Multimodal characterisation of acoustic liners using the MAINE Flow facility

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MAINE Flow is a large-scale duct facility that allows investigating the acoustic properties of liners with flow and acoustic conditions close to the ones typically found in nacelles of aircraft engines: the incident acoustic level can go up to 150 dB and the flow velocity up to Mach 0.63.

Compared to other large-scale duct experiments, this facility permits a precise control of the modal content and amplitude, as well as the measurement of the scattering matrix of the liner. In this paper, we compare three methods that allow calculating the insertion losses of a test liner by measuring the transmission losses with and without liner. Two are direct methods that use noise level measurements upstream and downstream the sample: one with an uncorrelated broadband excitation and one with a modal sine-sweep excitation. In the broadband case, robust measurements up to 10 kHz are obtained but the modal content is not controlled. The third method uses the coefficients of the liner scattering matrix to compute transmission losses. More physical insights are provided by this method which works on a more limited range of frequency.

I. Introduction

Most of liner studies in duct aeroacoustic are performed in small section facilities where plane wave propagation is considered upstream and downstream the tested sample [1–3]. Actually, this kind of studies is necessary and still represents our best tool to understand how the complex physics of liners in duct with flow works [4–6].

However, when dealing with aeronautic applications such as the optimisation of a liner for a turbo-engine nacelle, the situation becomes very far from plane wave configurations since the duct section is large and the acoustic source is rotating. Then, the most contributing acoustic modes would not be necessarily the plane wave and one should know how the tested liner would behave with particular high-order modes. Moreover, the overall sound pressure level is gigantic (more than 155 dB) and the flow velocity is large (up to Mach 0.7). During the liner conception phase, these data are taken into account in numerical simulations to find the target impedance for these typical conditions. Nevertheless, before any in-flight test, experimental qualifications in a duct are mandatory and these measurements should be performed in conditions as close as possible to the final application.

MAINE Flow (for Multimodal Acoustic ImpedaNce Eduction with Flow) is a facility built to investigate the acoustic properties of liners with flow velocity up to Mach 0.63 and incident acoustic level up to 150 dB [7, 8]. Appart from the maximum flow and noise conditions, the most original feature of this experimental platform is that the modal content and amplitude of the acoustic field sent to the studied liner sample are precisely controlled, as demonstrated in our previous papers. This permits measurements with complex and varied modal contents, as well as fundamental researches interrogating the link between the propagation direction of the incident wave, the interactions with the boundary layer, and thus the effective liner impedance seen by the waves. Also, previous studies on impedance eduction [9] have shown that measurement errors and uncertainties are reduced when the acoustic field is sufficiently attenuated by the liner. Modal knowledge and control would be thus a way to concentrate the energy on greatly attenuated modes, reducing then the uncertainties on impedance eduction.

Nevertheless, direct and indirect impedance measurements are not available yet on this facility, so that this paper focuses on insertion loss measurements for a typical SDOF liner. To that end, three methods are introduced and compared:

- noise level measurements upstream and downstream the sample for a broadband excitation,
- noise level measurements upstream and downstream the sample for a modal sine-sweep excitation,
- using the coefficients of the sample scattering matrix to compute transmission losses.

First, the main features of MAINE Flow facility as well as the methods for modal decomposition and generation are briefly recalled. Then, the three methods for transmission loss measurements are detailed. Finally, insertion loss are computed and the three method results are compared.

II. MAINE Flow: Multimodal Acoustic ImpedaNce Eduction with Flow

A. Experimental set-up

The MAINE Flow facility is a 150×280 mm^2 rectangular duct where the flow is produced by a fan working in suction mode. It is thus located downstream the schematic view displayed by Fig. 1. The test section is 800 mm long and one or two liner samples can be mounted on the small sides. Above the tested samples, the mean flow velocity can be set up to Mach 0.63. On each side of the test section, 24 loudspeakers are used for producing a plane wave below 600 Hz whereas 66 compression chambers are used to generate the rest of the acoustic field up to 10 kHz. These acoustic sources are driven by 4 generation channels for the loudspeakers and 66 generation channels for the compression chambers. Considering both sides, the total number of acoustic sources is 180. They can be controlled using sine sweep excitation or broadband noise, with an incident level up to 150 dB. Finally, the incident, transmitted and reflected sound fields are acquired simultaneously with two sets of 60 flush-mounted microphones which are placed in duct sections located

