Computational Structural Acoustics: Technology, Trends and Challenges

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CONSULTING ENGINEERS

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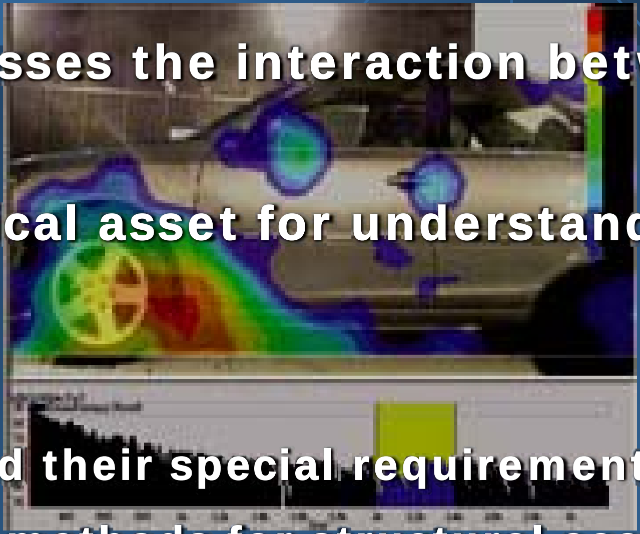
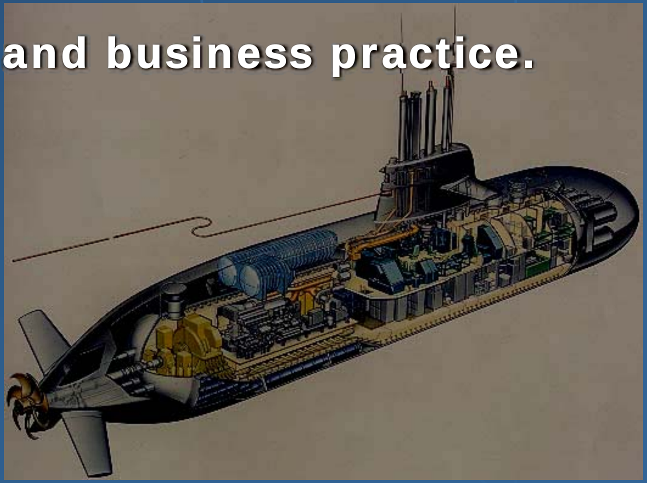
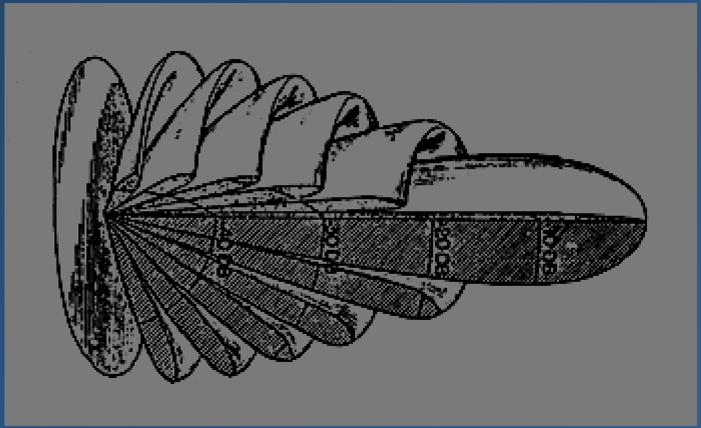
Computational Structural Acoustics



- "Structural acoustics" encompasses the interaction between vibrations in fluids and solids.
- Computational analysis is a critical asset for understanding the phenomenon.
- In this talk, we'll discuss:
  - A survey of application areas and their special requirements,
  - A brief history of computational methods for structural acoustics,
  - Near-term trends in technology and business practice.





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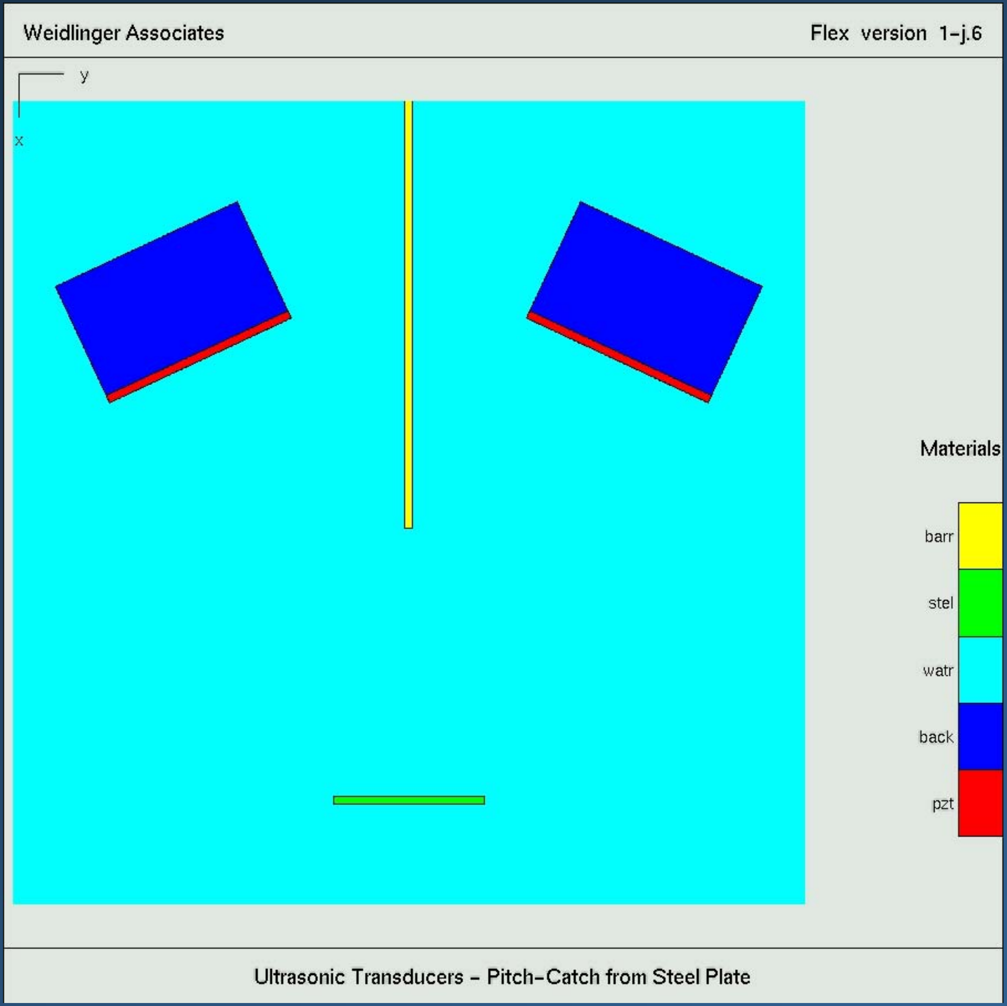
The phenomenon



Ultrasonic Transducers - Pitch-Catch from Steel Plate

Waves occur due to exchange between elastic potential energy and kinetic energy in fluids and solids.

"Fluids" here have dilatational waves only.

"Solids" support dilatation and shear.

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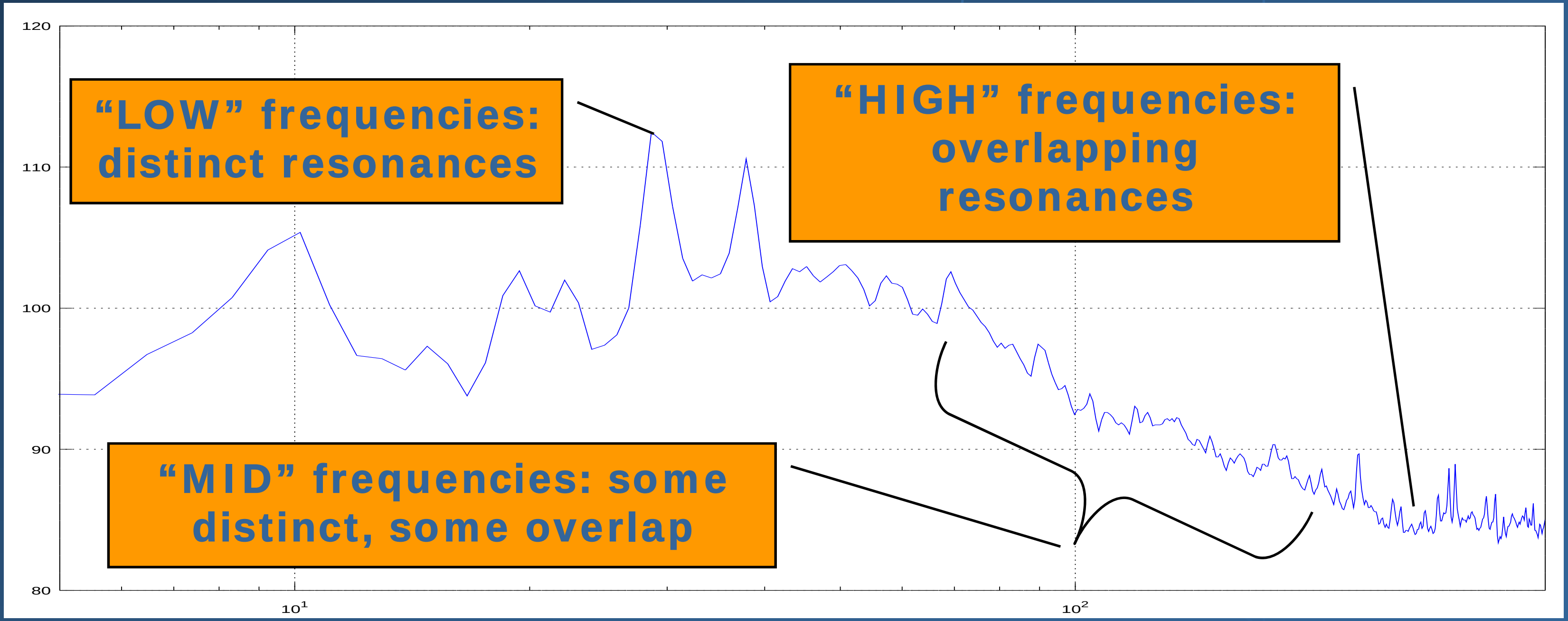
The Behavior of Real Systems

- Different physical phenomena across a range of frequencies.
- “Low”: distinct resonances, low smearing due to damping.
- “High”: many peaks, sufficient damping that response depends strongly on several / many modes.



