



Fantastic Vibroacoustic Resources and Where to Find Them

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ABSTRACT

The internet is full of fantastic vibroacoustic resources. In this paper I provide descriptions and links to teaching websites, reports, articles, and software that any vibroacoustician would find useful. Articles and reports include: Eric Ungar's humorous and insightful series *Acoustics from A to Z*, Arthur Leissa's classic compendia of mode shapes and frequencies for plates and shells, Pete Avitable's cartoons and short articles on the basics of Experimental Modal Analysis (EMA), classic Statistical Energy Analysis (SEA) references, general guidance on vibroacoustic analysis of space structures from the European Space Agency, and many others. ISVR and Penn State host outstanding teaching sites full of animations of vibroacoustic phenomena. Modern python-based software are also freely available for EMA, Finite Element (FE) structural analysis, and Boundary Element (BE) acoustic analysis. Finally, we must all remember Jack Mowry's wonderful magazine *Sound and Vibration*, the archives of which are still available and contain a vast number of practical articles. Join me as I navigate the internet and show you where to find these Fantastic Vibroacoustic Resources!

1. INTRODUCTION

Whenever a young vibroacoustician asks me for advice on a particular problem, I often refer them to classic reports and articles I've discovered through the years. While most of these resources were published many years ago, they remain relevant today. We are also fortunate to have access to online teaching resources which show, through animations, complex vibroacoustic phenomena. Finally, we live in an age of a rapidly expanding open source software community; powerful python-based vibroacoustic software is freely available to anyone.

All of the resources in this paper are completely free, except for three I list at the end. Note that there are no formal references in this article. Instead, I cite with footnotes to their URL locations. Unless a link has broken between my submission of this article and when you're reading it, the links should take you directly to the resources.

2. FANTASTIC TEACHING RESOURCES

We might modify the old adage 'a picture is worth a thousand words' to 'an animated GIF is worth a million words'. The Institute of Sound and Vibration Research (ISVR)² and Dr. Dan Russell of Penn State's Graduate Program in Acoustics³ have developed two fantastic teaching websites loaded with insightful animations of acoustic and vibration phenomena. The main page from ISVR is in Figure 1. While most of the site is devoted to acoustic waves, you will find a few animations of how structural waves radiate sound under '5. Further Concepts'.

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²<http://resource.isvr.soton.ac.uk/spcg/tutorial/tutorial/StartCD.htm>

³<https://www.acs.psu.edu/drussell/demos.html>

SOUND WAVES

Welcome to

ISVR Teaching Material

on

Waves and Acoustics

To learn more about sound waves and careers in sound and vibration visit

www.isvr.soton.ac.uk

Study BEng/MEng Acoustical Engineering (IMechE accredited),
BSc Acoustics and Music, BSc Audiology at a world centre for research.

Institute of Sound and Vibration Research
University of Southampton

1. **WAVE BASICS**

2. **WAVE INTERACTION**

3. **STANDING WAVES**

4. **HEARING SOUNDS**

5. **FURTHER CONCEPTS**

UNIVERSITY OF SOUTHAMPTON

Figure 1: ISVR's Sound Wave Teaching Site.

Dan Russell started his site of vibration and acoustic animations while at Kettering University, and has expanded it significantly since arriving at Penn State. His list of animations is extensive, and shown in Figure 2. He has been researching the vibroacoustics of sports equipment for the past several years, and you will find fun examples of his measurements under 'Animations of Experimental Results'. Dan's site is used not only for University level education, but for younger students in primary and secondary education, and has won several awards.

