HAL
open science

Effect of flow on an array of Helmholtz resonators: Is Kevlar a “magic layer”?

Yves Aurégan, M. d’Elia, T. Humbert

To cite this version:

Yves Aurégan, M. d’Elia, T. Humbert. Effect of flow on an array of Helmholtz resonators: Is Kevlar a “magic layer”?. Journal of the Acoustical Society of America, 2020, 148 (6), pp.3392-3396. 10.1121/10.0002642 . hal-03364985

HAL Id: hal-03364985

https://hal.science/hal-03364985v1

Submitted on 5 Oct 2021

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L’archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d’enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Effect of flow on an array of Helmholtz resonators: Is Kevlar a “magic layer”?

M. E. D'Elia, T. Humbert and Y. Aurégan

Citation: The Journal of the Acoustical Society of America **148**, 3392 (2020); doi: 10.1121/10.0002642
View online: https://doi.org/10.1121/10.0002642
View Table of Contents: https://asa.scitation.org/toc/jas/148/6
Published by the Acoustical Society of America

ARTICLES YOU MAY BE INTERESTED IN

An investigation on noise attenuation by acoustic liner constructed by Helmholtz resonators with extended necks
The Journal of the Acoustical Society of America **149**, 70 (2021); https://doi.org/10.1121/10.0002990

Machine learning in acoustics: Theory and applications
The Journal of the Acoustical Society of America **146**, 3590 (2019); https://doi.org/10.1121/1.5133944

Deconvolved frequency-difference beamforming for a linear array
The Journal of the Acoustical Society of America **148**, EL440 (2020); https://doi.org/10.1121/10.0002927

A computational method whose time had come
The Journal of the Acoustical Society of America **148**, R7 (2020); https://doi.org/10.1121/10.0002055

REVIEWS OF ACOUSTICAL PATENTS
The Journal of the Acoustical Society of America **148**, 3379 (2020); https://doi.org/10.1121/10.0002760

Acoustic metamaterial capsule for reduction of stage machinery noise
The Journal of the Acoustical Society of America **147**, 1491 (2020); https://doi.org/10.1121/10.0000857

ASA

Advance your science and career
as a member of the
ACOUSTICAL SOCIETY OF AMERICA

LEARN MORE

JASA LETTER TO THE EDITOR

Effect of flow on an array of Helmholtz resonators: Is Kevlar a "magic layer"? (L)

M. E. D'Elia, T. Humbert,[a)] and Y. Aurégan
Laboratoire d'Acoustique de l'Université du Mans, LAUM-UMR CNRS 6613, Avenue Olivier Messiaen, 72085 Le Mans Cedex 9, France

ABSTRACT:
The effects of flow on the acoustic behavior of metamaterials can be very significant and possibly destructive. To avoid these detrimental effects, it would be a good idea to have a "magic layer" that allows acoustics to pass through while suppressing the sound-flow interactions. A possible realization of this layer based on Kevlar fabric is tested in this paper. It is shown that, in the presence of Kevlar, flow-sound interactions that can lead to acoustic amplification and whistling phenomena are avoided. Thus, Kevlar will permit liner designs including large slits. However, it adds large acoustic losses, which limits interesting resonance effects in applications.
© *2020 Acoustical Society of America*. https://doi.org/10.1121/10.0002642

(Received 24 July 2020; revised 2 October 2020; accepted 25 October 2020; published online 1 December 2020)