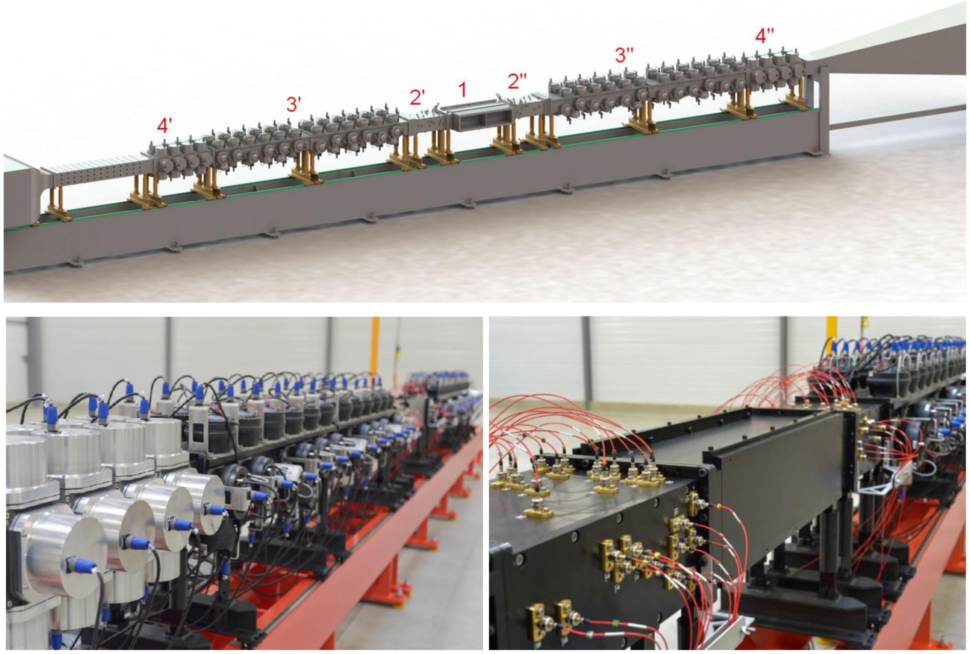

Fig. 1 Top: General view of the test section with (1) the sample support, (2' and 2'') the upstream and downstream microphone sections, (3' and 3'') the upstream and downstream HF-loudspeaker sections and (4' and 4'') the upstream and downstream LF-loudspeaker sections. Bottom left: picture of the 24 (grey) LF-loudspeakers and 66 (black) HF-compression chambers placed on each side of the test section. Bottom right: picture of the 60 microphones mounted on each side of the test section.

upstream and downstream the test section. Note that the position of the microphones and of the acoustic sources have been optimised to ensure the generation (and the decomposition) of the 24 modes that can propagate at 4000 Hz [7].

B. Modal identification and control of the modal content

More than the maximum mean flow velocity and the target sound pressure level, the control of the incident modal content and amplitude is the most original and interesting feature of the MAINE Flow facility. Since the methods implemented to that end have already been described and validated in [7, 8], we will only recall here what is used for the IL measurements of a test sample: the generation of a given mode or of a given combination of modes using one or several sources.

First, one has to construct the propagation matrix **M** that links the vector of acoustic pressures **p** at the microphone positions to the amplitudes of the $2N$ modes $\mathbf{p}^{\pm}$:

$$\mathbf{p}\left(\omega\right) = \mathbf{M}\left(\omega\right)\mathbf{p}^{\pm}\left(\omega\right). \tag{1}$$

Actually, each term of this propagation matrix **M** can be analytically calculated as the product of the modal shape function in a rigid rectangular duct times a propagation term depending on the modal wave number and on the microphone position. Once $\mathbf{M}$ is known, the modal decomposition for a particular acoustic excitation is done by inverting the propagation matrix: $\mathbf{M}$ and $\mathbf{p}$ are known so that the amplitudes $\mathbf{p}^{\pm}$ can be calculated.