“LOW” frequencies: distinct resonances

“HIGH” frequencies: overlapping resonances

“MID” frequencies: some distinct, some overlap

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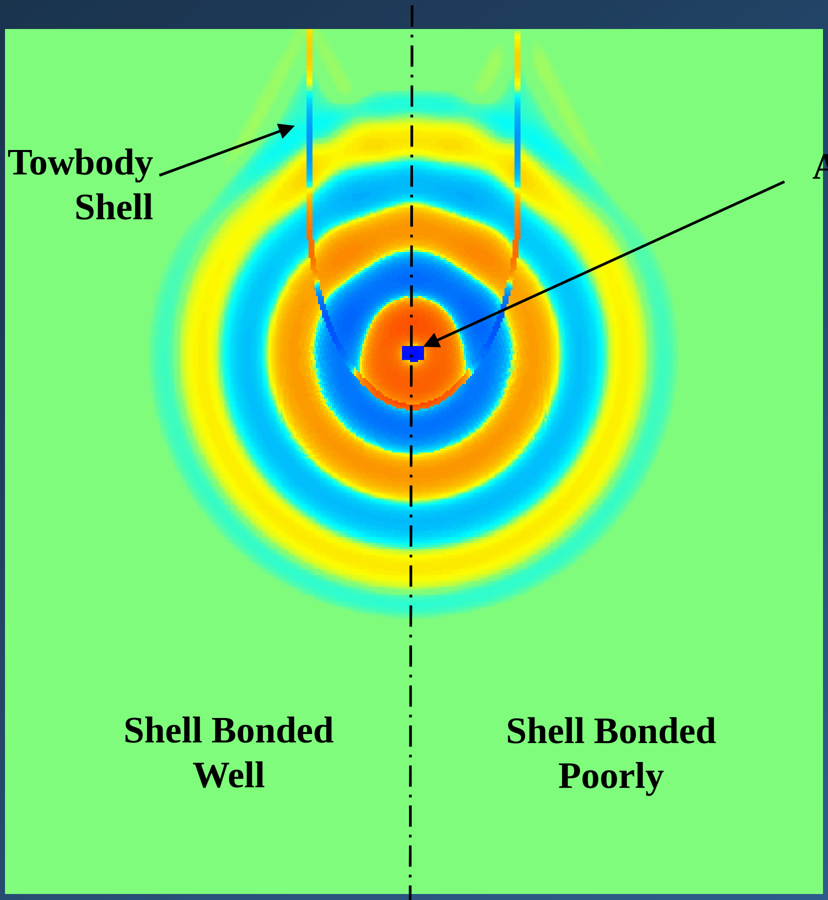
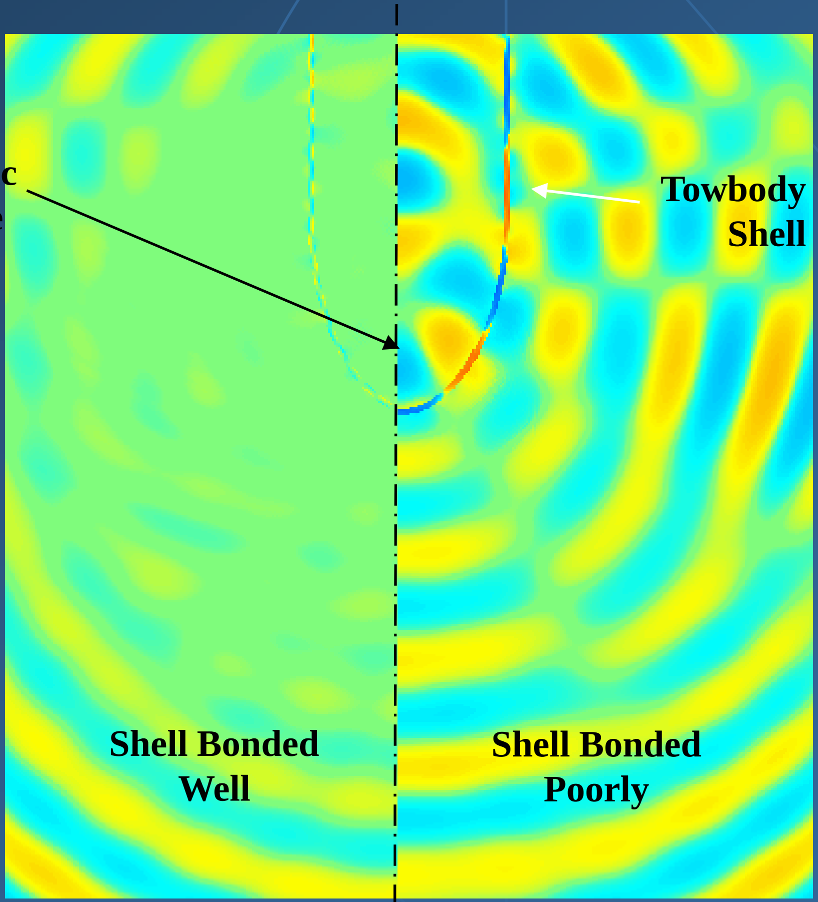
The Effect of Structural-Acoustic Coupling



Early Time



Late Time

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Application Areas

- **Acoustic Devices**
  - Audio systems, sonar transducers, etc. for which structural-acoustic effects are the primary functional requirement.
- **Aircraft & Vehicles**
  - Noise levels affect passengers and bystanders.
  - Some significant regulatory issues.
- **Ships and Ocean systems**
  - Very strong fluid-structure coupling.
  - Submarine acoustic stealth.
- **Biologic and Medical systems**
  - Medical ultrasound, High-Intensity Focused Ultrasound (HIFU).
  - Imaging & therapy.

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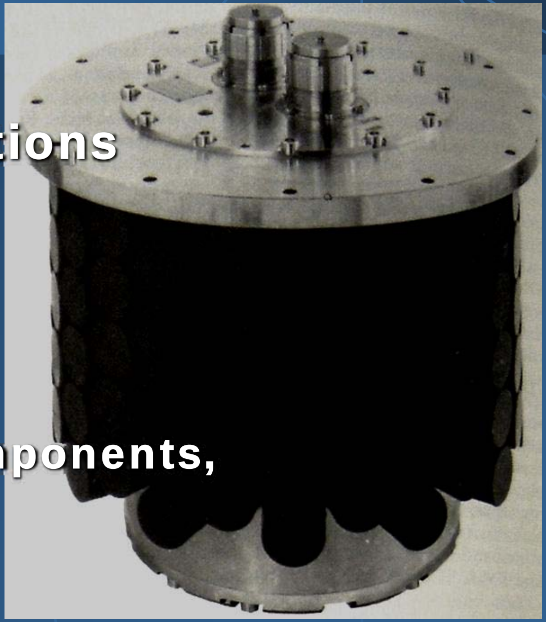
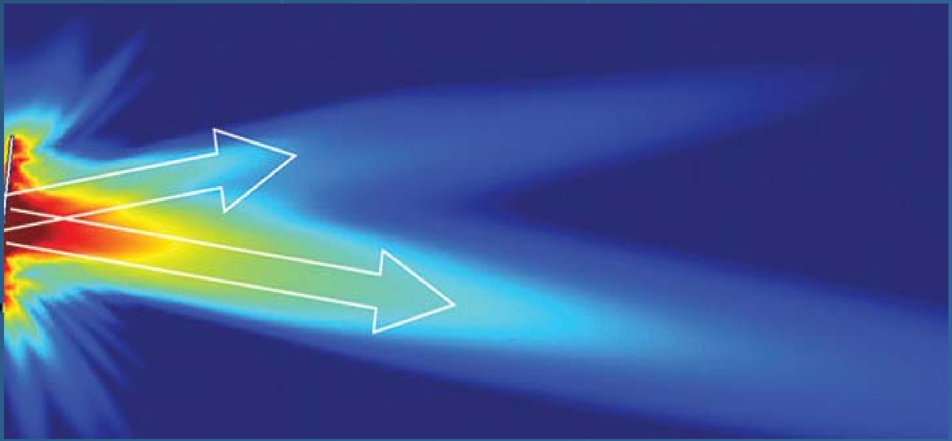
Application Areas



- Acoustic Devices: special considerations
  - Directivity,
  - Impedance,
  - Frequency-domain,
  - Mechanical systems as electrical components,
- Examples
  - Cell phones,
  - Ear phone,
  - Hearing aids,
  - Sonar,
  - MEMS devices: SAW / BAW.