[Editor: Likun Zhang] Pages: 3392–3396

I. INTRODUCTION

Metamaterials offer new opportunities to attenuate or redirect sound waves.[1,2] New applications are already being considered, particularly in the field of aeronautics.[3] In this framework, metamaterials are subjected to flows that can change their effect.[4,5] In some applications, the metamaterials under consideration are porous, which raises the question of how acoustic waves can penetrate the material without the flow penetrating it. In the same way, acoustic cloaking with flow relies on the assumption that "the cloak's metamaterials are rigid and impervious to fluid but are transparent to sound waves."[6] As this last research field is still mainly theoretical and numerical,[7,8] practical realizations of such a magic layer are not often discussed. The idea of using a Kevlar sheet is sometimes suggested[9] since acoustically transparent walls made from tensioned Kevlar cloth are nowadays used in wind tunnels.[10] However, the acoustic behavior of very large Kevlar walls (with respect to wavelength) is very different from that of smaller pieces. In fact, Kevlar cloth is a permeable membrane through which acoustics can pass in two ways. One is related to vibration, as through an impermeable wall, and the second to permeability, as through a rigid resistive wall. For the first effect the important parameters are the mass per unit area and the tension of the film, while for the second it is the acoustic resistance (pressure drop divided by the normal fluid velocity). Of course, these two effects are always present[11] but we can think that when the size of the panels is small compared to the wavelength, it is the resistive effect which predominates and that if vibrations are involved, it is in the form of resonances which are localized in frequency. That is the subject of this paper.

For this, we consider an array of Helmholtz resonators located in the wall of a waveguide. The acoustic behavior of this metamaterial is first analyzed without flow. Then, it is shown that the addition of a flow greatly disturbs the resonator's acoustic performance, as whistling is induced. Finally, the array is covered with a Kevlar fabric. The cloth strongly affects the acoustic behavior of the metamaterial in absence of flow, while whistling is prevented in presence of flow.

II. EXPERIMENTAL INVESTIGATION

The model metamaterial studied in this paper consists of five identical Helmholtz resonators mounted in series.[12,13] The scattering matrix of this sample is measured with and without flow, and with and without a Kevlar cloth glued on the top of the resonators.

A. Test rig and measurement procedure

An array of five Helmholtz resonators is located in the wall of a waveguide of rectangular section $H \times B$ with $H = 40$ mm and $B = 50$ mm, see Fig. 1(a). This duct facility has already been introduced in Ref. 14 and a mean flow whose velocity is up to 80 m/s can be produced by a centrifugal fan. The unit cell resonator is a square cuboid with a volume equal to 31 mm × 31 mm × B. Five resonators are placed side by side, forming an array with a period of 35 mm, and the surface in contact with the flow has been polished to avoid any discontinuity that could disturb the mean flow, see Fig. 1(b). The cavity volume has been chosen so that a large transmission loss should occur within the target frequency range of liners designed for aircraft nacelles. The neck of the resonator is a slit whose dimension in the direction of flow is $W = 5$ mm. The slit extends over the entire width of the waveguide B, and its thickness is equal to $t = 1.9$ mm. These dimensions have been picked so that whistling phenomena would be expected in

[a)]Electronic mail: thomas.humbert@univ-lemans.fr, ORCID: 0000-0003-3783-5290.