Among other things, this procedure for modal decomposition allows measuring the modes generated by a given source and thus permits evaluating at each frequency the transfer function between the signal sent to each acoustic source of the facility and each of the propagating incident modes. By doing this for each of the sources located upstream (or downstream) one-by-one, the transfer matrix $\mathbf{H}$ between the commands $\mathbf{c}$ sent to the upstream (or downstream) sources and the modes $\mathbf{p}$ incident on the sample from upstream (or downstream) can be identified:

$$\mathbf{p}_u^+ = \mathbf{H}_u \mathbf{c}_u, \qquad \mathbf{p}_d^- = \mathbf{H}_d \mathbf{c}_d. \tag{2}$$

Above, u and d subscripts denote cases with upstream and downstream acoustic excitation whereas exponents + and − correspond respectively to waves propagating with or against the flow. Once $\mathbf{H}$ is known, it is inverted to find the appropriate set of commands needed to generate a given mode as it will be done in section III.B for IL measurements with modal excitation and in section III.C for scattering matrix measurements.

III. Transmission loss (TL) measurement methods and results

In the following sections, three methods are introduced to calculate the Transmission Losses (TL) associated to an hard-wall configuration and to a lined case. These three methods are :

- direct measurement using an uncorrelated broadband signal;
- direct measurement using a modal sine-sweep excitation;
- computation from the liner scattering matrix.

For the whole study, the test sample is a 800 mm long typical Single Degree Of Freedom with a height roughly equal to 33 mm. The perforated plate at the top has 2 mm holes and a POA (Percent Open Area) of approximately 13%.

A. Direct TL measurements with broadband excitation

This first method is based on the measurement of the mean Sound Pressure Level (SPL) recorded by the 120 microphones placed upstream and downstream the test section (60 microphones on each side) when all the acoustic sources located on one side are activated simultaneously. The input signal, uncorrelated between the sources, is a broadband white-noise excitation spread between 300 Hz and 10 kHz. All the sources are controlled with the same electric tension which is chosen to reach a target overall incident SPL. The top row of Fig. 2 displays the mean SPL recorded upstream and downstream the test section in presence of the SDOF liner. In this example, only the upstream acoustic sources are on with a target level equal to 150 dB overall. Without flow (left column), both curves have a similar shape but the levels downstream are lower than upstream. When the mean Mach number in the test section is

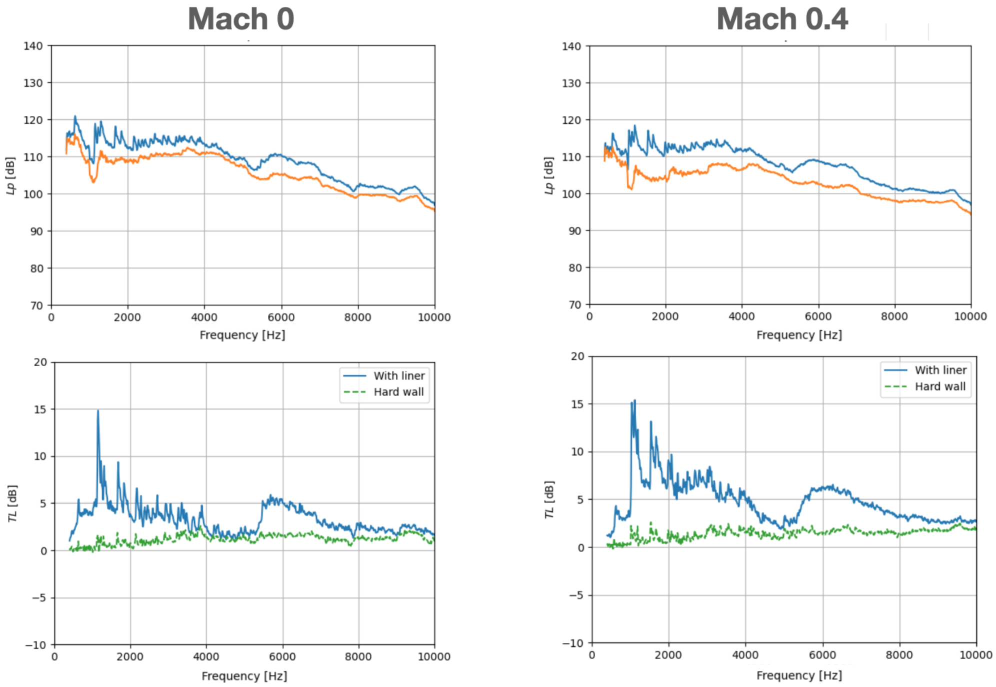

Fig. 2 Upstream acoustic excitation. Left column: Mach = 0. Right column: Mach = 0.4. Top row: mean Sound Pressure Level (SPL) at upstream (blue) and downstream (orange) measurement sections in presence of the SDOF liner for an incident target level equal to 150 **dB overall. Bottom row: Transmission Loss coefficients in dB for hard wall and lined cases.**