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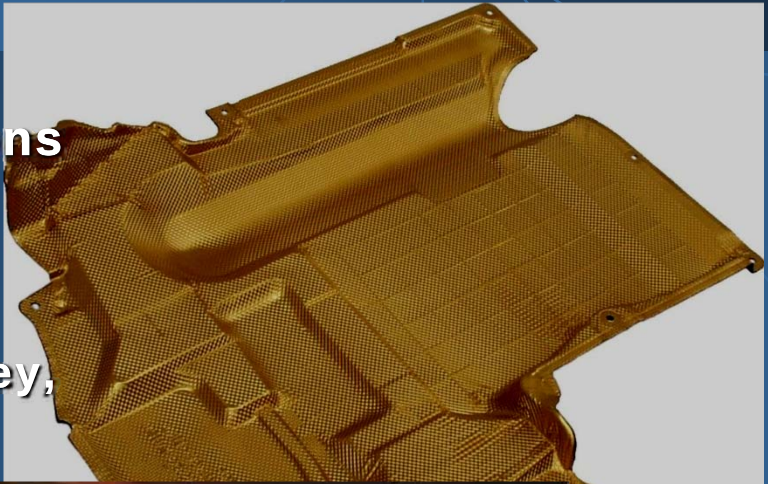
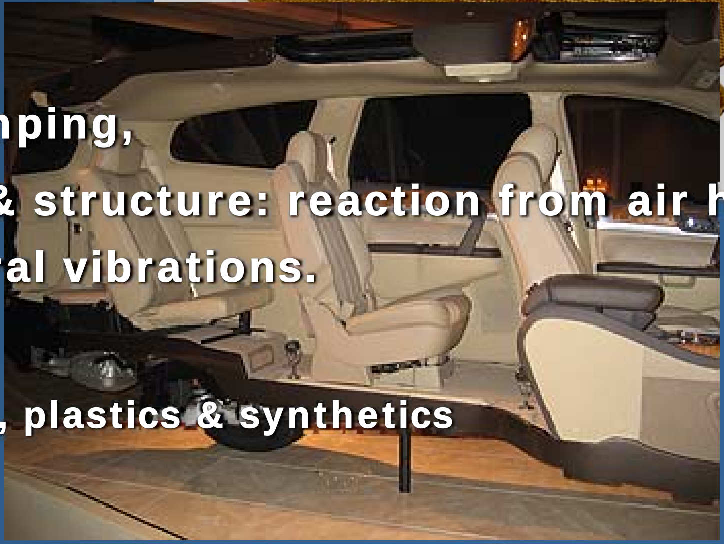
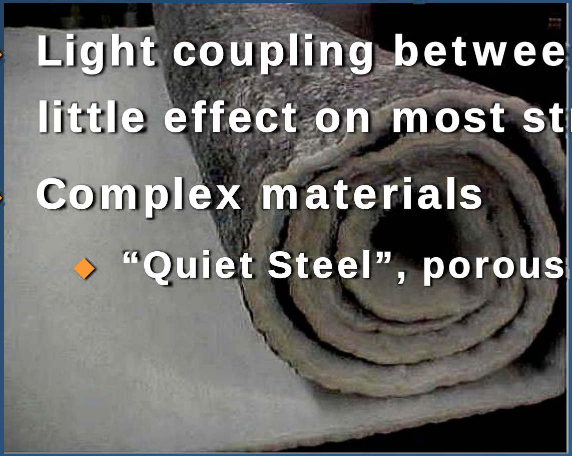
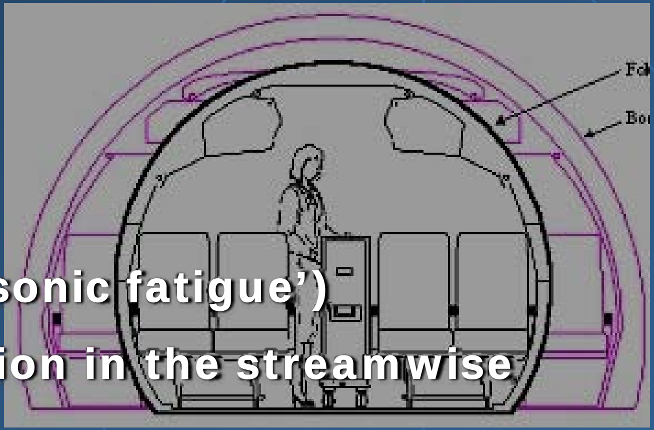
Application Areas

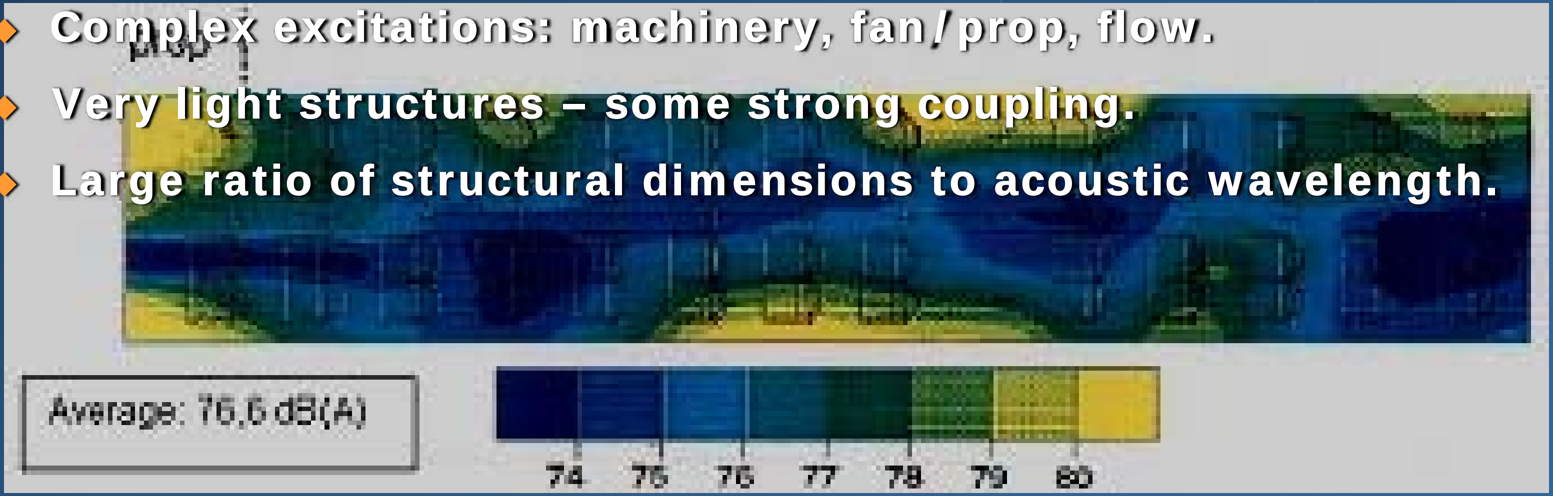




- Automobiles: special considerations
  - Overall levels for passengers,
  - "Brand Note" or "brand sound",
  - Human qualitative perception is key,
  - Complex excitations,
  - Rotating components,
  - Tires: rotation, preload, damping,
  - Light coupling between air & structure: reaction from air has little effect on most structural vibrations.
  - Complex materials
    - "Quiet Steel", porous media, plastics & synthetics

Computational Structural Acoustics
Application Areas



- Aircraft: special considerations
  - Overall levels for passengers,
  - Exterior radiated noise,
  - Structural Failure (aeroelasticity, ‘sonic fatigue’)
  - Moving air changes wave propagation in the streamwise directions
  - Complex excitations: machinery, fan/prop, flow.
  - Very light structures – some strong coupling.
  - Large ratio of structural dimensions to acoustic wavelength.