 © 2020 Acoustical Society of America

https://doi.org/10.1121/10.0002642

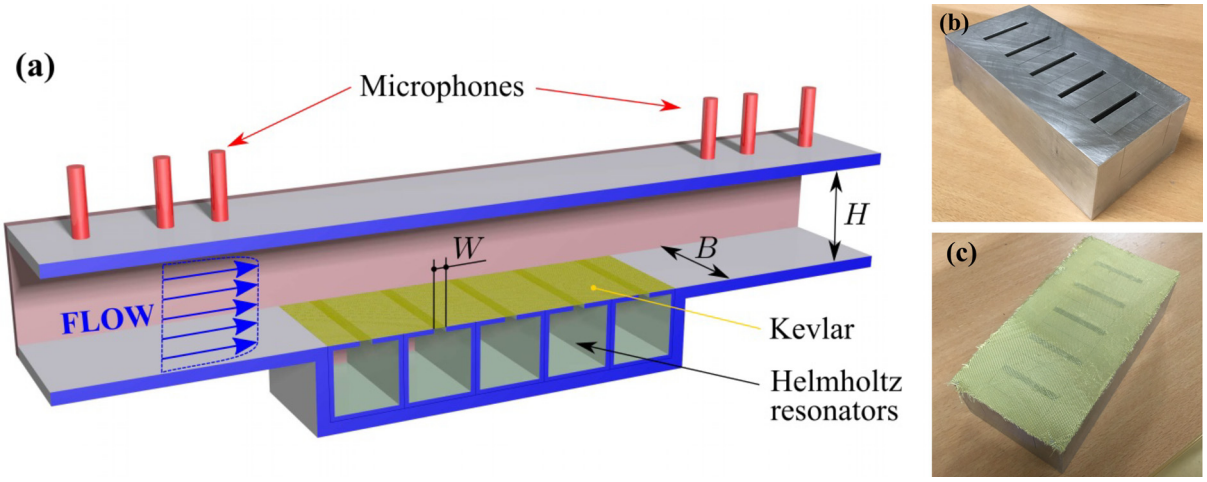

FIG. 1. (Color online) (a) Sketch of the Helmholtz resonators mounted in a waveguide of rectangular section $H \times B$ with $H = 40$ mm and $B = 50$ mm. Three microphones are located on each side of the sample to determine its scattering matrix. The resonator cavity is a square cuboid with a volume equal to 31 mm $\times$ 31 mm $\times$ B. The neck of the resonator is a slit of thickness $t = 1.9$ mm, and its dimension in the direction of the flow is $W = 5$ mm. (Below) Picture of the metamaterial, without (b) and with (c) the Kevlar cloth. Only the central part, where the slits can be seen, is in contact with the inside of the duct.

presence of flow for the range of flow velocities that are provided by the fan.

More than 2 m of duct separate the fan from the test section. Thus, the flow can be considered as turbulent and fully developed when it reaches the Helmholtz resonators. The flow velocity is evaluated at the center of the duct downstream of the test section by a Pitot tube connected to a differential pressure sensor. This measurement gives the maximum value of the flow velocity in the duct section. It is then multiplied by 0.8 so that the value of the average velocity and the Mach number M are obtained.[15] The temperature inside the duct is measured by a type K thermocouple placed upstream of the test section.

The acoustic waves are generated by two compression chambers which can be placed either upstream, or downstream, of the test section. A sinusoidal sweep ranging from 200 to 4000 Hz with a step of 5 Hz is used. As the frequencies studied are below the first cut-off frequency of the waveguide, only plane waves can propagate.

The sound pressure in the duct is recorded by two sets of three flush-mounted microphones located upstream (u_i) and downstream (d_i) of the test section, where $i = 1$ indicates the microphone located the closest to the test section. The positions of the microphones are $x_{u_1} - x_{u_2} = x_{d_2} - x_{d_1} = 30$ mm, $x_{u_1} - x_{u_3} = x_{d_3} - x_{d_1} = 175$ mm, and both u_1 and d_1 are placed 113 mm away from the metamaterial. All the microphones are calibrated relative to u_1 in a separate cavity mounted on a loudspeaker. Then, the acoustic pressure is obtained at each frequency step through an averaging procedure.

An overestimated determination of the incident and reflected waves on both sides of the metamaterial is performed. This decomposition is used to ensure, at each frequency step and for every flow velocity, a constant amplitude of the incident acoustic wave. For that purpose, a first measurement is performed with a constant source level, and the recorded pressure field is decomposed in terms of incident and reflected acoustic plane waves. It appears that depending on the duct resonances, the incident wave amplitude changes with frequency. Next, we estimate the voltage that should be applied to the loudspeakers to compensate for the resonances. The experiment is then run again using these estimated levels, and the amplitude of the propagating waves are computed. If the amplitude of the incident acoustic wave is not in a 2% interval around the target value, here chosen as 120 dB, the optimisation routine is repeated. Otherwise, the elements of the scattering matrix of the metamaterial, namely, the reflection and transmission coefficients ($R^{\pm}, T^{\pm}$) defined for incident plane waves coming from upstream (R^{+}, T^{+}) and downstream (R^{-}, T^{-}) of the sample, are computed. To obtain these four coefficients, two different acoustic states are needed. The first one is obtained by placing the compression chambers upstream of the resonators, the second one by placing them downstream. More details about this measurement technique, for the case of a cylindrical duct, can be found in Ref. 16.

