value lower than 0.99 illustrates a significant difference. Furthermore, a value lower than 0.9 directly shows a severe default on the concerned microphone.

3.3 Validation based on criteria in the modal domains

As the purpose of the bench is the modal generation, it is important to verify that the test has reached its objectives.

First, only the upstream detection array is considered. Figure 4 represents the intensities of the incident and reflected propagative modes of the testpoint α. The maximum modal intensity is identified, and its associated azimuthal order is compared to the target, and the criterion C8 is their difference. Any deviation would discard the testpoint, and a root cause analysis follows, as summarized in Table 8.

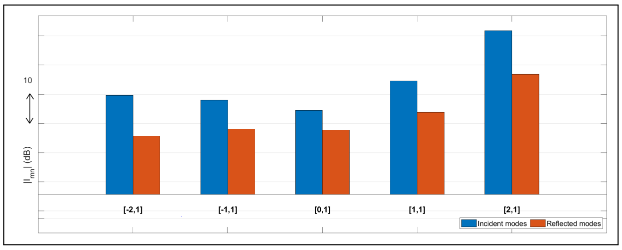

Figure 4. Intensities of the incident (blue) and reflected (orange) propagative modes in the upstream detection array for the testpoint α.

Table 8. Criterion C8: dominant mode identification.

C8 $=0$	Validated data
C8 $\neq 0$	Severe defaults

Then, the second maximum modal intensity is identified and analyzed. First, its modal intensity is compared to the maximum one, leading to Table 9 threshold values for this C9 criterion.

The way this criterion is computed has to be adapted when at least one second-order radial mode is cut-on. Indeed, the modal energy of the same azimuthal order will be spread over all radial cut-on modes.

Moreover, it is interesting to analyze which mode is the one with the second largest modal intensity. It could be the same mode but its reflected part, meaning the acoustic waves traveling backwards. It could also be another

Table 9. Criterion C9: difference between 1^{st} and 2^{nd} max modal intensities.

C9 > 20dB	Validated data
C9 $\in$ [10 ; 20] dB	Should be ok data
C9 < 10dB	Defaults

mode: the closest one in terms of azimuthal content, or the mode with the cut-on frequency being the nearest to the generation frequency for instance. There is no criterion on this aspect because it has to be analyzed case by case. Then, this C9 criterion can be computed for the downstream detection array as well, and the results have to be put into perspective regarding what has been found on the upstream detection array.

Finally, the last criterion is the transmission loss (TL) on the generated mode. With the bench in a "pure acoustic" configuration, it is assumed that it is equal to 0 when the rigid section is installed (if the viscous dissipation on the duct wall is not taken into account). Even if the approach followed in this study does not aim at assessing the experiment uncertainty, this final criterion provides a fair idea of the full method reliability and robustness, because it includes the impact of the bench mounting, the generation, the acquisition and the full data post-processing chain. A confidence interval of +/-1dB is proposed, as presented in Table 10.

Table 10. Criterion C10: transmission loss.

C10 $\in$ [-1 ; 1] dB	Validated data
C10 $\ni$ [-1 ; 1] dB	Defaults

4. DISCUSSION AND CONCLUSION

This study presents a methodology for the validation of experimental data, applied to a circular testrig that works on the principle of higher-order modal generation and detection. The approach is based on the computation of criteria in the temporal, frequency and modal domains, and to compare them with the target values and their associated thresholds.

The bench considered is CANNELLE, a circular waveguide built on modal generation and detection principles, generally used for acoustic liner characterization in pure acoustic or in aero-acoustic configurations, mounted in this study with a rigid part considered as a reference setup. Several criteria are computed from the microphone temporal raw data: 1 in the temporal domain, 6 in the frequency domain, and 3 in the modal domain. One or several thresholds are proposed, in order to establish if the criterion is considered: as nominal and lies within the expected target, so that the data are a priori validated; as barely nominal , with little investigation to perform, so that data "should be ok"; or as a default (more or less severe), which are requiring further analysis.

Several conclusions are drawn from this study. First, the criteria provide information for different validation aspects: at the instrumentation level, the measurement and the experiment itself. For the instrumentation, it can reflect if the acquisition has properly worked (no electrical perturbations or large faulty contact, microphones capturing the signal, etc.). About the measurement, it helps to identify if the generation is working as expected, or if the generated signal is emerging from the background noise, or if there are any other perturbations in the record, electrical or acoustical. Concerning the experiment, it helps to understand if the experiment has worked, meaning that the targeted mode is the dominant one, and that other cut-on modes, either created by error in the generation or by some modal re-distribution during propagation for instance are not perturbing the test. One of the key features of the criteria analysis is that these indicators clearly prepare the testpoint validation, and allows to put the focus towards particular results that might need further investigations to understand the abnormal behavior.

However, it clearly appears that the target values and their associated thresholds need to be refined. Although the values proposed in this study are based on the past experiences and testcampaign observations, with engineering judgment, a previous study on another testbench [14] has shown that a statistical analysis of a representative dataset could help to fine tune the values. Moreover, it is obvious that some thresholds should be adapted to the target level. Indeed, the compression drivers do not have the same behavior when excited to reach 130dB or 150dB. For instance, the harmonic distortion is strongly dependent on the voltage of the excitation. A consequence could be directly observed on the C6 criterion, the difference between the first and the second maximum levels of the mean-spectrum. Following the same reasoning, the thresholds should also be adapted to the frequency: the responses of the compression drivers differ a lot between 300 Hz and 5000 Hz. This might be considered in the next improvement phase of the methodology, to have frequency and level dependent thresholds for some specific criteria.

In order to continue the development of such a methodology, it will be interesting to apply this approach to other reference samples, which are measured several times during each testcampaign, mainly for reproducibility purposes.

Then, the step after could be to evaluate the limit of the criteria and associated target values, with for instance their application to *a priori* unknown liner sample. In addition, this method is planned to be extended to the bench when used in wind tunnel testing for aero-acoustic liner tests. The target values and the thresholds might be adapted, as well as some criteria (e.g. C5). Indeed, it sometimes happens that wind tunnel aerodynamic flow carries some tonal component, linked to the fan of the facility. In addition, the frequency computations might also be modified to use synchronous averaging as in [12].

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