Sound Waves and Sources

Basic Wave Phenomena

- [What is a Wave?](#) - a disturbance which travels through a medium
- [Wave Motion in Space and Time](#) - distinguishing between the time behavior and spatial behavior of waves
- [Superposition of Two Waves](#) - Interference, Standing Waves, and Beats
- [Fourier Decomposition](#) - building a wave shape from sines and cosines
- [Phase changes upon reflection](#) from hard, soft, and mixed boundaries
- [Reflections from Impedance and the Standing Wave Ratio](#). - A sinusoidal wave train reflects from an impedance discontinuity. The resulting wave pattern defines the Standing Wave Ratio used to measure impedance.
- [Refraction of Sound Waves](#) - how temperature gradients make sound waves change direction
- [The Doppler Effect](#) - moving sound sources and sonic booms

Sound Waves and Radiation from Sources

- [Longitudinal and Transverse Waves](#) - Particle Motion for Longitudinal, Transverse, Water and Rayleigh Surface Waves
- [Phase Between Pressure and Particle Velocity for Plane Waves](#) - p and u are in phase for forward going waves, but have opposite phase for backward going waves.

Vibration and Structural Waves

Vibration of 1-DOF Simple Oscillators

- [Comparing Circular and Sinusoidal Motion](#) - how is circular motion in the complex plane (magnitude and phase) related to sine and cosine functions?
- [Simple Harmonic Oscillator](#) - with and without damping, transfer of energy between kinetic and potential forms
- [Damped Harmonic Oscillator](#) - underdamped, overdamped, and critically damped
- [Phase-Space Diagrams for an Oscillator](#) - plotting velocity $v(t)$ as a function of position $x(t)$
- [Forced Harmonic Oscillator](#) - transient and steady state response to a force applied to the mass
- [Base Motion](#) - transient and steady state response of an oscillator to displacement of its support
- [The Simple Pendulum](#) - comparing the linear approximation (small angle) with a real pendulum.
- [Crankshaft: Non-harmonic Oscillator](#) - periodic oscillatory motion that is not sinusoidal.
- [Regions of Resonance](#) - interactive animation of the damping-controlled, stiffness-controlled, and mass-controlled regions in the displacement response of a forced mass-spring system. **New Page (8/6/2019)**

Vibration of Multi-DOF Systems

Figure 2: Dan Russell's Animations Site (there are many more animations than shown above).

3. FANTASTIC ARTICLES AND REPORTS

Although many technical journals are moving toward open access for their articles, much historical content remains under copyright to large publishing companies, and is not freely accessible, nor reusable in future publications without written consent (and sometimes fees). Fortunately, there are some fantastic articles and reports which are in the public domain, and freely available.

3.1. Sound and Vibration Magazine

For 50 years Jack Mowry published the marvelous Sound and Vibration magazine⁴. After Jack retired, the magazine moved to Tech Science Press, and is now being curated by Professors Jun Yang and Yan Gao⁵. Jack's monthly magazines were short - usually only two or three articles and an editorial, *but the articles were intended for the practicing engineer*. Many were written by consultants and engineers at companies (with a few also written by academics). Each issue focused on a particular topic, such as:

- Acoustics
- Automotive NVH
- Computer Aided Engineering
- Dynamic Testing
- Machinery Reliability
- Noise and Vibration Control
- Structural Analysis

along with annual Materials Reference and Instrumentation Reference issues, with links to advertisers who sold those products.

Jack was a constant presence at NoiseCon and InterNoise congresses, always recruiting prospective authors as well as advertisers from the vendor exhibition. You can still download PDFs of the magazine articles. Regrettably, the search feature on the site doesn't work well (if at all). However, you can use the google 'site' search feature to look for specific content or authors, for example the searches:

- site:<http://www.sandv.com> modal, or
- site:<http://www.sandv.com> Ungar

reveal two of my favorite Sound and Vibration magazine articles: *Acoustics from A to Z*, by Eric Ungar from the 35th Anniversary Issue⁶, and *Beware of these Top 10 Issues in Modal Testing*, by Pete Avitable from the 50th Anniversary Issue⁷.

Each letter of Eric Ungar's *Acoustics from A to Z* includes a cartoon, short poem, and several paragraphs of marvelous insights from one of the giants of vibroacoustics. My personal favorite - Damping - is in Figure 3. The 'Ungar' search also shows several of Eric's other articles and editorials. All are worth reading.

