Investigation of damping effects on low-frequency steady-state acoustical behaviour of coupled spaces

Mirosław Meissner and Krzysztof Wiśniewski

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Final acceptance: 20 July 2020

Note: Reports are unedited and appear as submitted by the referee. The review history appears in chronological order.

Review History
RSOS-200514.R0 (Original submission)

Review form: Reviewer 1

Is the manuscript scientifically sound in its present form?
Yes

Are the interpretations and conclusions justified by the results?
Yes

Is the language acceptable?
Yes

Do you have any ethical concerns with this paper?
No

Have you any concerns about statistical analyses in this paper?
No

Recommendation?
Accept with minor revision (please list in comments)
Comments to the Author(s)
The authors have stated that "The way to reduce the value of the parameter D is to increase the sound attenuation inside the coupled spaces. This is due to the fact that with increased sound damping, the energy of the acoustic modes is physically attenuated, reducing the point-to-point variations in the a sound pressure level." This explanation is not correct. Because the authors' standard deviation is calculated using decibel values, changing the modal energy will not change D. The reduction in D with increasing sound absorption is due to the increase in modal bandwidth which increases the modal overlap. The increased modal overlap means that more modes are excited at a given frequency and this reduces the spatial standard deviation of the sound pressure level in the room (D). The increase of modal bandwidth with increasing sound absorption also explains why the variation of D with frequency becomes slower as the sound absorption is increased.

The authors’ use of a sound source position that is equidistant (1 m) from the floor and two of walls will create an unusual situation. The authors should repeat their calculations with the distances of the source chosen so that they are not in the ratio of small integers to each other.

Review form: Reviewer 2

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3. There is a English usage error on line 43 of page 3.

4. In the Fig 10 caption, Hz is repeated unnecessarily in two places.
We hope you are keeping well at this difficult and unusual time. We continue to value your support of the journal in these challenging circumstances. If Royal Society Open Science can assist you at all, please don't hesitate to let us know at the email address below.

Dear Professor Meissner,

On behalf of the Editors, I am pleased to inform you that your Manuscript RSOS-200514 entitled "Investigation of damping effects on low-frequency steady-state acoustical behaviour of coupled spaces" has been accepted for publication in Royal Society Open Science subject to minor revision in accordance with the referee suggestions. Please find the referees' comments at the end of this email.

The reviewers and handling editors have recommended publication, but also suggest some minor revisions to your manuscript. Therefore, I invite you to respond to the comments and revise your manuscript.

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If your study uses humans or animals please include details of the ethical approval received, including the name of the committee that granted approval. For human studies please also detail whether informed consent was obtained. For field studies on animals please include details of all permissions, licences and/or approvals granted to carry out the fieldwork.

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It is a condition of publication that all supporting data are made available either as supplementary information or preferably in a suitable permanent repository. The data accessibility section should state where the article's supporting data can be accessed. This section should also include details, where possible of where to access other relevant research materials such as statistical tools, protocols, software etc can be accessed. If the data has been deposited in an external repository this section should list the database, accession number and link to the DOI for all data from the article that has been made publicly available. Data sets that have been deposited in an external repository and have a DOI should also be appropriately cited in the manuscript and included in the reference list.

If you wish to submit your supporting data or code to Dryad (http://datadryad.org/), or modify your current submission to dryad, please use the following link:
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• Competing interests
Please declare any financial or non-financial competing interests, or state that you have no competing interests.

• Authors’ contributions
All submissions, other than those with a single author, must include an Authors’ Contributions section which individually lists the specific contribution of each author. The list of Authors should meet all of the following criteria; 1) substantial contributions to conception and design, or acquisition of data, or analysis and interpretation of data; 2) drafting the article or revising it critically for important intellectual content; and 3) final approval of the version to be published.

All contributors who do not meet all of these criteria should be included in the acknowledgements.

We suggest the following format:
AB carried out the molecular lab work, participated in data analysis, carried out sequence alignments, participated in the design of the study and drafted the manuscript; CD carried out the statistical analyses; EF collected field data; GH conceived of the study, designed the study, coordinated the study and helped draft the manuscript. All authors gave final approval for publication.

- Acknowledgements
Please acknowledge anyone who contributed to the study but did not meet the authorship criteria.

- Funding statement
Please list the source of funding for each author.

Please ensure you have prepared your revision in accordance with the guidance at https://royalsociety.org/journals-authors-author-guidelines/ -- please note that we cannot publish your manuscript without the end statements. We have included a screenshot example of the end statements for reference. If you feel that a given heading is not relevant to your paper, please nevertheless include the heading and explicitly state that it is not relevant to your work.