equal to 0.4, the difference between upstream and downstream curves is larger, especially below 4000 Hz.

Once the mean SPL are recorded upstream and downstream the liner sample, the difference which corresponds to the Transmission Losses (TL) is calculated. The results are displayed in the bottom row of Fig. 2. To permit the comparison, the TL of the hard wall configuration is also plotted. In this case, attenuation caused by viscothermal propagation losses grows linearly with frequency to reach nearly 2 dB at 10000 Hz. When the liner is mounted, its influence is clearly visible. In particular, two bands of attenuation are spotted below 3500 Hz and around 6000 Hz. At Mach 0.4, this attenuation is increased.

Note that usually the experiment is repeated using all the downstream speakers together. Then, another TL is computed and the effect of the acoustic waves direction of propagation can be studied. In order to stay concise, only upstream results are shown here, but section IV latter in this paper also displays the insertion losses (IL) with opposite direction.

B. Direct TL measurements with modal excitation

In this subsection, TL measurements are performed using a swept-sine excitation. At a given frequency, the incident field is composed of all propagating modes and they share the same amplitude. To obtain such an incident field, we have to go back to eq.(2) and $\mathbf{H}$ is known. Then, the goal is to calculate the commands $\mathbf{c}_{u,d}$ corresponding to each

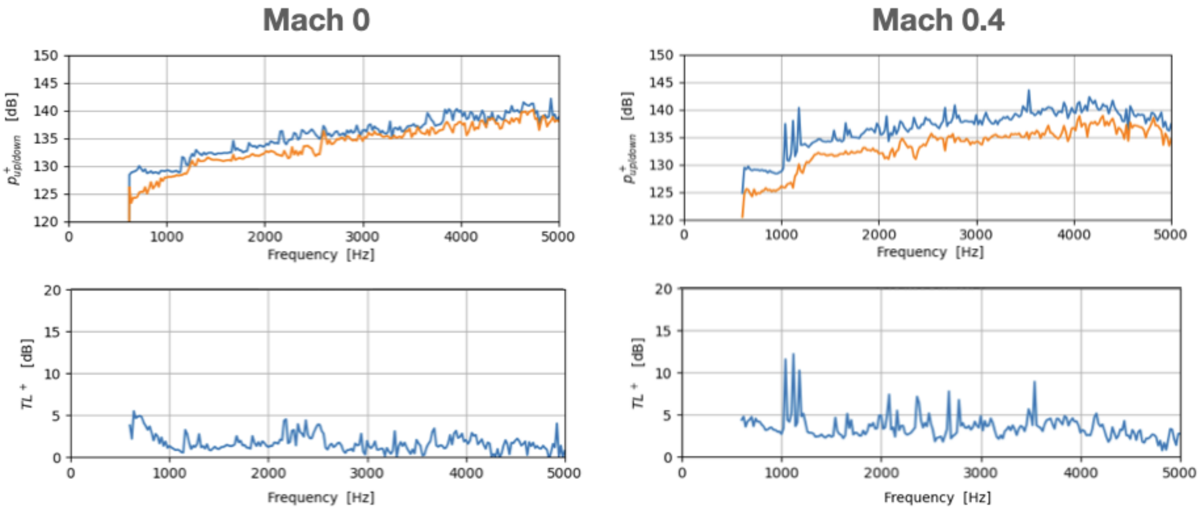

Fig. 3 Upstream acoustic modal excitation. Lined case. Left column: Mach = 0. Right column: Mach = 0.4. Top row: mean amplitude in dB of the waves propagating in upstream (blue) and downstream (orange) measurement sections. Bottom row: transmission loss as a function of frequency.

independent acoustic modes $\mathbf{p}^{\pm}_{u,d}$. This is done by performing a pseudo-inversion of the transfer matrix $\mathbf{H}_{u,d}$ for each mode. To preserve the physical integrity of all the sources, this pseudo inversion is done using a penalisation technique ensuring that no source is excited above a certain limit. Once the commands are calculated, the swept-sine excitation signal can be built.

