Structural intensity research at TU Darmstadt

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Introduction

The first papers on structural intensity (STI), which describes the magnitude and the direction of the vibratory energy flow in solid structures, were published in the 1970s (e.g., [1, 2]). In the following years various methods to experimentally measure (e.g., [3, 4]) or to numerically calculate the structural intensity (e.g., [5]) were developed and published. But only in recent years has this method been used to analyze "real life" noise and vibration problems, particularly in automotive applications, due to improved measurement techniques (e.g., [6]) and increased computing power (e.g., [7]). A quite comprehensive overview of structure borne sound energy was published by Maysenhölder [8].

This paper gives an overview of the structural intensity research activities of the research group "System Reliability, Adaptive Structures, and Machine Acoustics SAM" at Technische Universität (TU) Darmstadt, Germany, and its predecessors, starting in the 1990s and still ongoing at the present time. For this purpose, the PhD dissertations by Peter Meudt (1998), Marcus Stein (2005), Steffen Kuhl (2010), Thorsten Hering (2012), Sebastian Buckert (2013), and Torsten Stoewer (2015) will be summarized. In addition recent developments and future research activities will be presented.

PhD thesis by Peter Meudt (1998)

In his PhD dissertation [9] Peter Meudt describes various STI measurements using accelerometers. He compared measurement results using the 2-sensor method and the 8-sensor method and systematically investigated the capabilities of these two methods and of the errors associated with them. He also performed finite element (FE) calculations and compared their results with the results of analytic calculations. Furthermore, he compared his experimental results with numerical results for rectangular plates (see Fig. 1) and a box-shaped steel structure and found a good agreement. He also came up with some suggestions and approaches for potential design modifications. For this purpose he analyzed the effect of stiffening ribs, additional damping, and steps on the STI (see Fig. 2). As a final application example he investigated the effect of various mounting conditions of an electric motor on the STI (see Fig. 3).

PhD thesis by Marcus Stein (2005)

Based on Peter Meudt's results Marcus Stein [10] further explored the concept of using the STI to guide the vibratory energy in solid structures. The idea is to bundle vibratory energy in sensitive areas and transfer it to areas less sensitive to sound radiation. He performed FE simulations of in-plane waves and observed their conversion into flexural waves at abutting edges. He also used a combination of structure borne sound-guiding design elements (see Fig. 4) and viscous dampers as an effective means to steer the vibratory energy in a structure towards or away from certain sensitive areas. His final application example is the housing of a walkie-talkie (see Fig. 5).

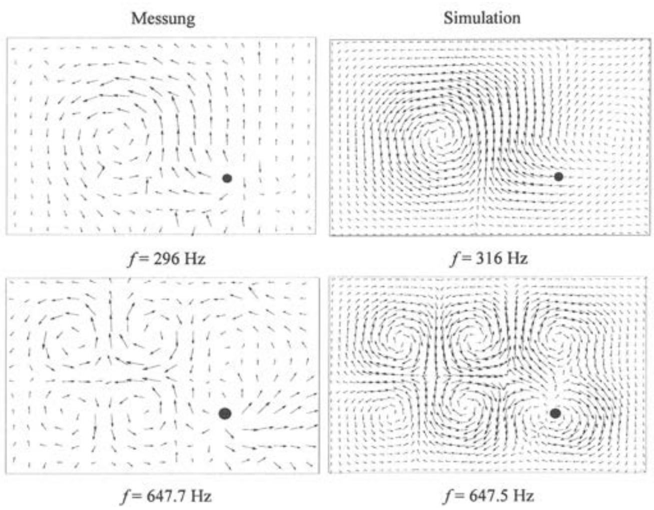

Figure 1: Comparison between STI measurement results (left) and numerical simulation results (right) for a simply supported rectangular plate for various frequencies (from [9]).

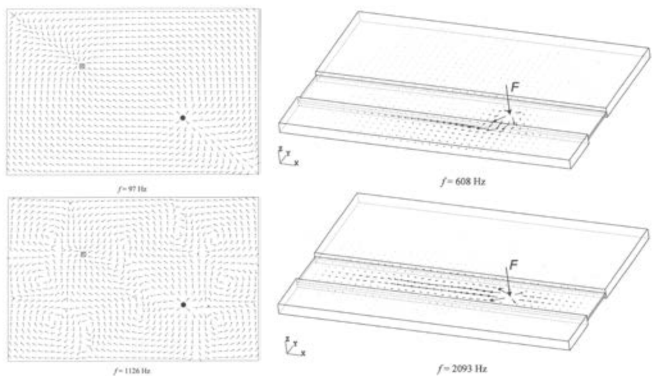

Figure 2: Effect of additional damping, marked by an open circle, (left) and of a step in a plate (right) on the STI for various frequencies (from [9]).