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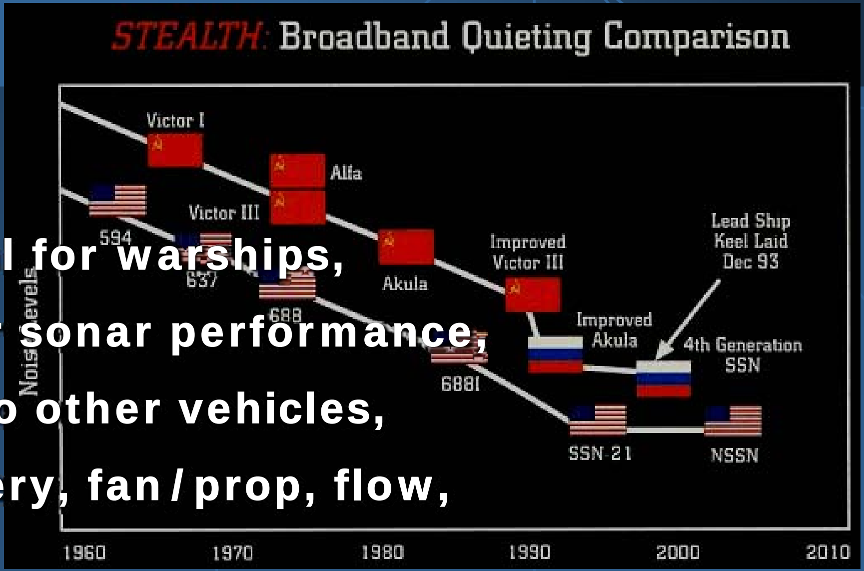
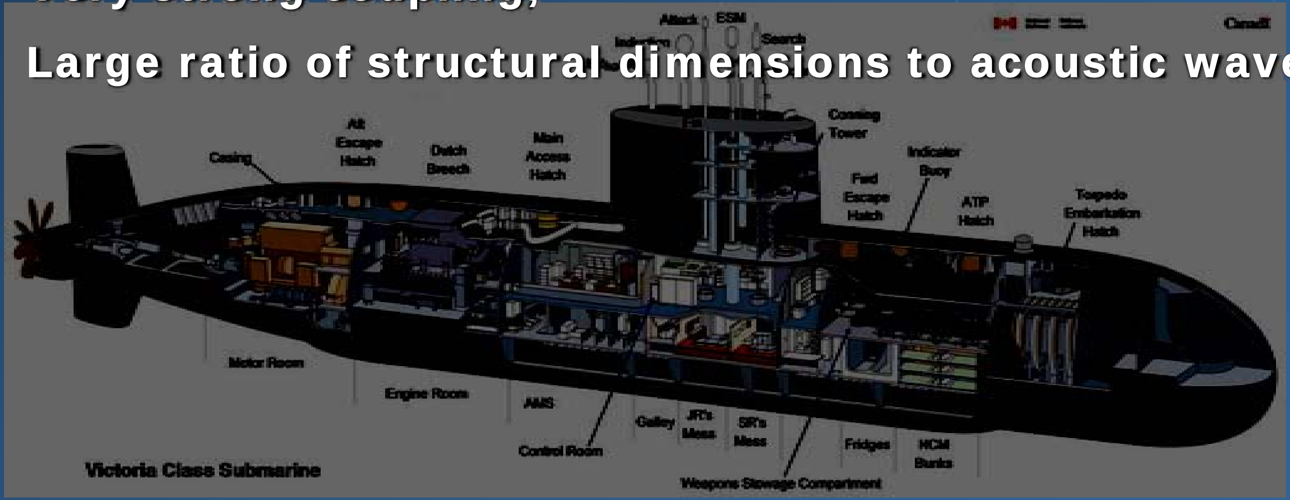
Application Areas

- Ships: special considerations
  - Exterior radiated noise critical for warships,
  - Onboard self-noise critical for sonar performance,
  - Passenger ship noise – akin to other vehicles,
  - Complex excitations: machinery, fan / prop, flow,
  - Very strong coupling,
  - Large ratio of structural dimensions to acoustic wavelength.


STEALTH: Broadband Quieting Comparison


Victoria Class Submarine

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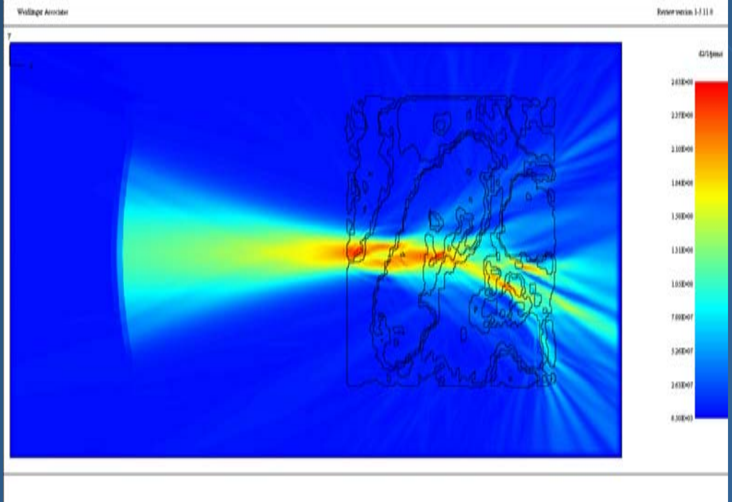
Application Areas

- Biological systems: special considerations
  - Piezoelectric transducers in Mhz range
  - Imaging and therapeutic applications
  - Phase information is critical to imaging
  - Time-of-arrival (same as phase) critical in therapy
  - Large ratio of structural dimensions to acoustic wavelength
  - Materials are highly variable and attenuation is high.

Computational Structural Acoustics

Parameters of the Computational Challenge

- Waves -> length scale -> resolve, or smear?
- Domain complexity / materials / geometry,
- Material variability & damping,
- Coupling between elastic solids and:
  - Bounded fluids,
  - Unbounded fluids,
  - Electric fields,
  - Thermal fields.
- Responses of interest range over many orders of magnitude.
- Typically, linear assumptions hold.



Computational Structural Acoustics

The Conventional Wisdom

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The Conventional Wisdom

- "Analytic" solutions
  - Classical mathematical methods.
  - Series expansions, Green's functions, WKB.
  - Fantastic – when they apply to your problem.
  - Many more assumptions have to be made a priori than with computational analysis.
  - Universities produce ever-fewer graduates able to do them.
  - Execution cost (work-hours) may be more than computer solutions.

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The Conventional Wisdom

- The finite difference method
  - Classical numerical method for PDEs – dates to Euler.
  - Direct expansion of derivatives.
  - Must resolve peaks & troughs of waves for accuracy.
  - Typically limited to structured grids – but high nonlinearity in the operators is OK,
  - ...inviting mappings of real geometry onto rectilinear domains.
  - Generally harder to integrate with CAD / CAE.
  - Extremely fast.
  - Lower per-node accuracy than FEA.
  - Generally fading in share of usage for Str. Ac.

Computational Structural Acoustics

The Conventional Wisdom

- The boundary element method
  - “Exact” (not really).
  - Acoustic PDE transforms nicely into a boundary integral eqn.
  - This eqn. is easy to discretize with (finite) elements.
  - Must resolve peaks & troughs of waves for accuracy.
  - Classic approach uses complex-exponential form.
  - Natural way to do exterior problems in acoustics.
  - Memory & CPU-intensive -> low speed.
  - Higher per-node accuracy than FEA.
  - Generally fading in share of usage for Str. Ac.

Computational Structural Acoustics

The Conventional Wisdom

- Statistical Energy Analysis method
  - Uses a thermal analogy for high-frequency vibrations.
  - Smear wave peaks & troughs using statistical assumptions, analogous to heat / temperature.
  - Valid from the limit of infinite frequency down to useful frequencies.
  - Lumped parameter / a priori discretization of systems.
  - Relatively more difficult to apply to general / new systems than BEM, FD, FEM.
  - Higher dependence on user skill than BEM / FD / FEM.
  - Many fewer journal papers / users / software licenses than FD / BEM / FEM.
  - The "only game in town" for very high frequencies.

Computational Structural Acoustics

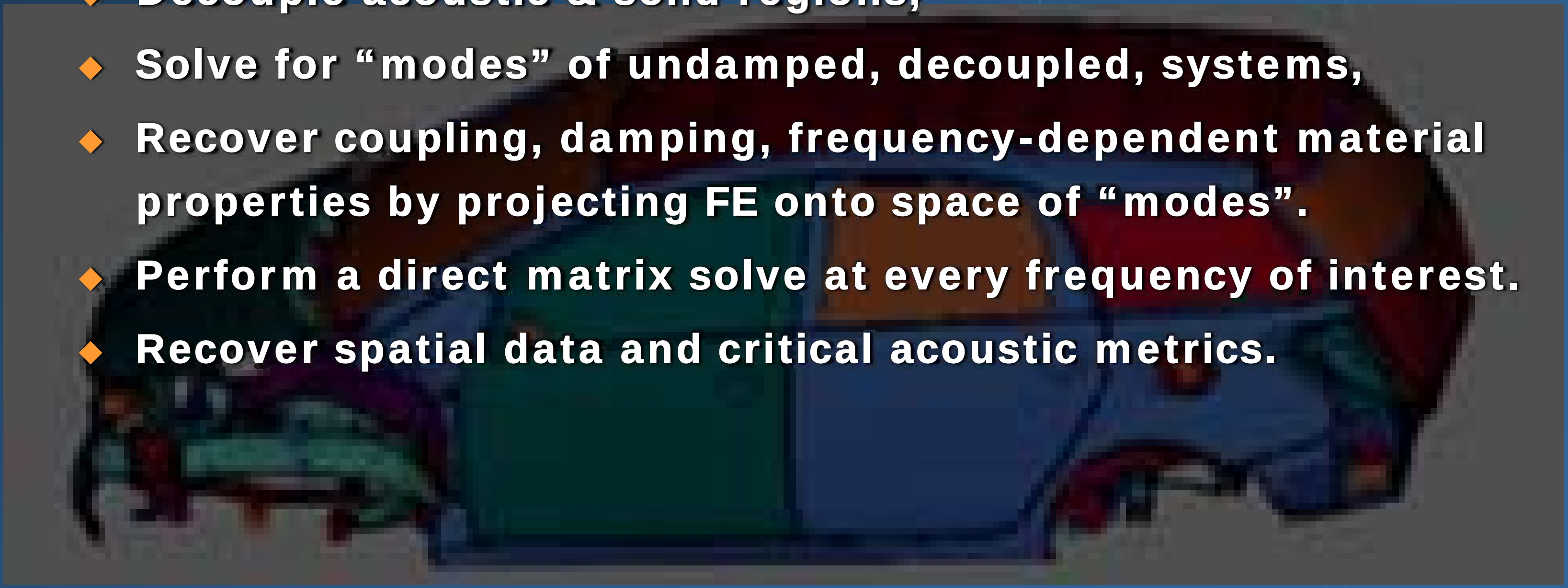
The Conventional Wisdom

- **Finite Element Method**
  - Versatile for geometry & materials.
  - Massive investments since 1960's.
  - Very easy to automate (too easy?).
  - Most highly tested & mathematically scrutinized method.
  - Must resolve peaks & troughs of waves for accuracy.
  - Trouble handling exterior acoustic problems.
  - Trouble with higher frequencies.