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When submitting your revised manuscript, you will be able to respond to the comments made by the referees and upload a file "Response to Referees" in "Section 6 - File Upload". You can use this to document any changes you make to the original manuscript. In order to expedite the processing of the revised manuscript, please be as specific as possible in your response to the referees. We strongly recommend uploading two versions of your revised manuscript:

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3) Included a 100 word media summary of your paper when requested at submission. Please ensure you have entered correct contact details (email, institution and telephone) in your user account;
4) Included the raw data to support the claims made in your paper. You can either include your data as electronic supplementary material or upload to a repository and include the relevant doi within your manuscript. Make sure it is clear in your data accessibility statement how the data can be accessed;
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Once again, thank you for submitting your manuscript to Royal Society Open Science and I look forward to receiving your revision. If you have any questions at all, please do not hesitate to get in touch.

Best regards,

Lianne Parkhouse
Editorial Coordinator
Royal Society Open Science
openscience@royalsociety.org

on behalf of Dr Philip Benson (Associate Editor) and R. Kerry Rowe (Subject Editor)
openscience@royalsociety.org

Reviewer comments to Author:

Reviewer: 1
Comments to the Author(s)

The authors have stated that "The way to reduce the value of the parameter D is to increase the sound attenuation inside the coupled spaces. This is due to the fact that with increased sound damping, the energy of the acoustic modes is physically attenuated, reducing the point-to-point variations in the a sound pressure level." This explanation is not correct. Because the authors' standard deviation is calculated using decibel values, changing the modal energy will not change D. The reduction in D with increasing sound absorption is due to the increase in modal bandwidth which increases the modal overlap. The increased modal overlap means that more modes are excited at a given frequency and this reduces the spatial standard deviation of the sound pressure level in the room (D). The increase of modal bandwidth with increasing sound absorption also explains why the variation of D with frequency becomes slower as the sound absorption is increased.

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Reviewer: 2
Comments to the Author(s)

This is a nicely presented paper. Well done! I have four minor comments:

1. I would suggest including some practical reasons why spatial variation of pressure fields may be an important metric in the design of acoustic enclosures.

2. The authors should check their use of "specific acoustic impedance" to describe their parameter zeta. Specific acoustic impedance is defined as pressure/velocity and is given by $Z=\rho c^2 \zeta$. Zeta is simply a convenient non-dimensional ratio of specific acoustic impedance to the characteristic impedance of the fluid.

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Author's Response to Decision Letter for (RSOS-200514.R0)

See Appendix A.

Decision letter (RSOS-200514.R1)

We hope you are keeping well at this difficult and unusual time. We continue to value your support of the journal in these challenging circumstances. If Royal Society Open Science can assist you at all, please don't hesitate to let us know at the email address below.

Dear Professor Meissner,

It is a pleasure to accept your manuscript entitled "Investigation of damping effects on low-frequency steady-state acoustical behaviour of coupled spaces" in its current form for publication in Royal Society Open Science. The comments of the reviewer(s) who reviewed your manuscript are included at the foot of this letter.

Please ensure that you send to the editorial office an editable version of your accepted manuscript, and individual files for each figure and table included in your manuscript. You can send these in a zip folder if more convenient. Failure to provide these files may delay the processing of your proof. You may disregard this request if you have already provided these files to the editorial office.

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Thank you for your fine contribution. On behalf of the Editors of Royal Society Open Science, we look forward to your continued contributions to the Journal.

Kind regards,
Anita Kristiansen
Editorial Coordinator

Royal Society Open Science
openscience@royalsociety.org

on behalf of Dr Philip Benson (Associate Editor) and R. Kerry Rowe (Subject Editor)
openscience@royalsociety.org

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Article title: Investigation of damping effects on low-frequency steady-state acoustical behaviour of coupled spaces

Authors: Miroslaw Meissner, Krzysztof Wisińiewski

Manuscript ID: RSOS-200514

We are thankful for the reviewer’s comments that helped to improve and clarify the manuscript. We hope that its revised version answers reviewer’s concerns. In the following we give detailed replies to the comments (in order of occurrence). The reviewer’s comments are reproduced for clarity. Changes in the manuscript corresponding to these comments were indicated by a blue color.