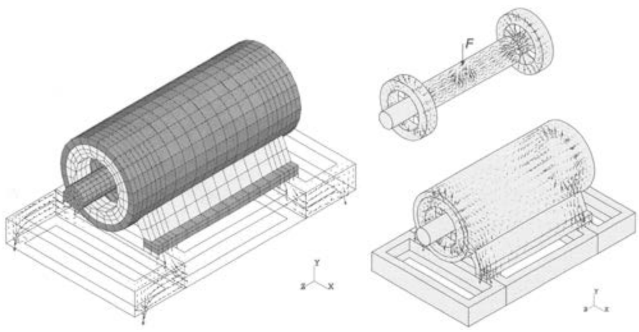

Figure 3: STI of an electric motor attached to a frame structure without (left) and with elastic mounts (spring-damper combination) (right) (from [9]).

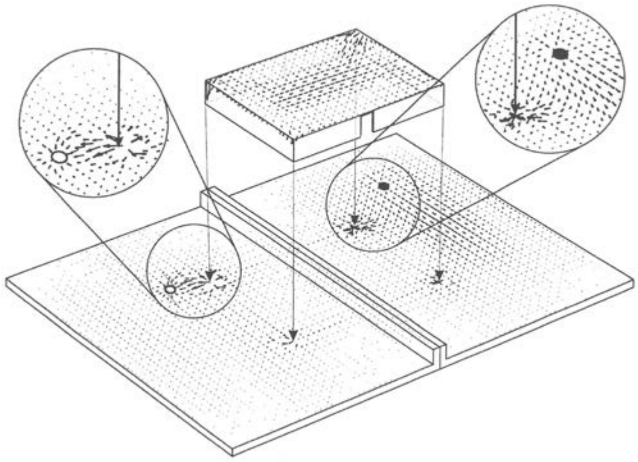

Figure 4: An additional sheet metal part is used to transfer the vibratory energy from the point of excitation on the right part of the structure (black dot) to the damper on the left part of the structure (open circle) (from [10]).

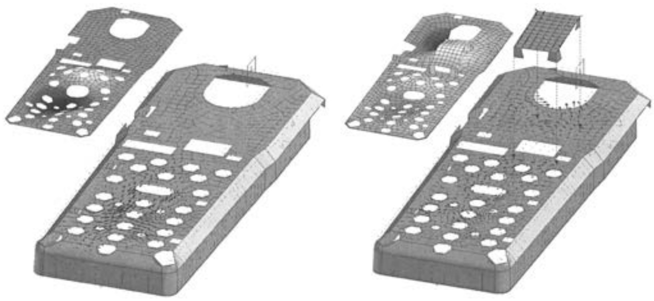

Figure 5: STI in the housing of a walkie-talkie: original state (left) and modified state with an additional part used to guide the vibratory energy (right) (from [10]).

PhD thesis by Steffen Kuhl (2010)

Steffen Kuhl [11] investigated the effects of design changes on the vibratory energy paths in plates and in a test structure made of a hollow profile and a sheet metal plate. He performed both experiments and numerical simulations and compared their results. He modified an established measurement method (i.e., the 2-sensor method) to reduce time and effort by using a scanning laser vibrometer instead of accelerometers. He identified those areas of a structure that contribute most to the vibratory energy transfer, applied design changes, and experimentally validated these design modifications. An example can be seen in Figs. 6 and 7 where he attached an additional tuned sheet metal part with a damping layer to the test structure (Fig. 6 right), which in turn radiated less sound (Fig. 7 right, compared to Fig. 7 left).

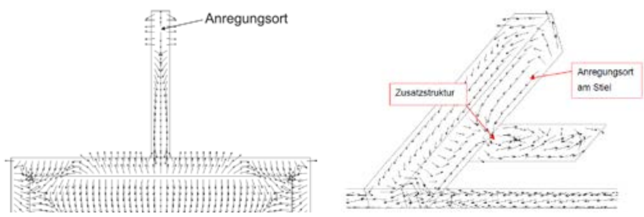

Figure 6: STI in the test structure before (left) and after (right) attaching an additional damped sheet metal part that absorbs most of the vibratory energy (from [11]).