For these TL measurements with modal excitation, note that the global level of the incident field depends on the frequency. Indeed, since each mode has the same amplitude, the global level depends on the number of propagating modes which increases with the frequency. This is clearly visible in the top row of Fig. 3 which displays the acoustic modes mean amplitude upstream (in blue) and downstream (in orange) the SDOF liner. In this example, only the acoustic sources are on so that downstream levels are lower than upstream levels. In presence of flow this difference is larger. Following the same procedure as for the broadband excitation, the TL are computed once the levels on both sides are known. The results are displayed in the bottom row of Fig. 3. Here, the attenuation seems nearly constant as a function of frequency, except at low frequency. In particular, the two absorption bands observed in Fig. 2 are not clearly visible. Finally, attenuation in presence of flow is greater than without flow. This should be explained by the evolution of the ratio between the liner impedance and the duct optimal impedance for attenuation.

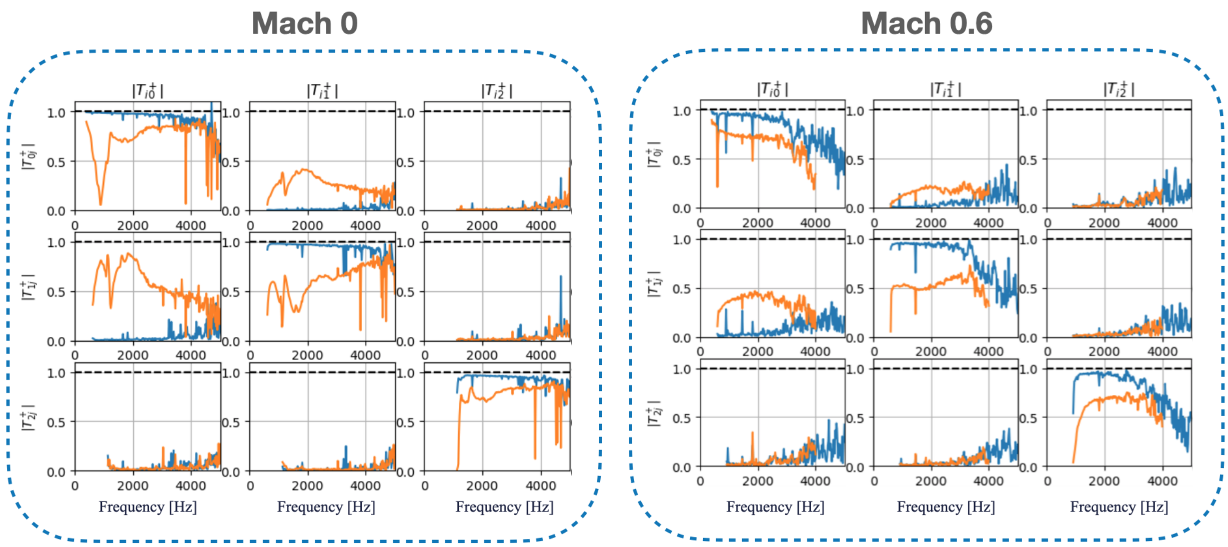

Fig. 4 Transmission matrix $\mathbf{T}^{+}$ associated to an upstream acoustic excitation for the Mach 0 and Mach 0.6 cases. Only the three first acoustic modes are shown. Blue lines: hard wall case. Orange lines: SDOF liner.