Computational Structural Acoustics

The Conventional Wisdom

- The Finite Element Method forms the basis for the dominant industrial approach to computational structural acoustics:
  - CAD-based geometry,
  - FE mesh of fluid & solids,
  - Decouple acoustic & solid regions,
  - Solve for “modes” of undamped, decoupled, systems,
  - Recover coupling, damping, frequency-dependent material properties by projecting FE onto space of “modes”.
  - Perform a direct matrix solve at every frequency of interest.
  - Recover spatial data and critical acoustic metrics.



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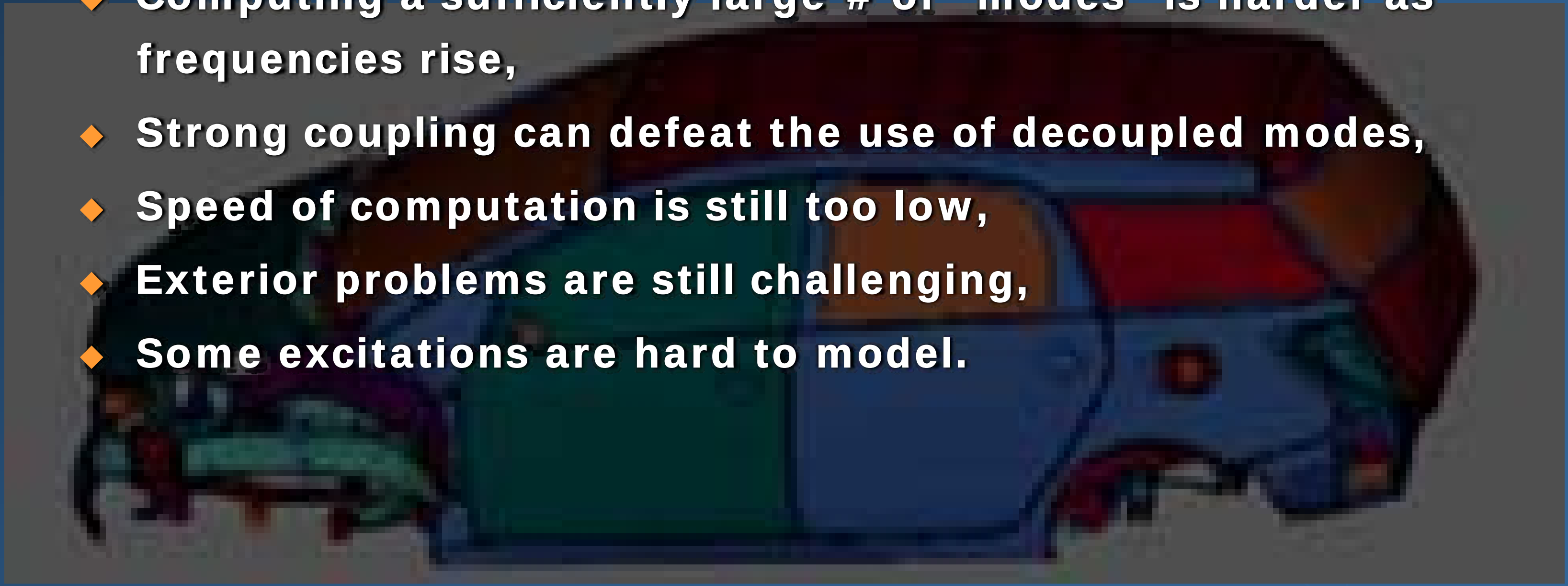
The Conventional Wisdom



- Shortcomings of the dominant approach:
  - FEM is a low-pass filter,
  - High frequencies obtainable only from exponentially larger problems,
  - Computing a sufficiently large # of “modes” is harder as frequencies rise,
  - Strong coupling can defeat the use of decoupled modes,
  - Speed of computation is still too low,
  - Exterior problems are still challenging,
  - Some excitations are hard to model.

Computational Structural Acoustics

Technology Innovations

Computational Structural Acoustics

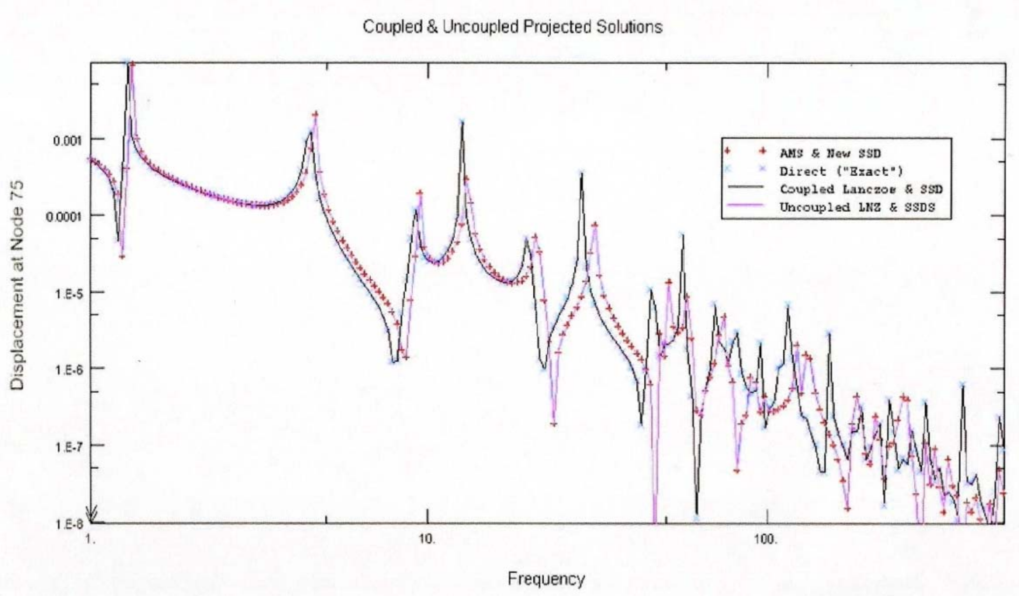
Technology Innovations

- Exterior problems with the finite element method
  - Nonreflecting boundary conditions are easy to build into FEA.
  - "Infinite element" technology has advanced rapidly
    - Bettess' first mapped & decay elements (1970s)
    - Allik's impedance-matched element (1980s)
    - Burnett's multipole expansion element (1980s) (published 1990s)
    - Astley's multipole expansion element (1980s)
  - "Perfectly Matched Layers" are new, possibly better.
  - *Upshot:* exterior problems became solvable using nearly identical data structures and solver technology as all FEM problems.
  - Status: technology is proven, commercially available (ABAQUS, SYSNOISE, ACTRAN), but not universal yet.

Computational Structural Acoustics

Technology Innovations

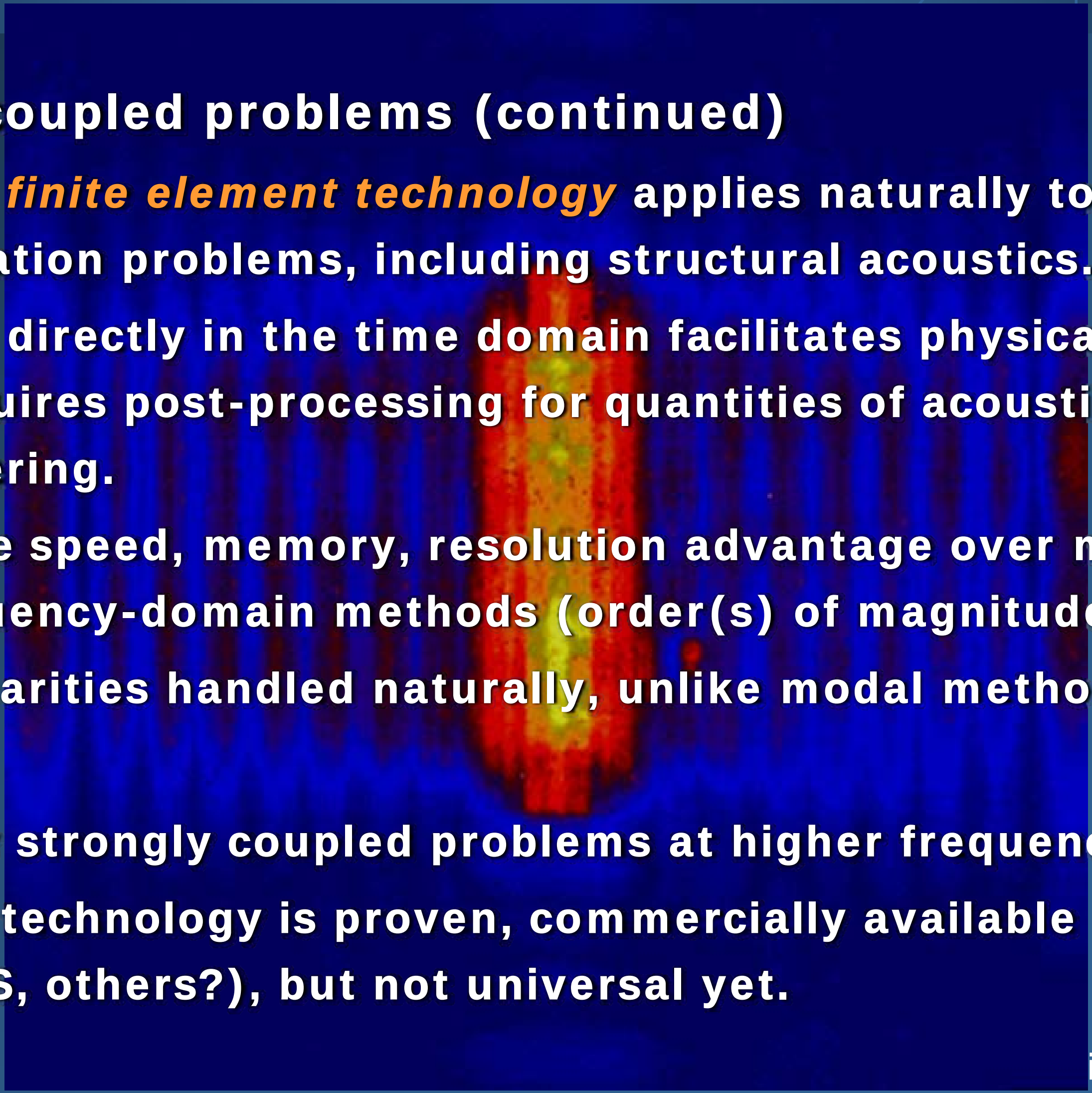
- Strongly coupled problems
  - The decoupled modal approach abandons the critical structural-acoustic coupling boundary condition at the outset
  - This leads to requiring many more “modes” than expected by a user.