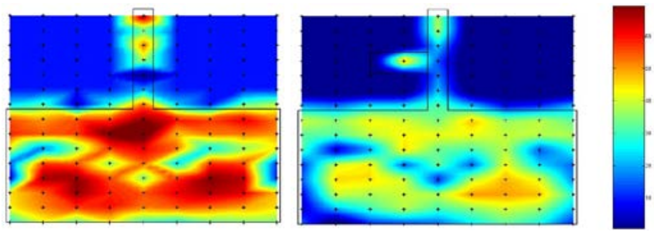

Figure 7: Effect of the additional damped sheet metal part on the radiated airborne sound intensity: left: without, right: with additional sheet metal part (from [11]).

PhD thesis by Thorsten Hering (2012)

Thorsten Hering [12] first analyzed the convergence of the numerical STI simulation using modal superposition. He then proved that the STI in thickness direction is indeed negligible (< 1%) for thin plate structures. He further showed that the time-averaged STI in the time domain represents a steady state and equals the STI in the frequency domain after 100 to 200 periods for qualitative results and after 1000 periods for quantitative results. For structures with geometric discontinuities such as steps or beads (e.g., an oil pan or a car floor panel) up to 90% of the vibratory energy is transported by means of in-plane waves (see Fig. 8). By placing a relatively small additional mass (impedance mismatch) at a location with high in-plane STI values (see Fig. 9) it is possible to reduce the surface velocity by an order of magnitude (see Fig. 10). This was confirmed by experiments.

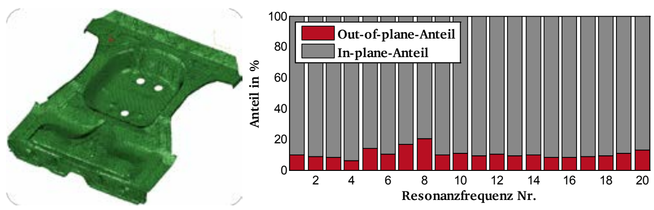

Figure 8: In a passenger car trunk floor panel (left) about 90% of the vibratory energy is transported by means of in-plane waves (right) due to the many steps, beads, and other geometric discontinuities (from [12]).

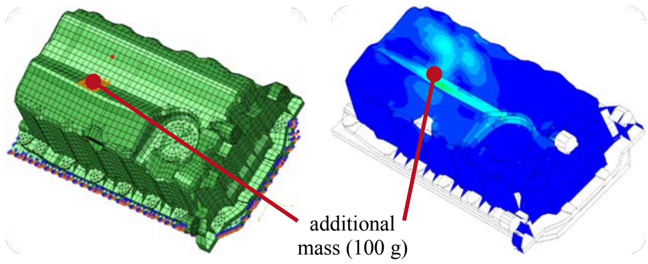

Figure 9: A small additional mass (100 g) is applied to a passenger car oil pan with a mass of 5.5 kg (left) at the location of the largest in-plane STI values (right) (from [12]).

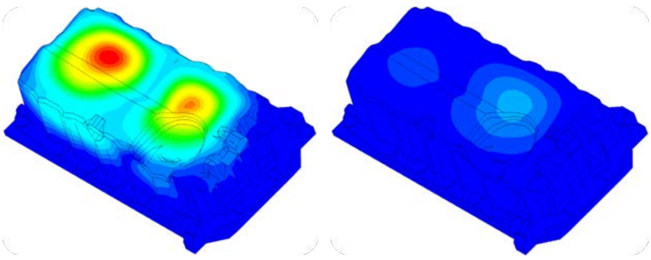

Figure 10: Surface velocity without (left) and with additional mass (right), reduced by an order of magnitude as a result of the reduced STI (from [12]).

PhD thesis by Sebastian Buckert (2013)

Sebastian Buckert [13] compared various STI measurement methods such as the 2-sensor and the 8-sensor method, the 2D Fourier transform, the gradient method, and the CDS method by means of Monte Carlo simulations of various FE discretizations and frequencies. He found out that the phase error is critical for STI measurements and came up with a method to filter the measurement data by means of a spatial averaging scheme that significantly improves the results (see Fig. 11). Both in numerical simulations and in experiments he used measured STI values as the error signal for an active vibration control system. In both cases the STI error signal performed better than a conventional accelerometer error signal (28.2 dB surface velocity reduction at 76 Hz using the measured STI compared to only 22.5 dB velocity reduction using an accelerometer signal).

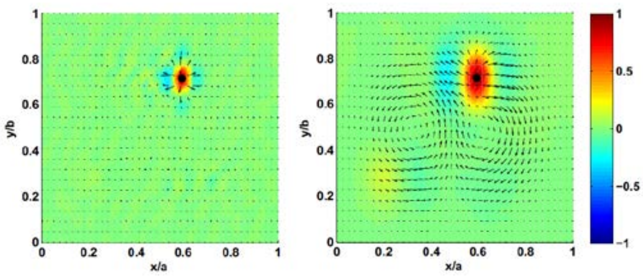

Figure 11: STI calculated from measured data without (left) and with a spatially averaging filter (right): improved results (from [13]).