C. TL calculation from the scattering matrix

The multimodal scattering matrix $\mathbf{S}$ relates the amplitudes of the waves $\mathbf{p}^{out}$ scattered by an element mounted in the test section and the vector of incident modes $\mathbf{p}^{in}$. Thus, we can write $\mathbf{p}^{out} = \mathbf{S} \cdot \mathbf{p}^{in}$ with :

$$\mathbf{S} = \begin{bmatrix} \mathbf{R}^{+} & \mathbf{T}^{-} \\ \mathbf{T}^{+} & \mathbf{R}^{-} \end{bmatrix}, \tag{3}$$

where $\mathbf{T}$ and $\mathbf{R}$ are respectively the transmission and reflection matrices for waves coming from upstream (exponent $+$, propagation in the same direction than the flow) and from downstream (exponent $-$, propagation against the flow). When N modes are cut-on in the rigid parts of the duct, the scattering matrix $\mathbf{S}$ has dimensions $2N \times 2N$ and it can be identified using more than 2N independent excitation cases [10]. In practice, the excitation cases are provided by sending a unit signal to each of the 70 upstream source channels and 70 downstream source channels [8]. To that end, we assume that the phases of the incident modes are random and not correlated with each other. Then, each realization with a given excitation provides a new relation $\mathbf{p}^{out} = \mathbf{S} \cdot \mathbf{p}^{in}$. Combined together, these realizations form a linear system that is solved to get $\mathbf{S}$.

Fig. 4 displays the upstream transmission matrix $\mathbf{T}^{+}$ extracted from the measurement of $\mathbf{S}$ for both lined and hard wall cases. Only the first three modes, ranked by their cut-on frequency, are shown. The subscript 0 corresponds to the plane wave and the diagonal of each case represents the transmission of each mode on itself. Extra-diagonal terms describe energy transfers between modes caused by the presence of the liner. Thus, for the hard wall case the transmission is equal to 0 on all the extra-diagonal terms. On the diagonal, the transmission is close to 1. When the

SDOF liner is mounted, the energy transfer between modes is not negligible. Moreover, a big transmission drops appears for the plane wave below 1000 Hz. Note that this drop disappears when Mach number is equal to 0.6 and the liner effect is then concentrated on high order modes.

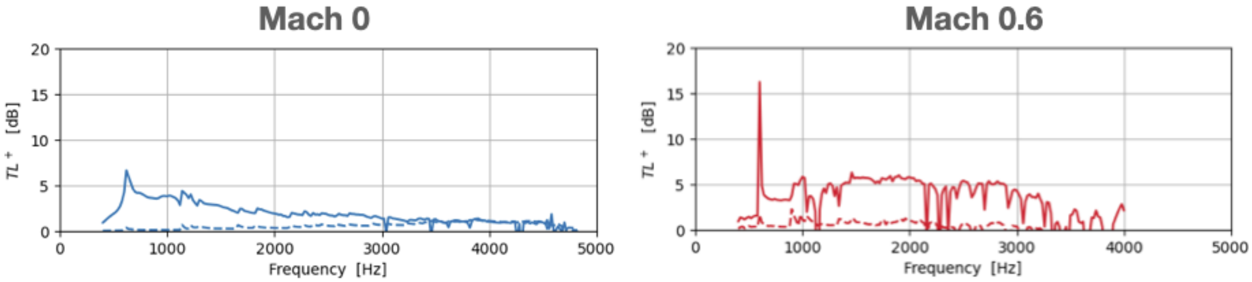

Fig. 5 Transmission losses computed from the scattering matrix for waves coming from upstream. Left column: Mach = 0. Right column: Mach = 0.6. Solid lines: lined case. Dashed lines: hard wall case.

The TLs are finally evaluated from the transmission coefficients using the formulas given by [11] using the assumption of uncorrelated incident modes which should correspond the most closely to the broadband excitation case for comparison. The results are displayed in Fig. 5 for both Mach 0 and 0.6 cases. Note that compared to the broadband excitation method used in III.A the results are only displayed up to 5000 Hz because we don't have enough acoustic sources to perform modal control above this limit. Also, for Mach 0.6 the results are stopped at 4000 Hz because then the signal to noise ratio is too low.

Without liner, the losses increase linearly with frequency as already noticed for the other TL measurement methods. In presence of liner and without flow, the attenuation maximum reaches 6 dB at the first liner resonance. When the flow velocity corresponds to a Mach number of 0.6, this value goes up to 16 dB and stays greater than 5 dB up to 3000 Hz. This liner sample performance are thus satisfying with flow.

IV. Insertion Loss (IL) results and method comparison

In the previous section, TL have been computed using three methods for an hard-wall configuration and for a lined one. The effect of the liner is now isolated by subtracting the first one to the last one, leading to insertion loss coefficients (IL).