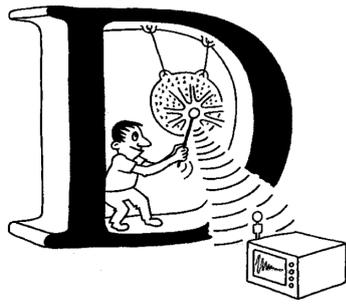
Pete Avitable's article on common issues in modal testing is a must read for those just starting out in experimental modal analysis. However, Pete is famous for his long series of modal articles *In Our Own Little World*, originally published between 1998 and 2014 for the Society of Experimental

⁴<http://www.sandv.com/home.html>

⁵<https://www.techscience.com/journal/sv>

⁶<http://www.sandv.com/downloads/0201unga.pdf>

⁷<http://www.sandv.com/downloads/1701avit.pdf>



*DAMPING's poorly understood.
It doesn't always do much good.
Although it may speed wave decay,
It makes few problems go away.
Damping does mean dissipation,
But may not yield attenuation.*

Figure 3: Excerpt from Eric Ungar's *ABCs of Acoustics*

Mechanics⁸. All the articles are available at the footnoted link. Each starts with a little cartoon with a common question, like 'What's the difference between operating deflection shapes and mode shapes?' Pete then describes the problem, and explains the answer in a page or two, with a few great figures.

Here are more of my favorite Sound and Vibration magazine articles:

- The Modal Assurance Criterion - Twenty Years of Use and Abuse⁹, by Randall Allemang of the University of Cincinnati, August 2003 issue
- State of the Art in Monitoring Rotating Machinery, by Bob Randall of the University of New South Wales, Part 1 in the March 2004 issue¹⁰ and Part 2 in the May 2004 issue¹¹

3.2. NASA's Technical Reports Server

All reports on projects performed for the US National Aviation and Space Agency (NASA) are archived on the NASA Technical Reports Server¹². The search feature is simple and efficient. Try searching for common vibroacoustic keywords like 'modal analysis' and 'statistical energy analysis'. You'll be overwhelmed by the volume of information available. Those of you who work in aerodynamics and aeroacoustics will also find the site a treasure trove.

Two of the resources I often recommend to young engineers and students are the classic reports by Arthur Leissa: *Vibration of Plates*¹³, and *Vibration of Shells*¹⁴. The breadth, quality, and level of detail in these works is astonishing. Along with describing the fundamentals of plate and shell vibration theory, Leissa provides a compendium of mode shapes and frequencies for rectangular plates, circular plates, triangular plates, plates with holes, plates with partial supports, cylindrical shells, spherical shells, and on and on and on. Nearly every type of edge boundary condition is included, along with countless references to other materials from previous authors. An example from the report of square plate mode shapes - measured the old fashioned way with Chladni patterns¹⁵ - is in Figure 4. Simply put, Leissa's reports are required in any practicing Vibroacoustician's library.

⁸<https://www.uml.edu/Research/SDASL/Education/Modal-Space.aspx>

⁹<http://www.sandv.com/downloads/0308alle.pdf>

¹⁰<http://www.sandv.com/downloads/0403rand.pdf>

¹¹<http://www.sandv.com/downloads/0405rand.pdf>

¹²<https://ntrs.nasa.gov/search.jsp>

¹³<https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19700009156.pdf>

¹⁴<http://hdl.handle.net/2060/19730018197>

¹⁵Here's a fantastic YouTube demonstration of Chladni patterns on a square plate from *Physics Girl* suitable for anybody, even non-vibroacousticians: <https://www.youtube.com/watch?v=wYox0JDrZzw>

