The effect of grazing mean flow on the acoustic properties of perforates as used in mufflers and acoustic liners.

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The last twenty years have seen a large development in inverse techniques for the determination of aircraft engine liner impedance under grazing flow conditions, so called impedance eduction techniques. This paper gives an overview of continuing efforts to gain confidence in results obtained under different acoustical excitation configurations. Many test rigs for determination of liner impedance including the effect of mean flow use plane wave excitation on the upstream side of the liner. Some studies has compared the result for downstream acoustic excitation and found that different acoustic impedances are obtained in the two cases. It is still an open question if this result is due to the application of the Ingard-Myers boundary condition or to other errors or flaws in the measurements. This paper collects data available in the literature to see if the trend of obtaining different results for upstream and downstream excitation is persistent.

1   Introduction

Optimized solutions for noise control are becoming more important for aircraft as well as for other vehicles and machines. Acoustic liners, used as absorbing wall treatment in aircraft engines, must therefore be tested under conditions as realistic as possible. Their properties and noise reduction depends on mean flow field as well as other parameters such as temperature and acoustic excitation level. Over the last 20 to 30 years there has been a large effort to develop methods to extract the relevant impedance properties, i.e., the acoustic impedance, under grazing flow conditions e.g., [1-12]. There are many test rigs around the world and a number of different techniques for extracting the liner impedance from measurement, often called impedance eduction techniques, have been developed. In order to gain confidence in the results, which may depend on both the test rig used and on the impedance education method, some comparative studies have been initiated [1,2,5,6,8,10-12].

The present paper builds on measurement data where both upstream and downstream acoustic excitation has been used making it possible to discuss the effect on the measured liner impedance of this factor. Published data from the literature [2,8,10-12] is compared and analyzed. This means that data for five different liners obtained in different test rigs using different impedance eduction techniques will be compared. As pointed out by Renou and Aurégan [7] the result can become different depending on the acoustic excitation, and this was attributed to a failure of the Ingard-Myers [13] boundary condition, which is usually applied together with plug flow conditions. Zhou et al [9] discusses the effect of choosing different flow Mach numbers for Ingard-Myers boundary condition as an alternative way of resolving this issue. The Ingard-Myers boundary condition was the first attempt to handle grazing flow effects by collapsing the

boundary layer. However, over the past years, this assumption has shown to lead to time domain instabilities [14] and differences between the measured impedance using downstream and upstream propagating waves. The first issue is related to numerical simulations, whereas the latter has several implications, such as erroneous calibration of semi-empirical models and incorrect impedance used in aeroacoustic simulations. Some attempts have been made to improve this boundary condition [7,15-16], Rienstra [15] and Brambley [16] included a small but finite boundary layer thickness in the mathematical formulation, whereas Renou and Aurégan [7] introduced a factor in the classical Ingard-Myers boundary condition.

2 Impedance eduction methods and test setups

In this section the test rigs, liner samples and impedance eduction methods used to obtain the data are briefly described. A number of different impedance eduction methods were discussed in [2]. The Linearized Euler Equation (LEE) method can handle plug as well as boundary layer shear flows. The Convected Helmholtz Equation (CHE) is used with plug flow and employs the Ingard-Myers boundary condition. The single mode method (SMM) assumes that there is one dominating mode in the lined section. It can employ the Pridmore-Brown equation [18] or the linearized Euler equations for solving for the sound field in the lined section. The impedance is then obtained by numerical integration of the sound field in the transverse direction. The straight forward method (SFM) [19] also assumes that there is uniform (plug) flow. A simplified version of this technique was used in [9].

2.1 NASA data set [2]

In [2] NASA conducted a comparison study of four different impedance eduction methods using the NASA Langley GFIT test rig. It has a rectangular cross section with 63.5 mm height and 50.8 mm width, where the liner sample covers one wall. The acoustic drivers can be mounted upstream or downstream of the test section, and are used to generate tones (one frequency at a time) at up to 150 dB over a frequency range of 400 to 3000 Hz. Fiftythree flush-mounted microphones located in the wall opposite to the liner are used to measure the acoustic pressure field. A dual-axis traverse pitot probe system is used to measure the flow profile. This system is used to acquire flow profiles upstream and downstream of the liner, from which a representative average flow Mach number is computed and then used as the uniform flow Mach number for the impedance eduction methodologies.