Comment 1

The authors have stated that "The way to reduce the value of the parameter D is to increase the sound attenuation inside the coupled spaces. This is due to the fact that with increased sound damping, the energy of the acoustic modes is physically attenuated, reducing the point-to-point variations in the a sound pressure level." This explanation is not correct. Because the authors' standard deviation is calculated using decibel values, changing the modal energy will not change D. The reduction in D with increasing sound absorption is due to the increase in modal bandwidth which increases the modal overlap. The increased modal overlap means that more modes are excited at a given frequency and this reduces the spatial standard deviation of the sound pressure level in the room (D). The increase of modal bandwidth with increasing sound absorption also explains why the variation of D with frequency becomes slower as the sound absorption is increased.

Response

Of course, the reviewer is right that this part of the paper is unclear. Therefore, in a revised version of the paper this part was replaced by:

“The way to reduce intense peaks of D is to increase the sound attenuation inside the coupled spaces. This is due to the fact that with increased sound damping, the energy of strongly localized mode is physically attenuated. Consequently, neighboring modes have a much greater impact on a distribution of a sound field for a frequency of localized mode, resulting in a reduction of point-to-point variations in a sound pressure level”.

Such a behaviour of a sound field is illustrated in the figure I below. It shows distributions of the sound pressure amplitude P on the observation plane z = 1.6 m for the source frequency of 119.6 Hz corresponding to the frequency of strongly localized mode (figures. 5, 6 and table 1 in the paper). For walls nearly hard acoustically (α = 10^{-4}), a distribution of the amplitude P reproduces exactly a modulus of the eigenfunction ϕ_{nm}(r) for this mode because for very small sound damping

\[ P(r) = \left( \sum_{m=1}^{\infty} a_m \phi_m(r)^2 \right)^{1/2} \left( \sum_{m=1}^{\infty} b_m \phi_m(r)^2 \right)^{1/2} \simeq \left( a_n^2 + b_n^2 \right)^{1/2} |\phi_n(r)|, \]  

(A1)

when \( \omega = \omega_n \). If value of \( \alpha \) increases to 10^{-3}, there is a significant decrease in P which is equivalent to reducing the sound pressure level by approximately 32 dB. This is due to energy suppression of the strongly localized mode. When mode energy drops significantly, equation (A1) is not satisfied.
because the first term on the right-hand side of this equation is so small that neighboring modes are starting to contribute in creating a sound field. This is reflected in a modification of the pressure amplitude distribution [figure I(b)]. A further increase in $\alpha$ causes visible changes in this distribution [figure I(c)], however, for values of $\alpha$ changing from 0.1 to 0.3 a relative stabilization of both pressure amplitude and its distribution is observed [figure I(d), (e), (f)].

![Figure I: Distribution of the sound pressure amplitude $P$ on the observation plane $z = 1.6$ m for the source frequency of 119.6 Hz and the absorption coefficient $\alpha$ equal to: (a) $10^{-4}$, (b) $10^{-3}$, (c) 0.01, (d) 0.1, (e) 0.2, (f) 0.3.](image)

**Comment 2**

The authors' use of a sound source position that is equidistant (1 m) from the floor and two of walls will create an unusual situation. The authors should repeat their calculations with the distances of the source chosen so that they are not in the ratio of small integers to each other.

**Response**

Calculations of the mean spatial deviation $D$ were repeated for a sound source located at the point: (8.9 m, 4.1 m, 1.2 m), so the distances from the source to the floor and room walls are not in the ratio of small integers to each other. Calculation results are shown in figures II–V and these data are equivalent to the results in figures 5 and 7–9 in the paper, obtained for the source located at the point: (9 m, 4 m, 1 m). Since there is a significant similarity of calculation results for both source positions, similar observations can be made and similar conclusions can be drawn for the newly selected source position, as in the case of the previously chosen source position.
Figure II: Frequency dependence of the mean spatial deviation $D$ for the absorption coefficient $\alpha$ of $10^{-4}$. Numbered peaks occur at frequencies: 60.68 Hz, 119.6 Hz and 165.03 Hz. Sound source located at the point: (8.9 m, 4.1 m, 1.2 m).

Figure III: Frequency dependence of the mean spatial deviation $D$ for the absorption coefficient $\alpha$ equal to: (a) 0.01, (b) 0.1. Sound source located at the point: (8.9 m, 4.1 m, 1.2 m).
Figure IV: Changes in $D_{\text{max}}$, $D_{\text{min}}$, and $D_{\text{avg}}$ with the absorption coefficient $\alpha$. Colored dots indicate calculation results. Sound source located at the point: (8.9 m, 4.1 m, 1.2 m).