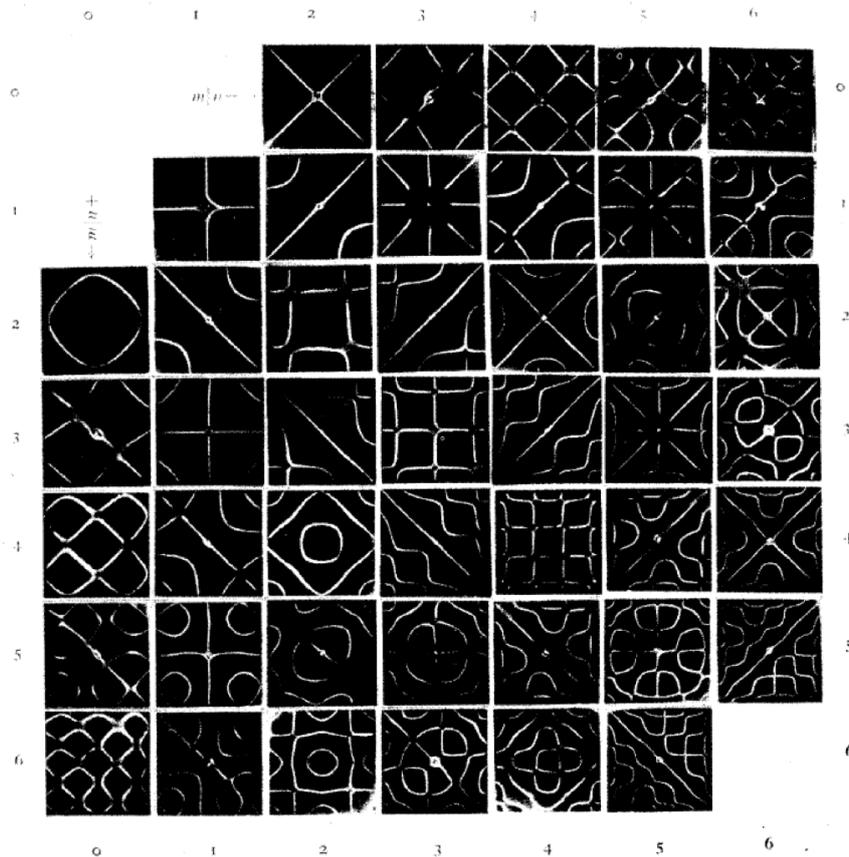


FIGURE 4.55.—Experimentally determined mode shapes for a completely free square plate. (From ref. 4.119)

Figure 4: Excerpt from Leissa's *Vibration of Plates*

3.3. Defense Technical Information Center (DTIC)

DTIC¹⁶ is similar to the NASA server, but is a repository of unclassified reports that have been cleared for public release by the United States Department of Defense (DoD). Sadly, there is no custom search feature for the site; instead a simple google search box is available (which just uses the 'site' feature to restrict searches to DTIC). So, you almost need to know the title and/or authors of what you're looking for to use the site.

Along with the reports, some conference proceedings are available that were supported in part by the DoD. One great example is thanks to the Office of Naval Research - Europe, which helped sponsor an international symposium on Statistical Energy Analysis (SEA) organized by the International Union of Theoretical and Applied Mechanics in Southampton, UK in 1997¹⁷. The author list includes most of the major developers of SEA. Just search for 'Statistical Energy Analysis' to find it. That search will also show you early articles from original SEA developers like Dick Lyon¹⁸ and many articles by the great Gideon Maidanik.

For over 90 years, the shock and vibration community has held an annual conference to discuss how to best measure and analyze the response of structures to impulsive and other strong vibration events, like earthquakes and explosions. Many of these proceedings are archived on DTIC - just use the search term 'shock and vibration'. In the late 1960s and early 1970s, the Shock and Vibration Information Center sponsored the Shock and Vibration Monograph Series - nine long reports on

¹⁶<https://discover.dtic.mil/>

¹⁷<https://apps.dtic.mil/sti/citations/ADA344218>

¹⁸Statistical Energy Analysis for Designers. Part 1. Basic Theory <https://apps.dtic.mil/sti/citations/ADA006413>

various aspects of shock and vibration testing, analysis, and mitigation. It's best to search for each article separately; here's the list:

- SVM-1 Random noise and vibration in space vehicles - Lyon
- SVM-2 Theory and practice of cushion design - Mustin
- SVM-3 Programming and analysis for digital time series data - Enochson and Otnes
- SVM-4 Dynamics of rotating shafts - Loewy and Piarulli
- SVM-5 Principles and techniques of shock data analysis - Kelly and Richman
- SVM-6 Optimum shock and vibration isolation - Sevin and Pilkey
- SVM-7 Influence of damping in vibration isolation - Ruzicka and Derby
- SVM-8 Selection and performance of vibration tests - Curtis, Tinling, and Abstein
- SVM-9 Equivalence techniques for vibration testing - Fackler

One of the most famous vibroacoustic reports on DTIC is Ross, Kerwin, and Ungar's report on estimating damping in structures treated with Constrained Layer Damping¹⁹ from 1959. Commonly denoted *RKU theory*, these methods are widely used even today. This report extends the authors earlier work on the damping effects of single viscoelastic layers to multiple layers (see the example in Figure 5). The authors worked for Bolt Beranek and Newman (BBN) at the time. BBN was responsible for much of the research in vibroacoustics between the 1950s through the 1980s. Search for BBN and you'll find Volume 1 of the *Handbook of Acoustic Noise Control*²⁰ along with many other articles.

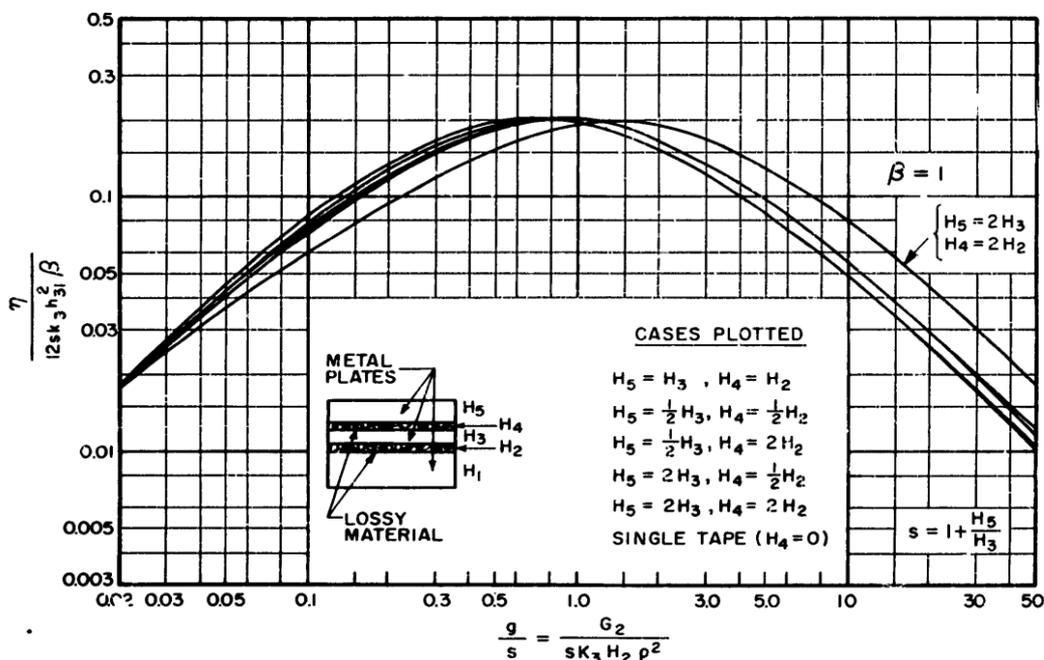


FIG. 1 DAMPING CURVES FOR 6 TAPES HAVING SAME TOTAL FOIL THICKNESS.

