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Influence of inhomogeneous damping distribution on sound radiation properties of complex vibration modes in rectangular plates

Oliver Unruh [a,b,*]

[a] German Aerospace Center (DLR), Institute of Composite Structures and Adaptive Systems, Lilienthalplatz 7, 38108 Braunschweig, Germany
[b] Technische Universitaet Braunschweig, Institute of Adaptronic and Functional Integration, Langer Kamp 6, 38106 Braunschweig, Germany

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ABSTRACT

In order to reduce noise emitted by vibrating structures additional damping treatments such as constraint layer damping or embedded elastomer layers can be used. To save weight and cost, the additional damping is often placed at some critical locations of the structure, what leads to spatially inhomogeneous distribution of damping. This inhomogeneous distribution of structural damping leads to an occurrence of complex vibration modes, which are no longer dominated by pure standing waves, but by a superposition of travelling and standing waves. The existence of complex vibration modes raises the question about their influence on sound radiation.

Previous studies on the sound radiation of complex modes of rectangular plates reveal, that, depending on the direction of travelling waves, the radiation efficiency of structural modes can slightly decrease or significantly increase. These observations have been made using a rectangular plate with a simple inhomogeneous damping configuration which includes a single plate boundary with a higher structural damping ratio. In order to answer the question about the influence of other possible damping configurations on the sound radiation properties, this paper addresses the self- and mutual-radiation efficiencies of the resulting complex vibration modes. Numerical simulations are used for the calculation of complex structural modes of different inhomogeneous damping configurations with varying geometrical form and symmetry. The evaluation of self- and mutual-radiation efficiencies reveals that primarily the symmetry properties of the inhomogeneous damping distribution affect the sound radiation characteristics. Especially the asymmetric distributions of inhomogeneous damping show a high influence on the investigated acoustic metrics. The presented study also reveals that the acoustic cross-coupling between structural modes, which is described by the mutual-radiation efficiencies, generally increases with the presence of travelling waves.

* Correspondence address: German Aerospace Center (DLR), Insitute of Composite Structures and Adaptive Systems, Lilienthalplatz 7, 38108 Braunschweig, Germany.
E-mail address: oliver.unruh@dlr.de

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1. Introduction

The reduction of structural weight is one of the key goals on the way to environmentally friendly and cost efficient transportation. It is well known that there is a contradiction between a consequent structural lightweight design and noise and vibration requirements. Due to the lower mass and higher stiffness, high performance lightweight structures such as carbon fibre reinforced plastics (CFRP) exhibit increased vibration amplitudes and noise levels. A possible solution is the application of additional damping treatments such as constraint layer damping (CLD) or embedded elastomer layers, which increases dissipation rates of vibration energy and improve vibro acoustic behaviour of the structure [1,2]. In order to save weight and cost, the placement of these damping treatments can be derived from an optimisation process, which is based on the modal strain energy [3] or structural intensity [4] consideration. The optimisation leads to a very local application of damping treatments, focussed on some critical locations of the vibrating structure [5–7]. In this case the spatial distribution of structural damping becomes inhomogeneous and it leads to an occurrence of complex vibration modes. Compared to real modes, complex modes are no longer dominated by pure standing waves but by a superposition of travelling and standing waves [8].

The influence of homogeneous damping on the sound radiation of vibrating plates is discussed by Xie et al. [9] or Fahy and Gardonio [10]. With increasing homogeneous damping the radiation efficiency of the plate also increases in the frequency range of edge and corner radiators. This occurs due to a strong coupling of neighbouring resonances with resulting piston-like vibration shapes and reduced acoustic short circuit phenomena.

Wodtke and Lamancusa [11] investigated the influence of inhomogeneous damping distribution and stated that it has a structural (loss factors) and an acoustic effect (radiation efficiency) on sound radiation. In this study modified vibration shapes, that occur due to inhomogeneous damping distribution, are mentioned as a reason for changes in radiation efficiency. Nevertheless, complex vibration modes with travelling wave components are not investigated here. Marburg [12] considered complex normal modes of a fluid in external acoustics using an example of an open cavity. Torres et al. [13] observed complex vibration modes in a top plate of a classic guitar. This is one of the very few publications that link the structural dynamic behaviour of complex vibration modes to the sound radiation. However, this study is focussed only on the methodology of recognising complex modes using frequency response functions calculated by the FE simulation. The acoustic relevance of complex vibration modes, and their influence on the radiation characteristics of the guitar is not investigated in this work.

Consideration of complex vibration modes regarding their acoustic properties is addressed in some recent publications by Unruh et al. [14,15]. In these studies, the acoustic metrics, such as self-radiation efficiency, spatial distribution of acoustic intensity and directivity of the radiated sound field are investigated and it is shown that travelling wave components of complex vibration modes can significantly influence the sound radiation of rectangular plates. Both publications investigate the case, where bending waves travel along one dominant direction of the plate. This configuration of travelling waves occurs, when one of the plates boundaries features an increased structural damping. In [14] it is shown that structural modes with even order in the main direction of travelling waves significantly increase their radiation efficiency below the coincidence frequency, due to a better coupling in the first radiation mode. In the case of structural modes with odd order, this coupling slightly decreases, which results in a lower radiation efficiency. The coupling in the first radiation mode correlates to the volume velocity of the mode shape, which is zero for real modes of even–even or even–odd order. For example, when an even–odd order mode is affected by travelling waves in the direction of the even order, the volume velocity becomes non-zero and the coupling in the first radiation mode increases.

The presence of inhomogeneous damping in plates not only leads to an occurrence of travelling waves but also to the redistribution of the vibration maxima and minima, which can affect the sound radiation. In order to separate these two mechanisms, a simplified analytical model is introduced in [15]. This model allows the calculation of complex vibration patterns with a variable amount of travelling waves without amplitude redistribution. The results show that this redistribution has a minor importance for the acoustic metrics and the presence of travelling waves dominates the sound radiation phenomena.

As it has already been mentioned, these two initial studies only address a simple case, where bending waves travel along one dominant direction of the vibrating plate. This simple approach is suitable for the basic understanding of the phenomena, which affects the sound radiation of complex vibration modes. Nevertheless, in real applications the spatial distribution of inhomogeneous damping and accordingly the configuration of travelling bending waves can be much more complicated.

For this reason, the present paper addresses the important question about the influence of other possible distributions of inhomogeneous damping on the acoustic properties of complex vibration modes. The presented research is focussed on the identification of relevant geometrical properties of additional damping, which influence the sound radiation.

The first part of the paper describes some basic damping configurations, which can be probably found in real applications. Therefore, the geometrical forms as well as symmetry properties of additional damping are varied. In the next part, the resulting complex vibration modes are characterised regarding their self-radiation efficiency using the elemental radiator approach [10]. This allows the identification of damping configuration with the biggest impact on sound radiation, which are investigated in more detail. The self-radiation efficiencies of complex vibration modes are considered and it is shown how the geometrical properties of additional damping determine the influence on sound radiation below the