B. Results without Kevlar

First, all the measurements with and without flow were carried out on the resonator array before gluing the Kevlar fabric on it. The results are shown by Fig. 2, which draws the transmission coefficients as functions of frequency. Without flow, there is a transmission dip in the vicinity of the resonance frequency of the Helmholtz resonators. There, the transmission goes down up to $|T| = 1.5 \times 10^{-4}$ (-76 dB). In the present investigation, the Bragg band gap lies outside the frequency range studied.

When the flow is present, it can be noticed that the transmission coefficients in both directions are now different. This is due to the loss of reciprocity when there is a flow. But the most striking fact is the peak at 1220 Hz which is larger than 1. It actually corresponds to a whistling that is audible through the whole duct even in the absence of

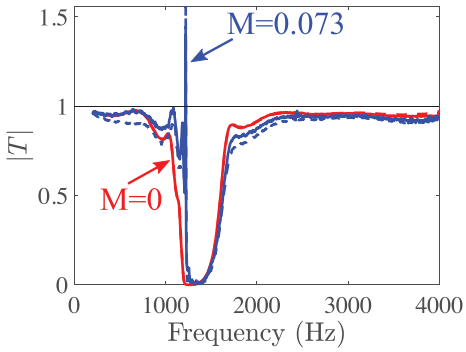

FIG. 2. (Color online) Transmission coefficients without Kevlar as a function of the frequency. The continuous lines represent T^+ (in the flow direction) while the dashed lines represent T^- (against the flow). The cases $M = 0$ and $M = 0.073$ are indicated in the figure.

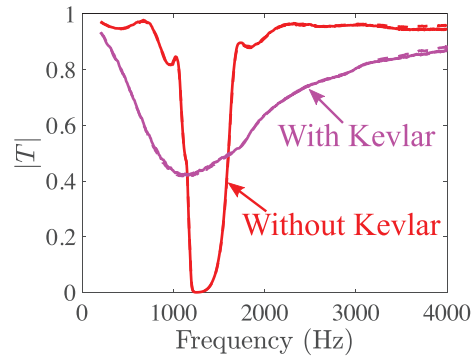

FIG. 3. (Color online) Transmission coefficients with and without Kevlar when there is no flow. The continuous lines represent T^+ (in the flow direction) while the dashed lines represent T^- (against the flow). The cases with Kevlar and without Kevlar are indicated in the figure.

acoustic excitation. It should be noted that when whistling is present, the phenomenon becomes non-linear and the linear transmission as given in Fig. 2 becomes meaningless at the frequency of the whistling.

Consequently, even a weak flow as in the present case (the mean velocity in the duct is $U = 25$ m s^{-1} corresponding to a Mach number $M = 0.073$) has a dramatic effect, since the metamaterial starts to produce sound. This whistling is quite usual when a flow grazes a Helmholtz resonator. Moreover, it appears in the classical range of the Strouhal number,[17] since here $S_r = fW/U = 0.24$, where f is the frequency.

These results prove that something has to be done to prevent such sound-flow interactions and instabilities when metamaterials are exposed to a flow.

C. Results with Kevlar

A lightweight Kevlar 49 fabric (weight = 61 g/m^2, thickness = 0.12 mm) is now used to cover the resonators,[18] see Fig. 1(c). Before being glued to the metamaterial, the piece of Kevlar was tensioned uniformly by using the mechanism of a 13-in. drum. The effect of the Kevlar sheet on the acoustic behavior of the Helmholtz resonators array when there is no flow is shown in Fig. 3, where the transmission coefficients measured with and without Kevlar are compared.

The drop in transmission in the vicinity of the resonance is much less pronounced with Kevlar (the minimum transmission is $|T| = 0.42$, i.e., -7.6 dB) than without it. On the other hand, this drop in transmission occurs over a much wider frequency range. This indicates that Kevlar produces a strong damping that decreases the resonance peak while widening it.

It is therefore incorrect to consider that the Kevlar sheet is completely transparent to acoustic waves.