Figure V: Frequency dependence of the mean spatial deviation $D$ for the absorption coefficient $\alpha$ equal to: (a) 0.25, (b) 0.35. Numbered peaks occur at frequencies: 37.97 Hz, 69.94 Hz, 108.7 Hz and 134.47 Hz. Sound source located at the point: (8.9 m, 4.1 m, 1.2 m).
**Responses to comments of Reviewer 2**

**Article title:** Investigation of damping effects on low-frequency steady-state acoustical behaviour of coupled spaces

**Authors:** Mirosław Meissner, Krzysztof Wiśniewski

**Manuscript ID:** RSOS-200514

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**Comment 1**
I would suggest including some practical reasons why spatial variation of pressure fields may be an important metric in the design of acoustic enclosures.

**Response**
To emphasize practical possibilities of using the proposed method, in Section 5 the text was added:

“A spatial irregularity of a sound field occurs in small rooms because at low frequencies room acoustic quality is strongly influenced by excited room modes. This irregularity can give rise to highly position-sensitive acoustical responses that significantly limit a correct perception of speech and music. Therefore, the proposed theoretical method can be applied in the design or acoustic treatment of small rooms such as performance studios, studio control rooms, listening rooms, audio program assessment rooms and small conference and lecture rooms where speech, music or listening is part of normal use”.

**Comment 2**
The authors should check their use of "specific acoustic impedance" to describe their parameter zeta. Specific acoustic impedance is defined as pressure/velocity and is given by $Z=\rho c\zeta$. Zeta is simply a convenient non-dimensional ratio of specific acoustic impedance to the characteristic impedance of the fluid.

**Response**
According to the reviewer’s comment, in a revised version of the paper the term “specific acoustic impedance” was changed to the term “normalized impedance” which has been used, for example, in the work: M. Aretz, P. Dietrich, M. Vorländer, “Application of the mirror source method for low frequency sound prediction in rectangular rooms”, *Acta Acust. Acust.*, 100(2), 306–319, 2014. We called the quantity $\zeta = Z/\rho c$ as “specific acoustic impedance” according to the nomenclature used by Kuttruff (see page 37 from H. Kuttruff, “Room acoustics”, 4th ed.), but now it seems to us that more appropriate terms are “normalized impedance” or “impedance ratio”.

**Comment 3**
There is an English usage error on line 43 of page 3

**Response**
We made changes to the text on page 3 in line 43, although we are not sure if such changes were expected by the reviewer.
is defined by

\[ Z = \left( \frac{p}{v_n} \right)_{\text{surface}} \]  \hspace{1cm} (2.2)

where \( v_n \) denotes the velocity component normal to the wall. For non-porous walls which are excited into vibration by the sound field, the normal component of the particle velocity is identical to the velocity of the wall vibration. Like the reflection factor, the wall impedance is generally complex and a function of the angle of sound incidence.

Frequently the 'specific acoustic impedance' is used, which is the wall impedance divided by the characteristic impedance of the air:

\[ \zeta = \frac{Z}{\rho_0 c} \]  \hspace{1cm} (2.2a)

The reciprocal of the wall impedance is the 'wall admittance'; the reciprocal of \( \zeta \) is called the 'specific acoustic admittance' of the wall.

As explained in Section 1.2 any complex quantity can be represented in a rectangular coordinate system (see Fig. 1.2). This holds also for the wall impedance. In this case, the length of that arrow corresponds to the magnitude of \( Z \) while its inclination angle is the phase angle of the wall impedance:

\[ \mu = \arg(Z) = \arctan \left( \frac{\text{Im} Z}{\text{Re} Z} \right) \]  \hspace{1cm} (2.3)

If the frequency changes, the impedance will usually change as well and also the length and inclination of the arrow representing it. The curve connecting the tips of all arrows is called the 'locus of the impedance in the complex plane'. A simple example of such a curve is shown in Fig. 2.9a.

### 2.2 Sound reflection at normal incidence

First we assume the wall to be normal to the direction in which the incident wave is travelling, which is chosen as the \( x \)-axis of a rectangular coordinate system. The wall intersects the \( x \)-axis at \( x = 0 \) (Fig. 2.1). The wave is coming from the left and its sound pressure is

\[ p_i(x, t) = \hat{p}_0 \exp \left[ i(\omega t - kx) \right] \]  \hspace{1cm} (2.4a)

The particle velocity in the incident wave is according to eqn (1.9):

\[ v_i(x, t) = \frac{\hat{p}_0}{\rho_0 c} \exp \left[ i(\omega t - kx) \right] \]  \hspace{1cm} (2.4b)