2.2 Renou and Aurégan data set [7]

In [7] a rectangular test rig was used with 15 mm height and 100 mm width. At each end of the duct there were acoustic sources and anechoic terminations. Two sets of microphones are used for determining the liner impedance. Four microphones on each side of the lined section are used to determine the scattering matrix. The axial wave numbers are determined using the Prony method by means of an array of 11 flush mounted microphones in the wall opposite to the liner. These microphones are evenly distributed with a distance of 2 cm. The mean flow profile was measured using a 1 mm diameter pitot tube. The impedance is obtained using the straight forward method (SFM).

2.3 KTH data set 1 [10]

High flow speed measurements at moderate temperatures were made using a compressed air facility in the CICERO lab at KTH. Stepped sine excitation with a frequency step of 50 Hz was used. Three high temperature Kulite pressure transducers were used on each side of the liner sample section. The transducer spacing was 25 mm. External excitation drivers were used both upstream and downstream of the test section so that the plane wave scattering matrix of the lined section could be measured. Stepped sine excitation with a frequency step of 50 Hz was used. In order to characterize the flow field, a Pitot tube and temperature sensor section was included upstream of the sample. The Convected Helmholtz Equation (CHE) with plug flow and the Ingard-Myers boundary condition was used for the impedance eduction. Details of this method has been published elsewhere [10]. Mode matching is used to calculate the transmission between the lined and the hard wall duct sections. The impedance is obtained by minimizing the difference between the measured and calculated pressures at the microphone positions in the hard wall ducts on both sides of the lined section.
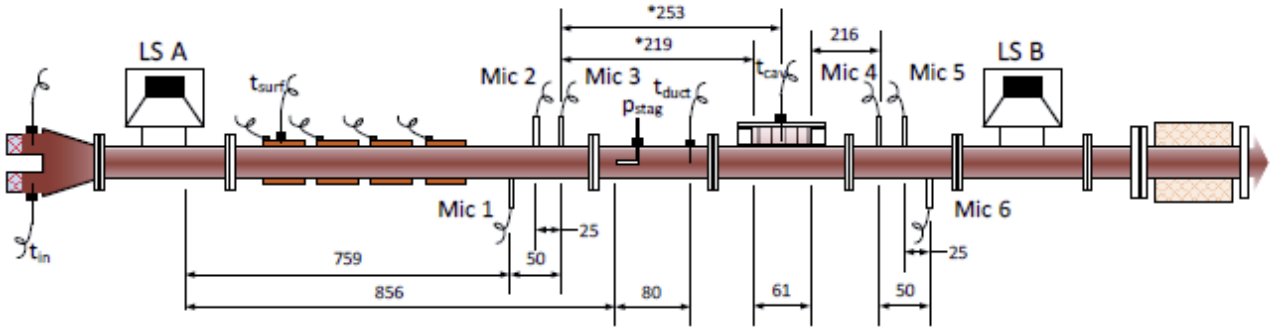
Figure 1: Sketch of liner test setup used to obtain KTH data set 1 [10].