Figure 5: Excerpt from Ross, Kerwin, and Ungar's report on Viscoelastic layer damping

¹⁹Damping of Flexural Vibrations by Alternating Visco-elastic and elastic layers, <https://apps.dtic.mil/sti/citations/AD0232152>

²⁰<https://apps.dtic.mil/sti/citations/AD0012015> and the supplement <https://apps.dtic.mil/sti/pdfs/AD0066250.pdf>

In the mid 1970's, the Office of Naval Research (ONR) sponsored Donald Ross, formerly of BBN and the David Taylor Research Center, to write a book on Underwater Sound. The result, published in 1975, is freely available on DTIC²¹. The book includes basic vibroacoustic formulations, including thick plate theory (often ignored in textbooks), the effects of heavy fluids (water) on structures, and many other topics of interest. Be warned - the PDF is huge - over 200 MB - so budget some time and ensure a strong internet connection before downloading.

3.4. Other Fantastic Publications

Here's a fantastic, but endangered, resource: the Structural Acoustics Design Manual published by the European Space Agency in 1996 (ESA PSS-03-204)²². The manual provides basic vibroacoustic theory, along with a lot of SEA theory, focused on the vibroacoustic analysis and measurement of spacecraft structures. A particularly useful part of the manual is guidance on approximate damping levels in common spacecraft materials, and layered composites in particular, even for varying layup angles, as shown in the excerpt in Figure 6. Sadly, this manual is no longer available on the ESA site, but is currently on <http://everyspec.com>. I recommend downloading it immediately before it disappears for good.

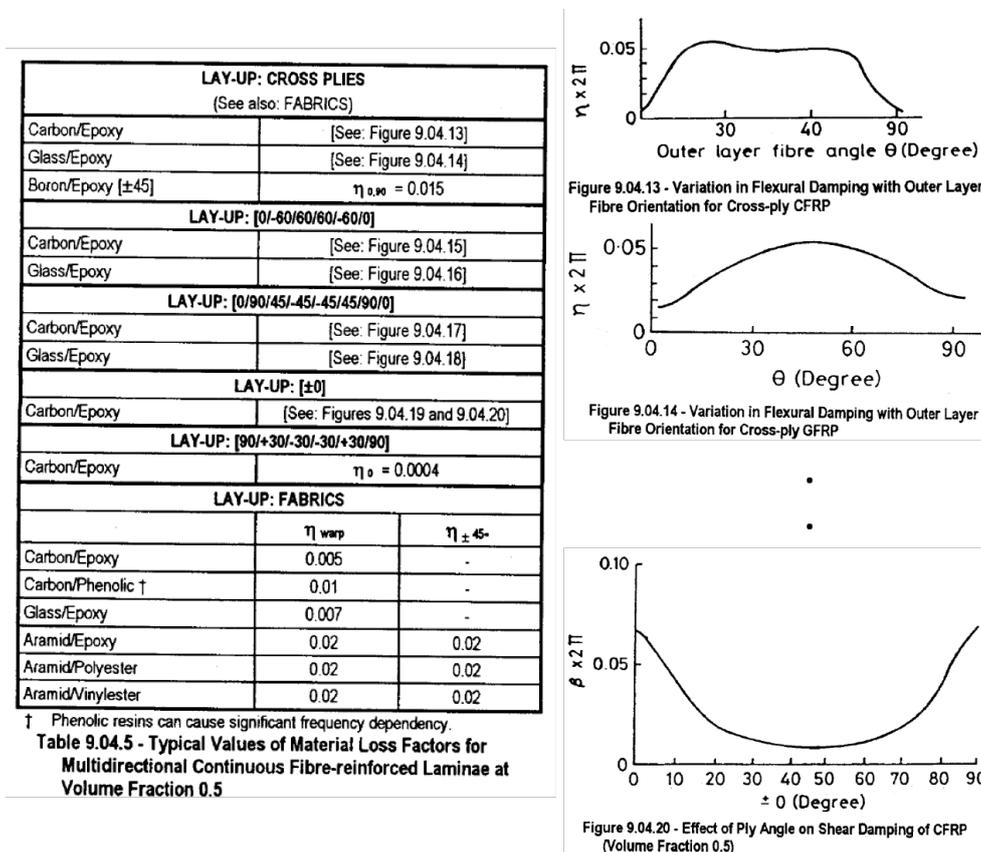


Figure 6: Composite damping excerpt from European Space Agency Structural Acoustics Design Manual