The effect of flow on a Kevlar coated metamaterial is shown in Fig. 4. Again, it can be noted that, due to the lack of reciprocity, the transmissions in both directions are slightly different. Most noticeably, the effect of the flow is now much weaker than without the Kevlar cover. In particular, the whistling that appeared without Kevlar, has now completely disappeared.

III. NUMERICAL APPROACH

In order to better understand the phenomena involved in both Kevlar coating and flow, a numerical simulation is carried out. To this end, a multimodal method is used to calculate the linearized two-dimensional lossless problem with and without flow and to compare its results with experimental data. This method has already been described in detail elsewhere[19–21] and therefore only a few points are reported.

The linear propagation of small perturbations in a parallel sheared flow can be described by the linearized Euler equations (LEE). The multimodal method is used, and the perturbations are therefore expressed as a linear combination of acoustic and hydrodynamic transverse modes. These modes and wave numbers are computed on uniform segments using a finite difference method by discretizing the LEE in the transverse y-direction. The modes must be calculated in the neck of the resonator, knowing that there is a shear flow above (for $0 < y < H$), a pressure discontinuity due to an impedance Z at $y = 0$, and no flow in the cavity (for $-t - C < y < 0$, where C is the cavity depth). The modes must also be computed outside the neck in the rigid

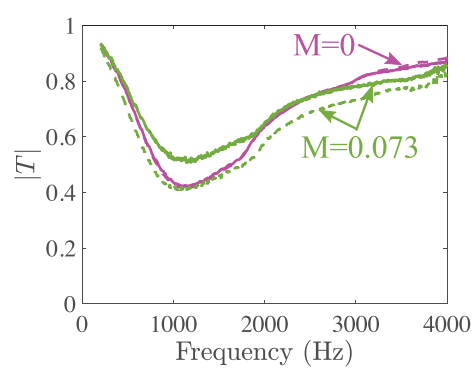

FIG. 4. (Color online) Transmission coefficients with Kevlar as a function of the frequency. The continuous lines represent T^+ (in the flow direction) while the dashed lines represent T^- (against the flow). The cases $M = 0$ and $M = 0.073$ are indicated in the figure.

https://doi.org/10.1121/10.0002642

pipe with a shear flow ($0 < y < H$) and in the cavity ($-t - C < y < -t$). The scattering matrix of one cell is found by using axial velocity cancellation on the vertical walls and by matching the modes at each discontinuity. The transmission and reflection coefficients of all five Helmholtz resonators are determined by combining the unit scattering matrices.

The results without flow are presented in Fig. 5. Without Kevlar, the agreement between the measurements and the calculations is quite good, although there is a small deviation at high frequency which must be due to the lack of consideration of viscous losses in the model. The presence of Kevlar was first modeled by a pure resistance and this gives the dash-dotted curve in the Fig. 5. In this case, the reduced impedance of Kevlar is purely real and equals $Z = 0.34$, where $Z = \Delta p/\rho_0 c_0 v$, Δp is the difference in sound pressure between the two faces of Kevlar, ρ_0 is the density of the air, c_0 is the speed of sound, and v is the acoustic velocity through Kevlar. The main effect of Kevlar is therefore the addition of a resistance. Beside this, a slight shift in frequency of the attenuation peak is observed and a better tuning is obtained when an inertial part is added to the impedance as $Z = 0.34 + \mathrm{i}\,0.075(f/f_R)$, where $f_R = 1250$ Hz is the resonance frequency of the resonator. However, our experimental device does not allow us to know if this added mass comes from a vibration of the Kevlar or from a contraction effect when the sound enters the Kevlar fabric openings.