2.4 KTH data set 2 [8]

A sketch of the test setup at KTH is shown in Fig. 2. The test section had a rectangular cross section with a width of 70 mm, where liner was mounted at one side, and a height of 25 mm. At each end of the duct, acoustic sources and acoustic anechoic terminations were present, which make the possibility for the acoustic scattering matrix identification with the two-source method. Up to twelve BK ¼-inch microphones have been installed in the middle of the hard wall opposite to the liner sample with four microphones mounted on each side of the sample and four microphones mounted in the lined section. Stepped sine excitation with a step of 40 Hz between 200 Hz and 2600 Hz was used. The flow profile was also monitored across the lined section at a number of positions using a Pitot tube. For the acoustic testing, loudspeakers upstream and downstream of the lined section were used. Different acoustic excitation levels from 100dB to 145dB were obtained at the microphones closest to the liner. The test object in this case was the locally reacting single degree of freedom Helmholtz resonator liner sample which was also tested at DLR and at NASA Langley [5, 6]. Impedance eduction was made using a simplified version of the straight forward method where the axial wave number is obtained directly from the measured scattering matrix [8].
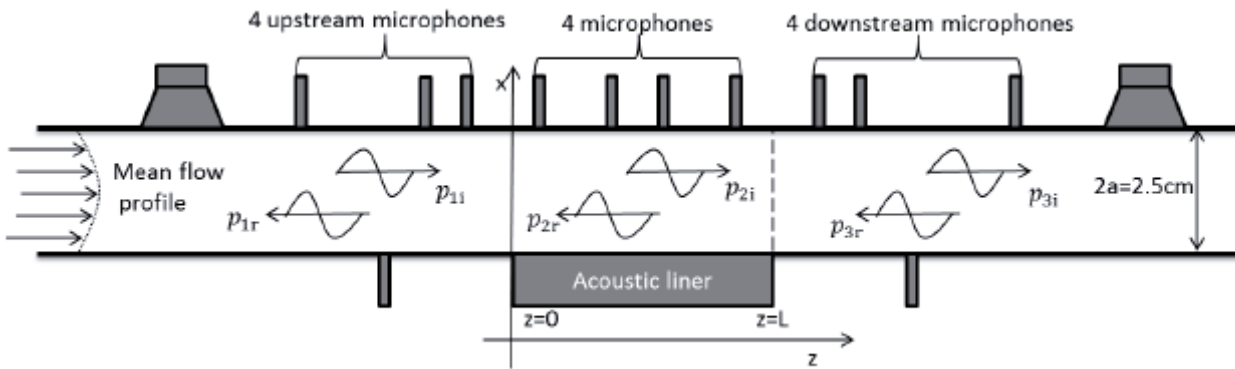

Figure 2: Sketch of liner test setup used to obtain KTH data set 2 [8].

2.5 UFSC data set [20]

A sketch of the test rig at the Federal University of Santa Catarina is shown in Fig. 3 [20]. The test

section consists of 5 ducts, whose position can be switched to accommodate different test configurations. For instance, the source section, where the speakers are connected, can be positioned upstream (closer to the nozzle) or downstream (closer to the fan) of the liner sample. Eight compression drivers are used to generate the acoustic field exceeding 130 dB at the test section. The liner test section consists of a straight duct with an opening where the liner sample is positioned. The wall opposite the liner can be instrumented with 10 ¼microphones, while 8 microphones can be positioned in sections adjacent to the liner section (4 microphones in each section). The liner sample is 0.20 m long, covering the entire duct height. The cross section of the test section is 0.04 m by 0.10 m, which results in a no-flow cut-on frequency of 1700 Hz the first transverse mode. Discrete, sinusoidal excitation, from 500 to 3000 Hz, in steps of 20

Hz was used. Liners were measured from no-flow (Mach 0) to Mach 0.25, in increments of Mach 0.05. Both the MMM and SFM impedance eduction techniques were used to obtained the liner acoustic impedance.
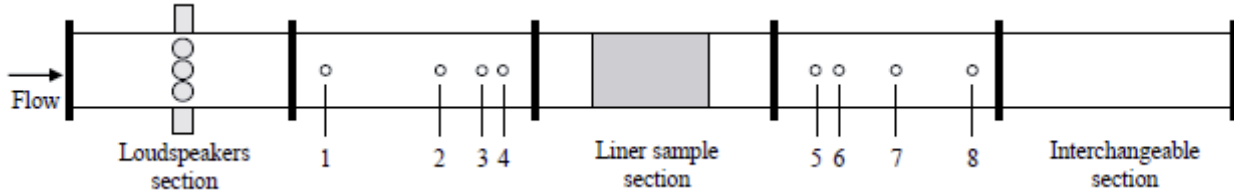

Figure 3: Sketch of liner test setup used to obtain the UFSC data sets [20].