In 1980, the US National Institute for Occupational Safety and Health (NIOSH) published the NIOSH Compendium of Materials for Noise Control²³. Although some of the companies cited in this 1980 report are no longer with us, much of the basic information in this report remains relevant.

²¹<https://apps.dtic.mil/sti/pdfs/ADA075101.pdf>

²²http://everyspec.com/ESA/ESA_PSS-03-204-1_1996_28721/

²³<https://www.cdc.gov/niosh/docs/80-116/pdfs/80-116.pdf?id=10.26616/NIOSH PUB80116>

4. FANTASTIC SOFTWARE

The Open Source movement, along with the ascension of Python as the programming language of choice around the world, has led to many free vibroacoustic software options. I list here only a few of those that have been recommended to me, have a wide following, and have current updates.

4.1. Experimental Modal Analysis

Until recently Experimental Modal Analysis software was only available from commercial vendors. The OpenModal team²⁴ have developed open python software with all of the main features of basic EMA, including defining geometry, importing Universal File Format (UFF) and LabView measurement files, curvefitting modal parameters, and animating mode shapes. Experimental (where input sources are known) and operational (where input sources are unknown) modal analyses (OMA) are possible using modern curve fitting methods similar to those in commercial software.

4.2. Structural Finite Element Analysis

One of the first structural Finite Element (FE) software packages to be used widely is NASTRAN. NASTRAN, which actually stands for NASA STructural ANalysis, was first released in the late 1960s. Although it originated at NASA, the US Navy and Air Force also helped develop later versions of the software. The MacNeal Schwendler Corporation (MSC) expanded the US government (and free) version of NASTRAN and sold it as MSC/NASTRAN. Other companies later developed different versions, but MSC has remained the most popular.

For several years Stephen Doyle has been publishing a python tool which reads NASTRAN input and output files on github²⁵. The software includes several utilities and includes a simple Graphical User Interface (GUI) to visualize models and results from external solvers. A free version of NASTRAN itself is available from Bill Case called 'MYSTRAN'²⁶. MYSTRAN is available on github, and includes the Fortran source code²⁷. As of this writing, Bill and his colleagues are working to ensure the code compiles with 'gfortran'. With some effort, a knowledgeable programmer should be able to compile MYSTRAN with commercial development software.

4.3. Acoustic Boundary Element Analysis

The general Acoustic Helmholtz problem is solved using traditional boundary element techniques in the ABEMFULL software by Stephen Kirkup²⁸. Kirkup's version is in Fortran, but fortunately the software was later ported to Python²⁹. The methods are based on traditional BE formulations, and therefore limit the size of problems that can be solved.

Another more general purpose and advanced python-based BE tool is Bempp (which stands for BEM++)³⁰, which also solves electromagnetic problems. The tool requires triangular surface meshes generated over general surfaces using the popular Gmsh³¹. The BEM++ software includes modern methods for reducing memory requirements and solving very large problems quickly using Hierarchical Matrices (H-Matrices) and Adaptive Cross Approximation (ACA)³².