Coupled & Uncoupled Projected Solutions

- Morand & Ohayon (1980s) showed that modes of *coupled structural-acoustic systems can be found directly*.
- *Upshot:* Many fewer modes are needed; accuracy rises.
- Status: technology is proven, commercially available (ABAQUS, ANSYS), but not universal yet.

Computational Structural Acoustics

Technology Innovations

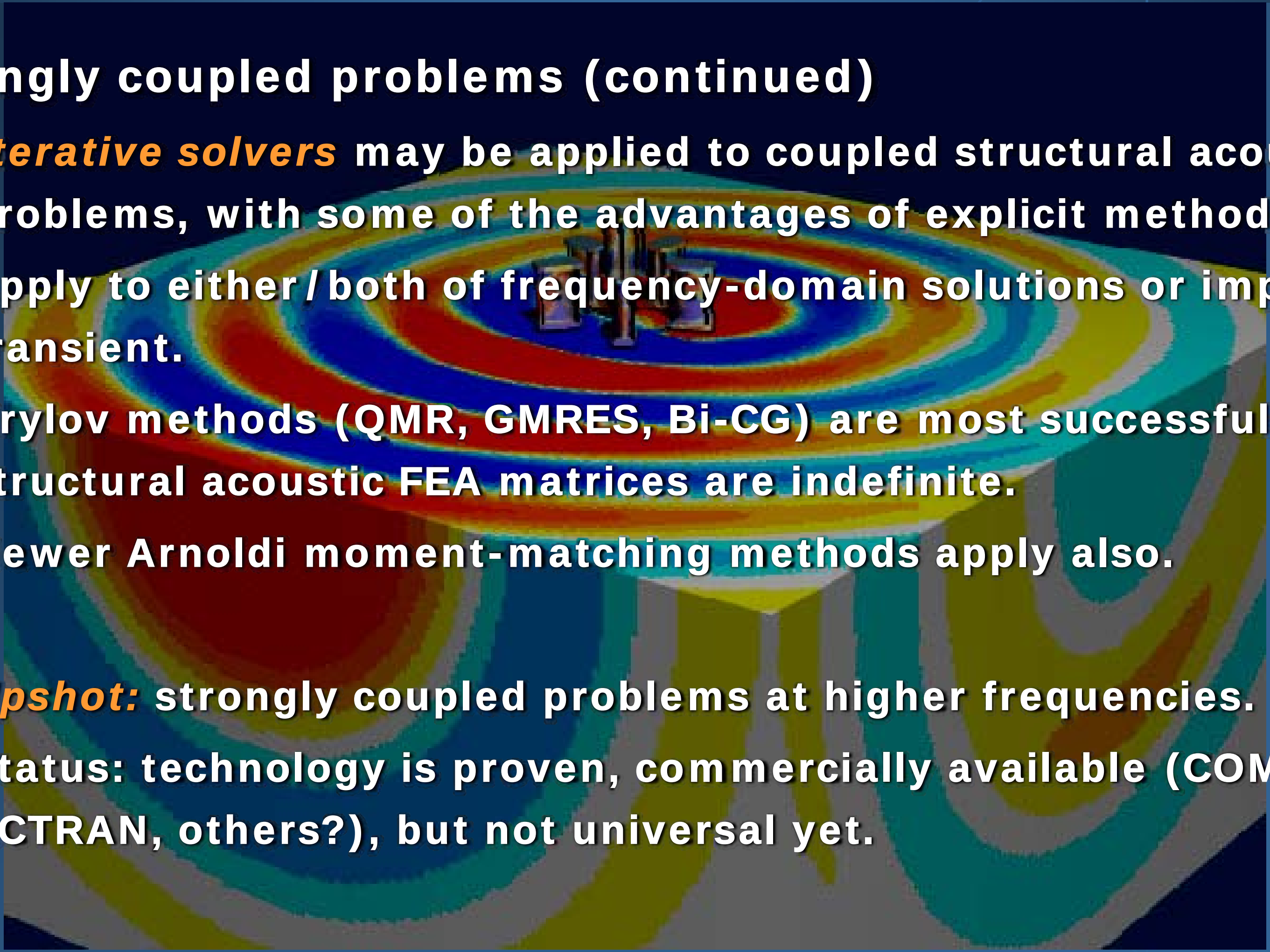


- Strongly coupled problems (continued)
    - *Explicit finite element technology* applies naturally to all wave propagation problems, including structural acoustics.
    - Solving directly in the time domain facilitates physical realism, but requires post-processing for quantities of acoustic engineering.
    - Extreme speed, memory, resolution advantage over mode-based or frequency-domain methods (order(s) of magnitude).
    - Nonlinearities handled naturally, unlike modal methods.

    - *Upshot:* strongly coupled problems at higher frequencies.
    - Status: technology is proven, commercially available (PZFLEX, ABAQUS, others?), but not universal yet.

Computational Structural Acoustics

Technology Innovations

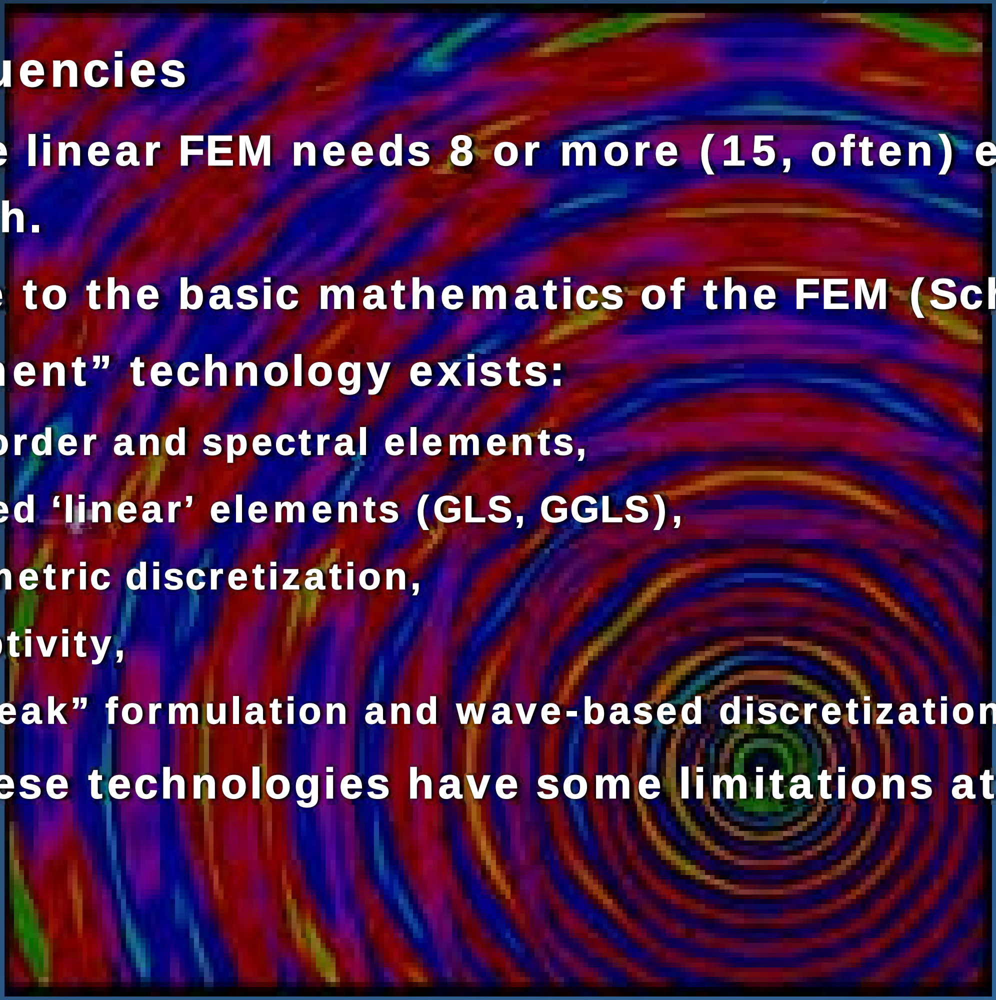


- Strongly coupled problems (continued)
  - *Iterative solvers* may be applied to coupled structural acoustics problems, with some of the advantages of explicit methods.
  - Apply to either / both of frequency-domain solutions or implicit transient.
  - Krylov methods (QMR, GMRES, Bi-CG) are most successful: structural acoustic FEA matrices are indefinite.
  - Newer Arnoldi moment-matching methods apply also.