2.6 Liner samples and test conditions

Table 1 summarizes the specifications of the liner samples tested and some test conditions. All samples considered are conventional single degree of freedom Helmholtz resonator liners. In [2] and [10] several different liner configurations were tested but only data from one sample is included the present study. Two samples were measured using the UFSC test rig: UFSC1 and UFSC2.

Table 1: Liner specifications.

| Liner sample	Hole diameter [mm]	Plate thickness [mm]	Cavity depth [mm]	Length/ width [mm]	Percentage open are	Flow Mach numbers	Impedance eduction technique
NASA[2]	0.99	0.635	38.2	610/50.8	8.7 %	0.3, 0.5	SFM
Renou[7]	1.3	1.2	37.5	200/100	10.5 %	0.2	SFM
KTH1[10]	1.0	1.0	40.0	558/63	1.5 %	0.1, 0.2	MMM
KTH2[8]	0.75	0.6	19.0	56/28	16.3 %	0.12, 0.24	SFM
UFSC1	1.0	0.65	19.0	200/100	5.18 %	0.1, 0.20, 0.25	SFM/MMM
UFSC2	2.0	0.8	19.0	200/100	8.63 %	0.1, 0.20, 0.25	SFM/MMM

3 Results and discussion

Figure 4 shows some results from [2] for upstream and downstream conditions and two Mach numbers: $M = 0.3$ and $M = 0.5$. In all the figures presented in this section upstream excitation means that the source is on the downstream side and upstream excitation means that the source is on the upstream side. In the original study results were also presented for different impedance eduction methods. Figure 4 only shows results using the straight forward method (SFM), but similar results were achieved with other techniques. For $M = 0.3$ both curves show similar values and the resistance is approximately constant over most of the frequency range. For $M = 0.5$ the results diverge significantly, mainly at low frequencies for the resistance and also at high frequencies for the reactance. This is the highest flow velocity from all data sets considered here.