²⁴<http://www.openmodal.com/>

²⁵<https://github.com/SteveDoyle2/pyNastran>

²⁶<https://www.mystran.com/>

²⁷<https://github.com/dr-bill-c/MYSTRAN>

²⁸<https://www.boundary-element-method.com/acoustics/>

²⁹<https://pypi.org/project/abem/>

³⁰<http://bempp.com/index.html>

³¹<https://gmsh.info/>

³²See the developers 2015 article in ACM Transactions on Mathematical Software: <https://dl.acm.org/doi/pdf/>

5. FANTASTIC RESOURCES WHICH ARE NOT FREE

I mention only three resources which cost money. The first is a marvelous booklet on noise control written by the late Stig Ingemansson. Stig summarized complex vibroacoustic and noise control concepts in simple cartoons and short explanations. I refer often to my copy when explaining these concepts to others. The booklet is available to donors of the INCE Foundation³³. I include in Figure 7 one image from the booklet with permission of the INCE Foundation to show the clarity and usefulness of Stig's work.

B2 SOUND FROM VIBRATING PLATES - SIZE AND THICKNESS

DENSELY PERFORATED PLATES PRODUCE LESS NOISE

Large vibrating surfaces cannot always be avoided. The vibrating surface pumps air back and forth like the piston of a pump, causing sound radiation. If the panel is perforated, the "piston" leaks, and the pump functions poorly. Alternatives to perforated plates include mesh, gratings, and expanded metal.

Principle

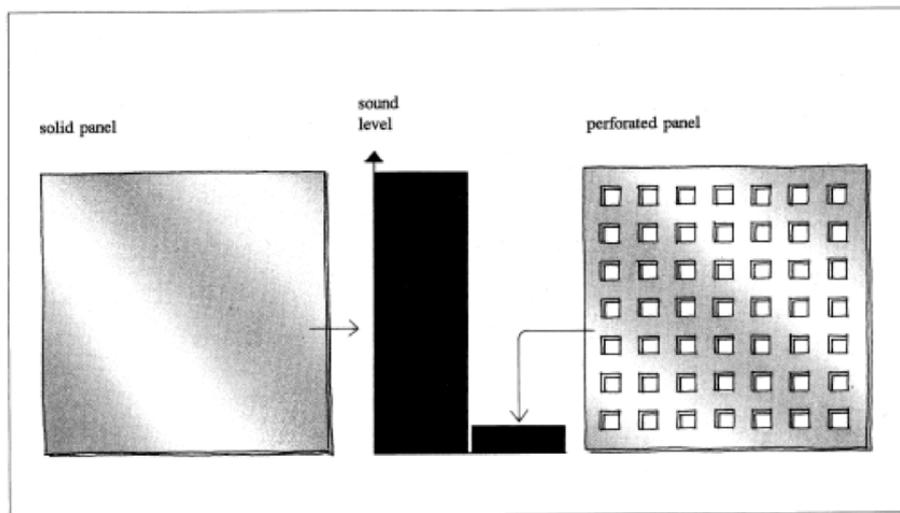


Figure 7: Excerpt from Stig Ingemansson's *Noise and Vibration Control* booklet

The second resource is indispensable to me - Robert Blevins's book *Formulas for Natural Frequencies and Mode Shape*. It's the first resource I turn to when trying to recall formulae for particular structures. Finally, while not related to vibroacoustics, I also highly recommend Roark and Young's *Formulas for Stress and Strain* for those working in the field of alternating stresses and fatigue life. Roark includes many common stress concentration factors for holes, notches, and other discontinuities which cause local stress amplifications.

6. CONCLUSIONS

I hope you will take advantage of these Amazing Vibroacoustic Resources. While the list is long and a bit daunting, I suggest you set aside an hour or so each week to start acquiring and browsing them. I am always surprised at what I find in these great reports and articles when I refer back to them (as I did during the writing of this paper). Also, internet links have a way of breaking and changing over time, so I highly recommend downloading the resources soon.

You are also welcome to download the various tutorials I have written over the years³⁴. These are also free resources, but it seemed self serving to denote them 'Fantastic' in the sections above.

Disclaimers: while the resources I have described here have proven valuable to me over the years, I do not endorse them without reservation, nor do I accept any responsibility for others who use the methods inappropriately or incorrectly. Also, I am solely responsible for any errors or omissions in this paper.

³⁴www.hambricacoustics.com