The numerical results with flow are compared in Fig. 6 with the experimental results. An amplification ($|T| > 1$) at a frequency very close to the whistling frequency is predicted by the model. This amplification is very sensitive to the shape of the profile which is here defined by a number n such that $U = U_m(1 - (1 - y/H)^n)(n+1)/n$, where U_m is the mean velocity. In the present calculation, this number is equal to $n = 15$ and the profile is given in the inset in Fig. 6. As n increases, the flow boundary layer becomes thinner and the calculation becomes more unstable. In the presence of Kevlar, the computation correctly predicts the measurements when the

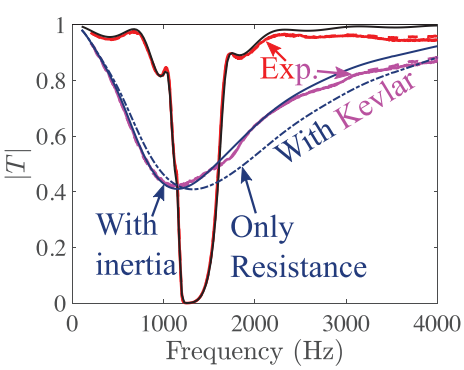

FIG. 5. (Color online) Transmission coefficients without flow ($M = 0$) with and without Kevlar as a function of the frequency. The experimental results are indicated in the figure, all the other curves are obtained with the multimodal method. For the results with Kevlar, the dash-dotted line is produced when $Z = 0.34$ (purely resistive case) and the continuous line when inertia is added: $Z = 0.34 + \mathrm{i}\,0.075(f/f_R)$, where $f_R = 1250$ Hz.

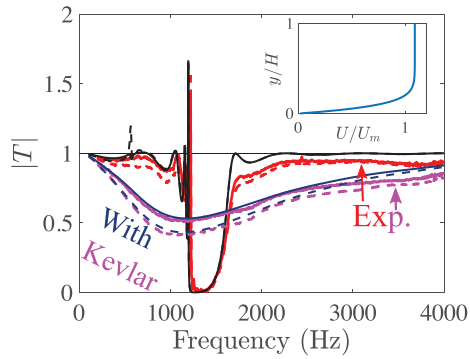

FIG. 6. (Color online) Transmission coefficients with flow $M = 0.073$ with and without Kevlar as a function of the frequency. The experimental results are indicated in the figure, all the other curves are obtained with the multimodal method. The continuous lines are in flow direction and the dashed lines are measured or computed against the flow. The multimodal method results with Kevlar are obtained with $Z = 0.42 + \mathrm{i}\,0.062(f/f_R)$, where $f_R = 1250$ Hz. The inset gives the flow profile used during the computation.

impedance is equal to $Z = 0.42 + \mathrm{i}\,0.062(f/f_R)$. It can be noticed that with flow, the resistance of Kevlar is slightly greater than without flow, and the added mass is smaller. The same observations have, for instance, already been made for perforated plates[22] or for a thin slow sound material.[5] The boundary layer instability that occurs in the neck of the resonator in the absence of Kevlar is completely removed by the addition of the resistive layer that Kevlar constitutes. In this sense, Kevlar allows much closer acoustic behavior with and without flow.

IV. CONCLUSION

The metamaterials must be protected from flow, otherwise extremely unpleasant interactions between acoustics and flow can occur. For the metamaterial studied in this paper, this is materialized by the appearance of a loud whistling sound in the vicinity of its resonance frequency. To avoid these undesirable effects, it would be good to have a "magic layer" that allows acoustics to pass through while suppressing sound-flow interactions in the vicinity of the material. A possible realization of this layer based on Kevlar fabric has been tested. Although reducing the effects of flow, this Kevlar layer is not acoustically neutral. It can be described by an acoustic resistance (associated with a low inertial effect). This resistance partly destroys the effect of the metamaterial on the sound when it is not accounted for in the design. Thus, Kevlar is not a magic layer.

Other realizations can be imagined (membranes, flexible beams with micro-slits, etc.) which overcome the effect of the flow, but which also allow taking advantage of the interactions between the flow and the deformable structures to have very original behaviors.

ACKNOWLEDGMENTS

This research was supported by the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No. 722401 ("SmartAnswer"[23]).