  - *Upshot:* strongly coupled problems at higher frequencies.
  - Status: technology is proven, commercially available (COMSOL, ACTRAN, others?), but not universal yet.

Computational Structural Acoustics

Technology Innovations



- Higher Frequencies
  - Workhorse linear FEM needs 8 or more (15, often) elements per wavelength.
  - This is due to the basic mathematics of the FEM (Schatz, 1970)
  - New “element” technology exists:
    - Higher order and spectral elements,
    - Improved ‘linear’ elements (GLS, GGLS),
    - Isogeometric discretization,
    - *hp*-adaptivity,
    - “Ultraweak” formulation and wave-based discretizations.
  - Most of these technologies have some limitations at present.

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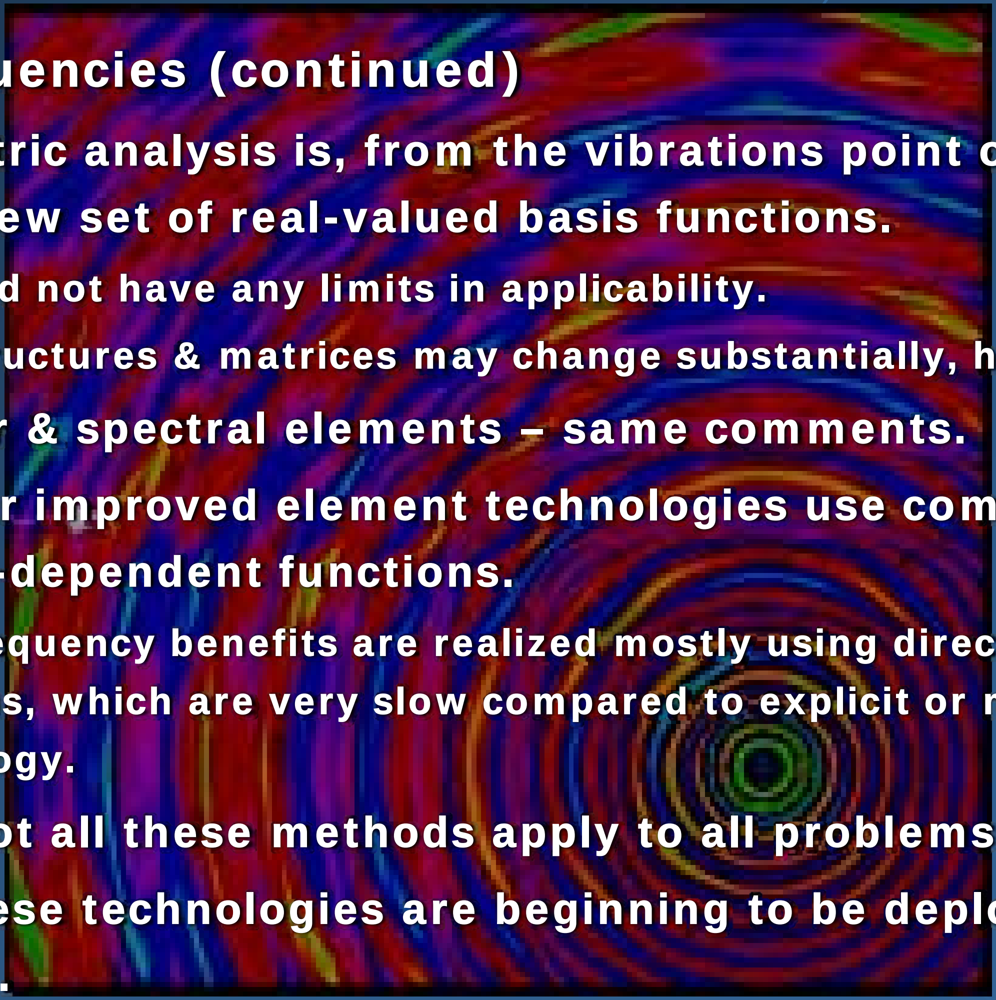
Technology Innovations



- Higher Frequencies (continued)
  - Isogeometric analysis is, from the vibrations point of view, simply a new set of real-valued basis functions.
    - It should not have any limits in applicability.
    - Data structures & matrices may change substantially, however.
  - High-order & spectral elements – same comments.
  - Many other improved element technologies use complex, frequency-dependent functions.
    - High-frequency benefits are realized mostly using direct linear solutions, which are very slow compared to explicit or modal technology.
  - *Upshot:* Not all these methods apply to all problems of interest.
  - Status: these technologies are beginning to be deployed (COMSOL).

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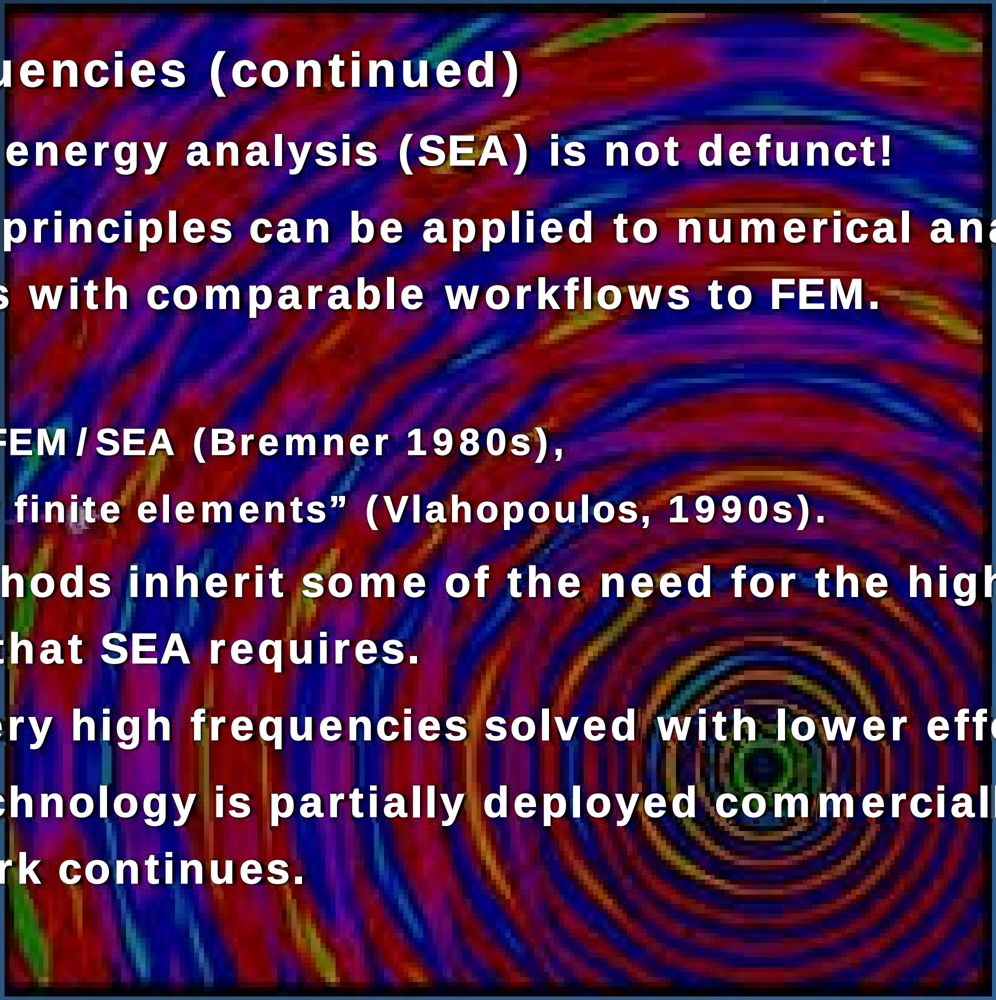
Technology Innovations



- **Higher Frequencies (continued)**
  - Statistical energy analysis (SEA) is not defunct!
  - Analytical principles can be applied to numerical analysis techniques with comparable workflows to FEM.
  - Examples:
    - Hybrid FEM / SEA (Bremner 1980s),
    - “Energy finite elements” (Vlahopoulos, 1990s).
  - These methods inherit some of the need for the high user expertise that SEA requires.
  - *Upshot:* very high frequencies solved with lower effort.
  - Status: technology is partially deployed commercially (VA One, EFEA); work continues.