Figure 5 shows results from the Renou and Aurégan data set for $M = 0.2$. It can be noted that there are some discrepancies between upstream and downstream results, with the first displaying higher values at low frequency. In the original study, the introduction of the frequency dependent β factor and the use of the modified Ingard-Myers boundary conditions lead to a collapse of the curves. This suggests that the classical Ingard-Myers boundary conditions may be unable to properly represent the acoustic field in the presence of flow and an absorptive wall. Results from [9] based on the same experimental data are also shown in Fig. 5, where a local Mach number M_δ has been used for the Ingard-Myers boundary condition to reduce the difference in results obtained for upstream and downstream excitation. The approach can be seen as a simplification of Renou and Aurégan proposed modification, and seems to be capable of reducing the differences between upstream and downstream results.
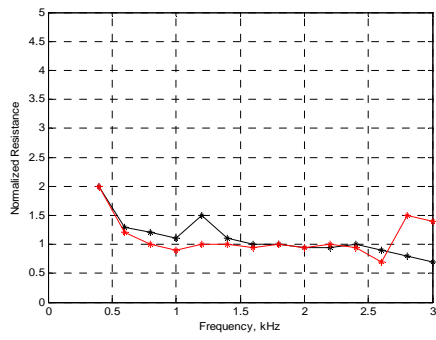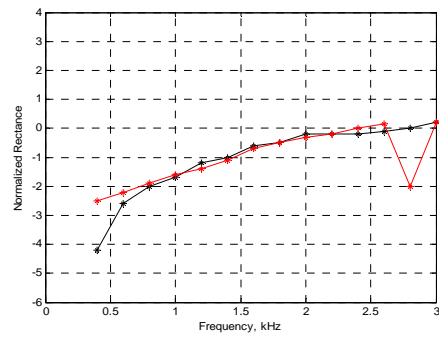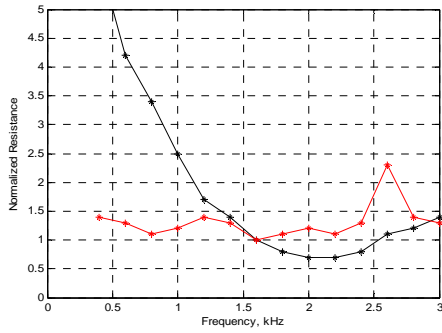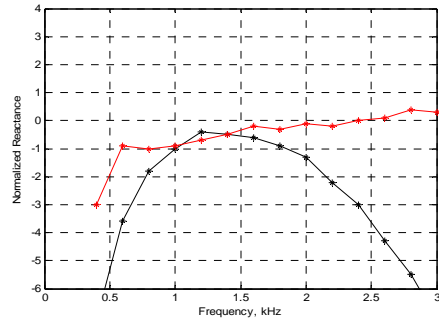
Figure 4: NASA data set from [2]: black line - upstream excitation, red line - downstream excitation, (a) Normalized resistance at $M = 0.3$, (b) Normalized reactance at $M = 0.3$, (c) Normalized resistance at $M = 0.5$, (d) Normalized reactance at $M = 0.5$.
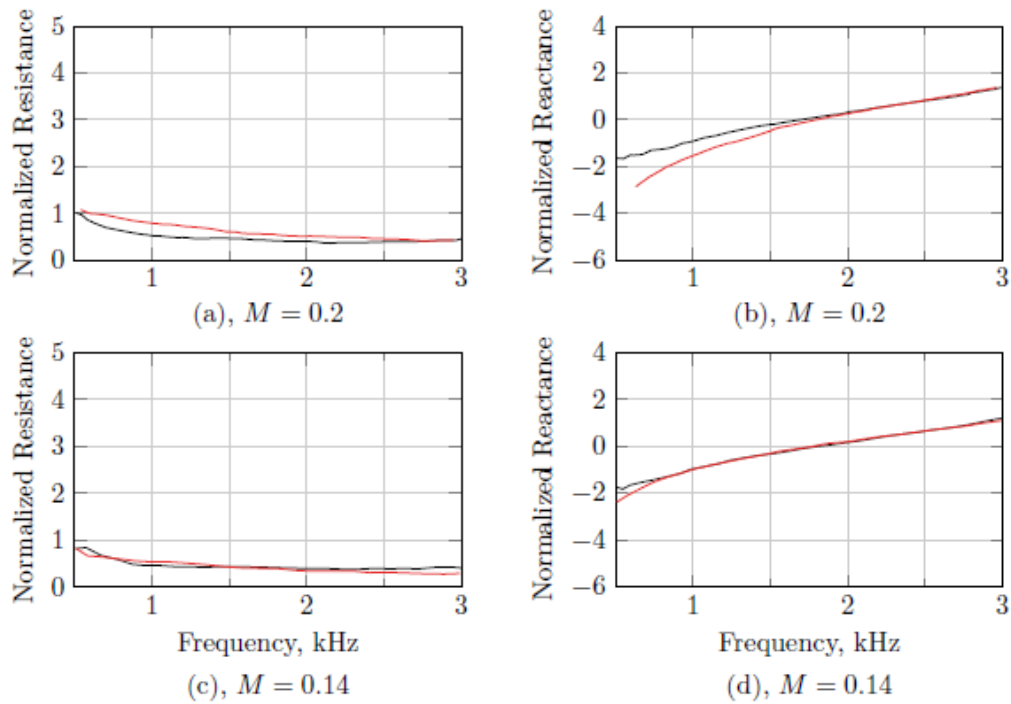
Figure 5: Renou and Aurégan data set from [7] using SFM: black line - upstream excitation, red line - downstream excitation. (a) and (b) Original data from [7] with $M = 0.2$, (c) and (d) Result from [9] with local Mach number $M_d = 0.14$ for Ingard-Myers boundary condition.