[1]G. Ma and P. Sheng, "Acoustic metamaterials: From local resonances to broad horizons," Sci. Adv. **2**(2), e1501595 (2016).
[2]S. A. Cummer, J. Christensen, and A. Alù, "Controlling sound with acoustic metamaterials," Nat. Rev. Mater. **1**(3), 16001 (2016).
[3]G. Palma, H. Mao, L. Burghignoli, P. Göransson, and U. Iemma, "Acoustic metamaterials in aeronautics," Appl. Sci. **8**(6), 971 (2018).
[4]T. Elnady, A. Elsabbagh, W. Akl, O. Mohamady, V. M. Garcia-Chocano, D. Torrent, F. Cervera, and J. Sánchez-Dehesa, "Quenching of acoustic bandgaps by flow noise," Appl. Phys. Lett. **94**(13), 134104 (2009).
[5]Y. Aurégan, M. Farooqui, and J.-P. Groby, "Low frequency sound attenuation in a flow duct using a thin slow sound material," J. Acoust. Soc. Am. **139**(5), EL149–EL153 (2016).
[6]X. Huang, S. Zhong, and O. Stalnov, "Analysis of scattering from an acoustic cloak in a moving fluid," J. Acoust. Soc. Am. **135**(5), 2571–2580 (2014).
[7]U. Iemma and G. Palma, "Convective correction of metafluid devices based on Taylor transformation," J. Sound Vib. **443**, 238–252 (2019).
[8]Y. He, S. Zhong, and X. Huang, "Extensions to the acoustic scattering analysis for cloaks in non-uniform mean flows," J. Acoust. Soc. Am. **146**(1), 41–49 (2019).
[9]Z. Ma, O. Stalnov, and X. Huang, "Design method for an acoustic cloak in flows by topology optimization," Acta Mech. Sin. **35**(5), 964–971 (2019).
[10]W. J. Devenport, R. A. Burdisso, A. Borgoltz, P. A. Ravetta, M. F. Barone, K. A. Brown, and M. A. Morton, "The Kevlar-walled anechoic wind tunnel," J. Sound Vib. **332**(17), 3971–3991 (2013).
[11]U. Ingard, *Notes on Acoustics* (Infinity Science Press, Hingham, MA, 2008).
[12]N. Sugimoto and T. Horioka, "Dispersion characteristics of sound waves in a tunnel with an array of Helmholtz resonators," J. Acoust. Soc. Am. **97**(3), 1446–1459 (1995).
[13]C. Cai and C. M. Mak, "Noise control zone for a periodic ducted Helmholtz resonator system," J. Acoust. Soc. Am. **140**(6), EL471–EL477 (2016).
[14]M. E. d'Elia, T. Humbert, Y. Auregan, and J. Golliard, "Optical measurements of the linear sound-flow interaction above a corrugated plate," in *25th AIAA/CEAS Aeroacoustics Conference* (2019), p. 2716.
[15]H. Schlichting, *Boundary Layer Theory*, 7th ed. (McGraw-Hill, New York, 1979).
[16]Y. Aurégan, M. Leroux, and V. Pagneux, "Measurement of liner impedance with flow by an inverse method," in *10th AIAA/CEAS Aeroacoustics Conference* (2004), p. 2838.
[17]S. Dequand, X. Luo, J. Willems, and A. Hirschberg, "Helmholtz-like resonator self-sustained oscillations, Part 1: Acoustical measurements and analytical models," AIAA J. **41**(3), 408–415 (2003).
[18]J. Kennedy, Trinity College, Dublin (private communication, 2019).
[19]X. Dai and Y. Aurégan, "Acoustic of a perforated liner with grazing flow: Floquet-bloch periodical approach versus impedance continuous approach," J. Acoust. Soc. Am. **140**(3), 2047–2055 (2016).
[20]X. Dai and Y. Aurégan, "Flexural instability and sound amplification of a membrane-cavity configuration in shear flow," J. Acoust. Soc. Am. **142**(4), 1934–1942 (2017).
[21]X. Dai and Y. Aurégan, "A cavity-by-cavity description of the aeroacoustic instability over a liner with a grazing flow," J. Fluid Mech. **852**, 126–145 (2018).
[22]A. Guess, "Calculation of perforated plate liner parameters from specified acoustic resistance and reactance," J. Sound Vib. **40**(1), 119–137 (1975).
[23]SmartAnswer, https://www.h2020-smartanswer.eu/ (2020) (Last viewed 11/16/2020).