Fig. 6 displays the insertion losses obtained by the previously described methods. For both scattering and modal methods, the modal control abilities of the MAINE Flow facility limit the measurements to a frequency of 5 kHz, while the broadband method goes up to 10 kHz. The smoothest curves are obtained by the scattering method. For both direct methods, the cut-on frequencies of the duct transverse modes seem to pollute the measurements which look noisier than for the scattering matrix based method. Despite that, the average level of absorption for the several flow cases is the same for each method.

Fig. 6 also allows evaluating flow and direction of propagation effects. The increase of the flow Mach number is nearly always followed by an increase of absorption probably linked to an increase of the liner resistance. This effect is here for both directions of wave propagation. However, in presence of flow, IL are slightly higher below 3000 Hz for waves coming from downstream than for waves coming for upstream, whereas the values are the same without flow.

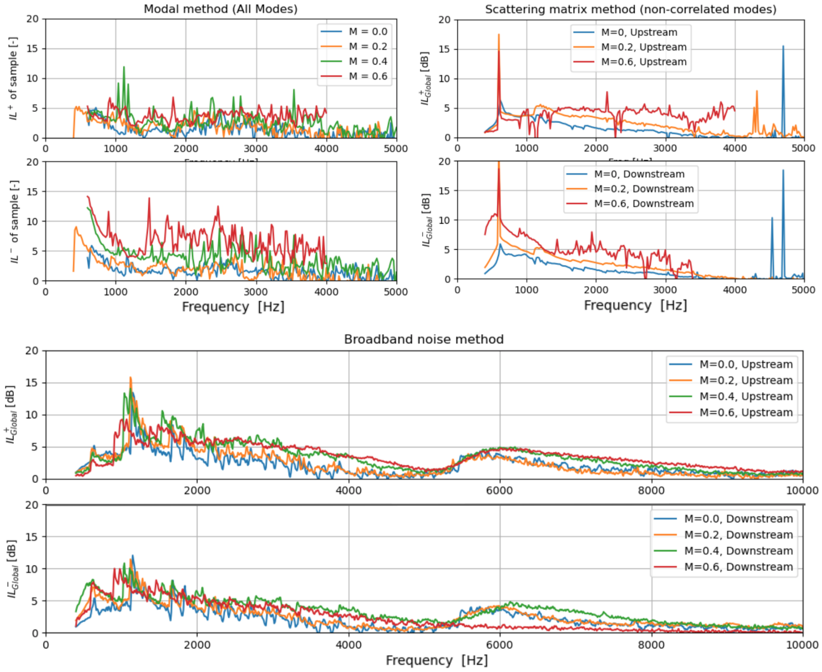

Fig. 6 Insertion losses in dB as functions of the frequency for several flows ranging from Mach 0 to Mach 0.6. Top left: modal excitation method. Top right: calculation from the scattering matrix. Bottom: broadband noise method. For each method, the top panel corresponds to the upstream case and the bottom one to the downstream case.

V. Conclusions

Maine Flow facility allows a precise control of the complex acoustic field that propagates in a duct with high flow speed and large acoustic levels. In this paper, three methods have been implemented for evaluating the losses caused by the introduction of a liner in the wall of the facility test section.

The broadband method has the advantage of allowing measurements up to 10000 Hz for several controlled overall SPL whereas the other methods are limited to 5000 Hz. It thus gives a good overview of the liner effect, even for high Mach numbers. However, the modal content is not controlled so that few physical insights are really provided. In fact, this modal information is supplied by the two other methods: IL computation from the sample scattering matrix and IL direct measurements with modal excitation. Unfortunately, this last method is polluted by experimental uncertainties and flow noise. On the other hand, the IL computed from the scattering matrix is more robust and permits either isolating the contribution of each mode, either providing a global information that fits with the broadband direct measurements.

Nevertheless, measuring the scattering matrix at one Mach number takes approximatively 4 hours, which is 5 times longer than the other method.

This analysis shows that each method has its advantages and drawbacks. Depending on the purpose of the experimental campaign, one can be more adapted than an other. Nevertheless, all these liner characterisations are completely dependant on the size of the duct section. Thus, in order to get a more intrinsic quantity, direct and indirect impedance eduction have now to be implemented in the MAINE Flow facility.

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