Figures 6 show results from [8] for $M = 0.1$ and $M = 0.2$ (KTH data set 2). Results considering a local Mach number M_δ in the Ingard-Myers boundary condition ([9] approach) are also shown.Discrepancies can be seen between downstream and upstream results at both low and high frequency ranges. It is interesting to note that the sample considered in this study has the lowest Helmholtz resonance frequency. For low frequencies, where the acoustic boundary layer is much larger than the viscous sublayer, the results are in line with observation from Renou and Aurégan, with larger impedance values for the downstream condition. The difference are considered reduced if a local Mach number is used.
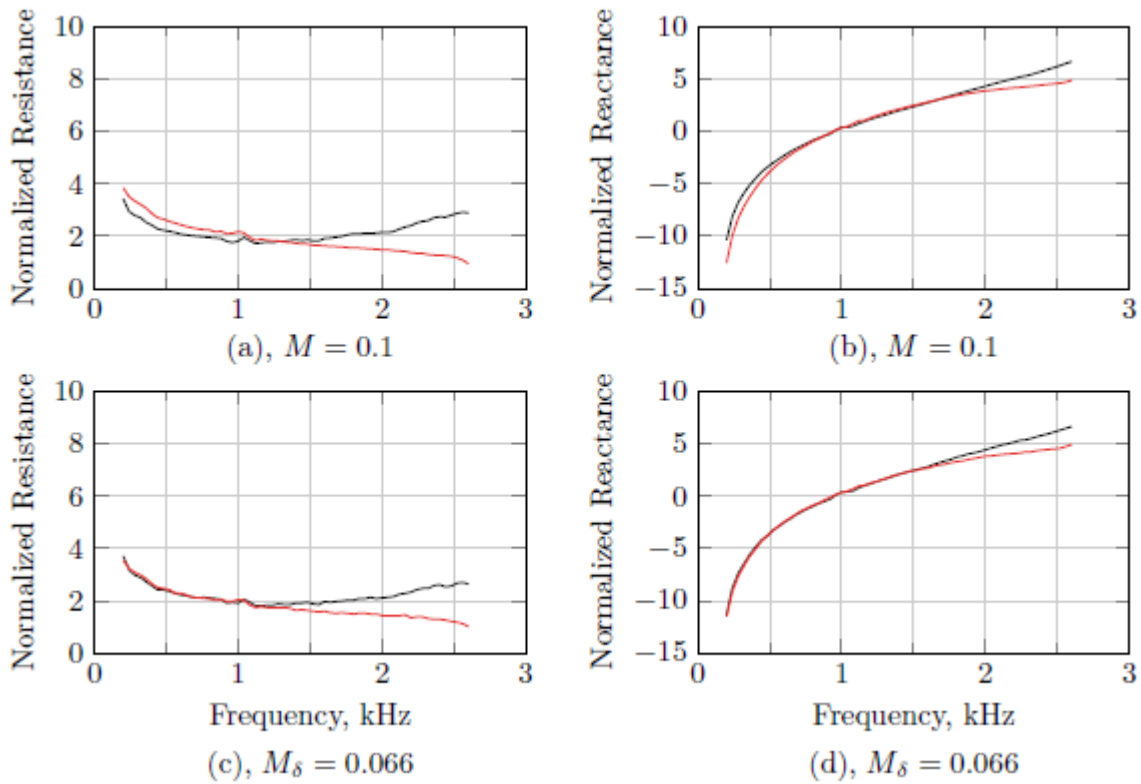
Figure 6: KTH data set 2 for educed normalized impedances from [8,9] for the upstream (black line) and downstream excitation case (red line) using the straight forward method. (a) and (b) Result for mean Mach number $M = 0.1$. (c) and (d) Local Mach number $M_d = 0.066$ for Ingard-Myers boundary condition.