PhD thesis by Torsten Stoewer (2015)

The currently latest PhD thesis in this series of PhD theses on the STI was published by Torsten Stoewer [14]. He compared numerical and experimental results as well and performed numerical simulations in the time-domain for various design modifications (see Fig. 12).

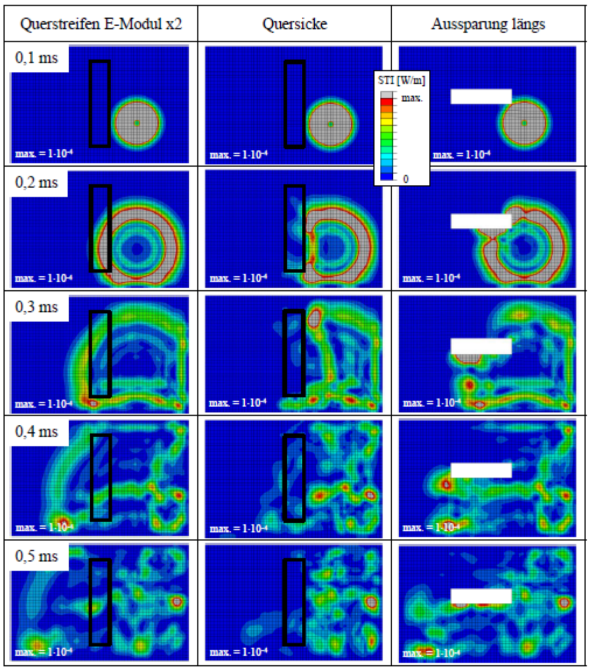

Figure 12: STI calculations in the time domain for various design modifications (from left to right: increased Young's modulus, bead, and rectangular opening) (from [14]).

He significantly reduced the surface displacement of a car floor panel (by a factor of 66) by fixing just two nodes on the other side of the transmission tunnel by choosing the location of these two nodes based on high in-plane STI values (see Fig. 13).

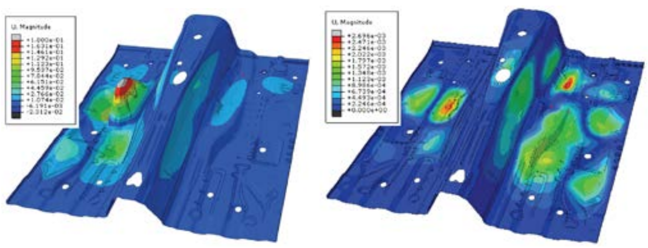

Figure 13: Original displacement of a car floor panel (left) and displacement reduced by a factor of 66 (right) due to only two fixed nodes on the right-hand side of the panel based on STI calculations (from [14]).

Furthermore, he calculated the STI for a concept model and for a refined model of a car's body in white both in the frequency and in the time domain (see Fig. 14).

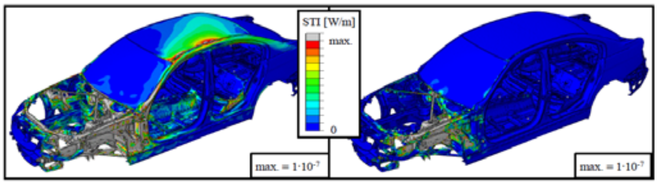

Figure 14: In-plane (left) and out-of-plane components of the STI (right) in the time domain after 1.5 ms in a refined model of a car's body in white (from [14]).

Finally, he also performed STI simulations for anisotropic material, i.e., a vehicle structure made of fiber-reinforced composite with two different fiber orientation angles.

Recent activities and future work

The research group SAM recently also used STI simulations to reduce the equivalent radiated power of an electric motor [15]. Schaal [16] investigated the relation between structural intensity-based scalars and sound radiation. The energy exchange between coupled subsystems is analyzed by means of the divergence of the STI in [17]. Adams [18] presents a benchmark case for structural intensity calculations that will be included in the EAA benchmark cases for computational acoustics [19].

Just very recently the research group SAM received funding from the German National Research Foundation DFG for the purchase of a 3D laser vibrometer system. We also received funding for a DFG research project called "Development and validation of a generally valid measurement method for determining the structural intensity based on 3D laser vibrometer measurements". Both grants ensure that we will be able to continue our research on the STI. The authors of this paper and the entire research group SAM gratefully acknowledge this generous funding.

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