In order to allow a better comparison between the data sets, the resistances were normalized by their respective percentage of open areas, and the frequency was normalized by the liner resonance frequency. Figure 7 shows the new curves for downstream and upstream conditions. Only the resistance is considered since most discrepancies in the results between upstream and downstream excitation were observed. Even though other parameters are left outside the normalization applied (such as Mach number and hole geometry), the procedure seems to result in a good collapse of the curves for upstream excitation, with the exception of UFSC2 data set at low frequency and KTH2 at high frequencies. In general, the resistance under upstream condition shows an almost frequency-independent behavior. This agrees with some semi-empirical models for the acoustic impedance of liners [21-25]. Since these models have been adjusted based on experimental measurements, it may be that they were optimized for upstream excitation, without regarding the possible difference between upstream and downstream conditions. A very good collapse of the curves can be observed for the resistance obtained with downstream excitation. In this case, a clear frequency-dependent behavior can be noted, with an almost constant decrease of the resistance with frequency. Such trend is also observed in some liner impedance semi-empirical models, suggesting that these models were derived from experimental data obtained under downstream condition. Overall, the data sets show a clear difference between educed liner resistance for upstream and downstream conditions. This supports the analysis carried out in the previous sections and reinforce the need of alternatives for the use of the Ingard-Myers boundary conditions in impedance eduction techniques. One recent suggestion [25] is a two parameter model to include the effect of momentum transfer in the boundary layer above the liner.
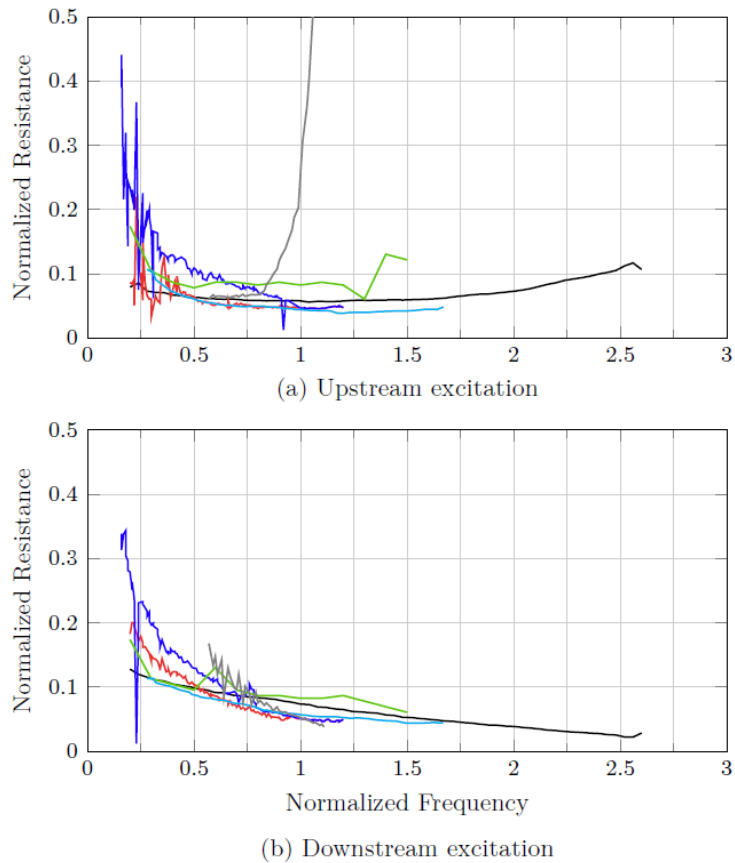
Figure 7: Normalized impedance multiplied by the percentage of open area: black - KTH1 at $M = 0.2$, gray - KTH2 at $M = 0.24$, red - UFSC1 at $M = 0.25$, blue - UFSC 2 at $M = 0.25$, green - NASA at $M = 0.3$, cyan - Renou and Aurégan at $M = 0.2$.
(a) Upstream excitation (b) Downstream excitation.

4   Conclusions

Six different data sets of educed liner impedance have been compared regarding source location, and covering different liner samples, flow velocities and impedance eduction techniques. In general, significant differences between upstream and downstream conditions were observed for educed impedance, specially for its resistive part. The behavior observed is in agreement with the analysis carried out in [7], which suggests that the discrepancies are due to the failure of Ingard-Myers boundary conditions to properly represent the interaction between the acoustic field and a lined wall in the presence of a shear layer. A simplified version of Renou and Aurégan's Modified Ingard-Myers boundary conditions (MIMC) was implemented using a local Mach number in the impedance eduction method as proposed in [9]. The procedure reduces the upstream/downstream differences for some case, but fails in other cases, where it seems that a frequency-dependent correction must be used as originally proposed in [7]. A normalization procedure for the resistance by means of the POA and the liner resonance frequency showed a good collapse of the curves for both upstream and downstream data. The analysis of the curves confirms previous conclusions and hints that semi-empirical liner models may have been adjusted based on a specific source configuration, what should be considered when using results from such models.

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