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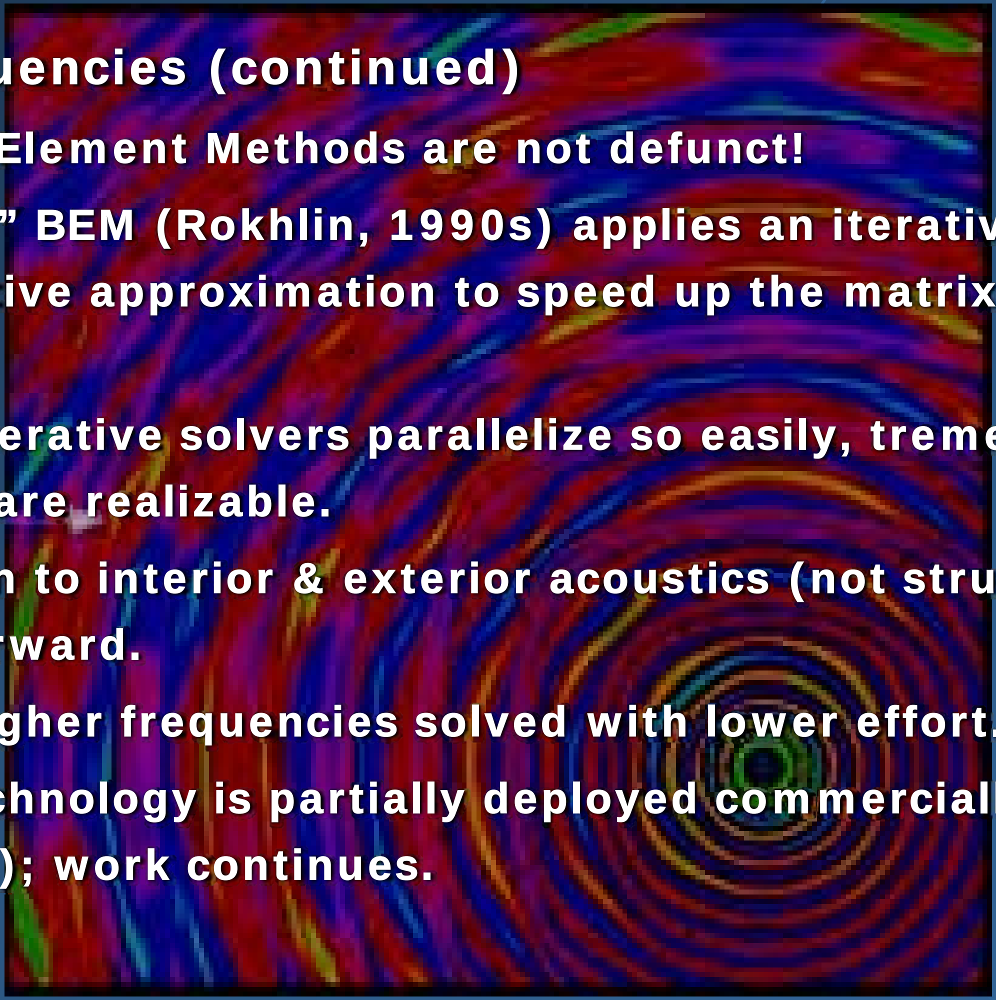
Technology Innovations

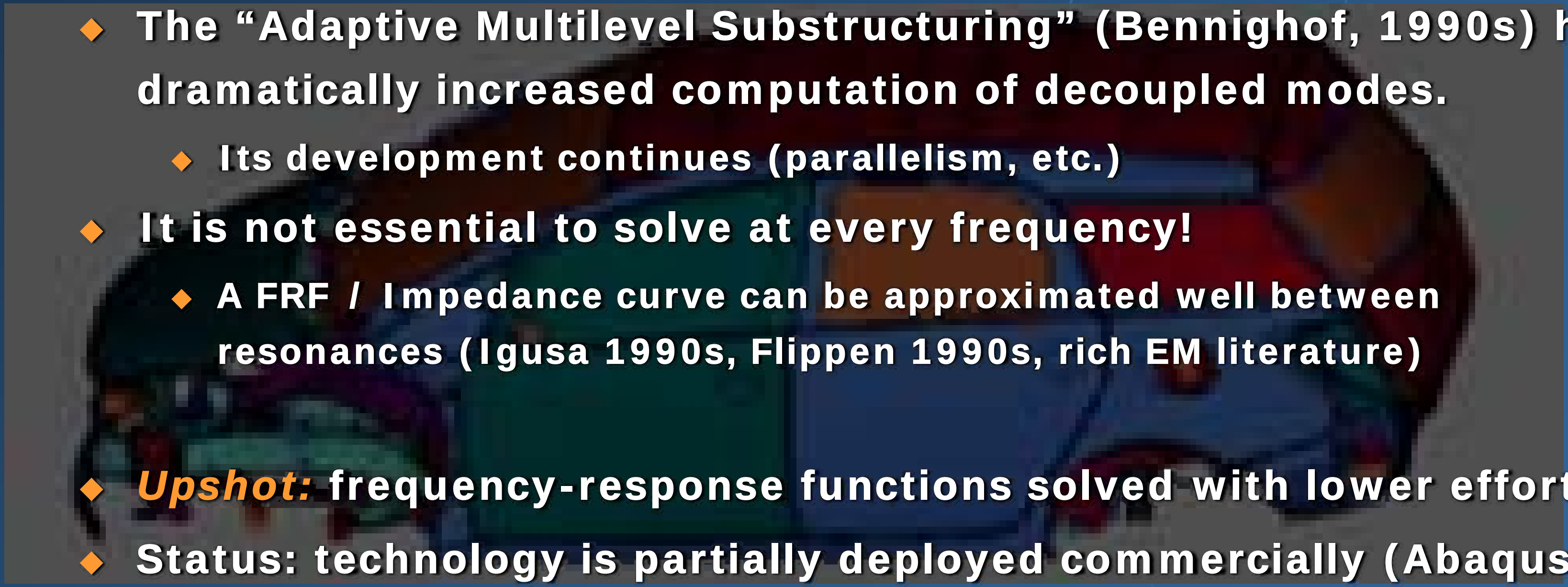


- Higher Frequencies (continued)
  - Boundary Element Methods are not defunct!
  - "Multipole" BEM (Rokhlin, 1990s) applies an iterative solver and an innovative approximation to speed up the matrix-vector products.
  - Because iterative solvers parallelize so easily, tremendous speedups are realizable.
  - Application to interior & exterior acoustics (not structures) is straightforward.
  - *Upshot:* higher frequencies solved with lower effort.
  - Status: technology is partially deployed commercially (LMS SYSNOISE); work continues.

Computational Structural Acoustics

Technology Innovations

- Speeding up the "conventional approach".
  - Buying faster machines is lazy, but fairly effective.

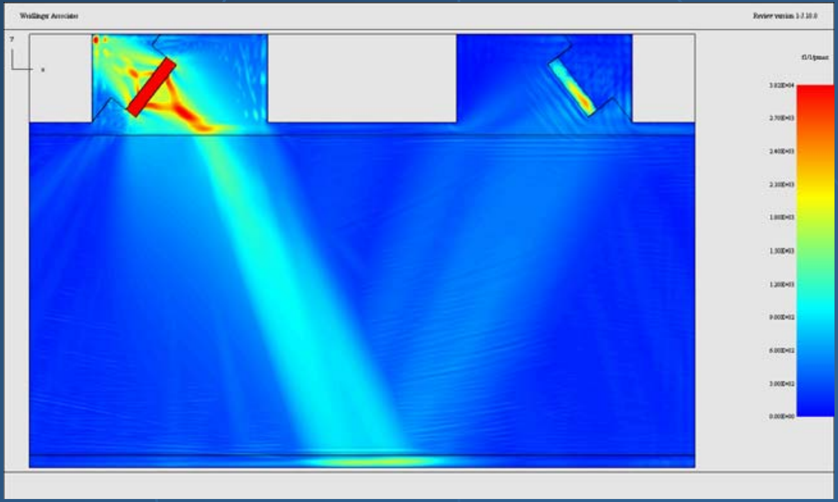


  - The "Adaptive Multilevel Substructuring" (Bennighof, 1990s) has dramatically increased computation of decoupled modes.
    - Its development continues (parallelism, etc.)
  - It is not essential to solve at every frequency!
    - A FRF / Impedance curve can be approximated well between resonances (Igusa 1990s, Flippen 1990s, rich EM literature)
  - *Upshot:* frequency-response functions solved with lower effort.
  - Status: technology is partially deployed commercially (Abaqus, NASTRAN, Cadoe, ANSYS); work continues.

Computational Structural Acoustics

Technology Innovations

- Multi-physical effects
  - Flow noise
  - Electrical fields: piezoelectricity
  - Porous media
  - Unresolved scales of vibration
  - Magnetic fields (magnetostriction)
  - Heat generated by vibration



- Status: many codes handle at least some of the problems (PZFLEX, Abaqus, ANSYS, SYSNOISE, ACTRAN, COMSOL), but a robust universal solution is unavailable.
- *Upshot:* these problems remain at the expert level.

Computational Structural Acoustics

The Near Horizon

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The Near Horizon

- Enhancements to the Conventional Approach
  - Software vendors will broaden the deployment of:
    - *coupled modes,*
    - *faster frequency sweeps, and possibly*
    - *enhanced element technology.*
- Explicit time-domain (XTD) methods will gain acceptance among structural acousticians.
  - Speed and memory advantages will be telling.

Computational Structural Acoustics

The Near Horizon

- The Market for structural acoustics simulations
  - **Automotive** industry will remain the most important, and therefore innovations in the “conventional” approaches will be very important to software vendors.
  - **Acoustic devices**: more aggressive deployment of innovative technology, especially as devices increase in complexity and analytic solutions falter.
  - **Aircraft**: greater emphasis on the higher frequency problems; greater acceptance of AMLS and XTD.
  - **Shipbuilding**: new generations of submarine construction renew interest in underwater acoustic stealth.
  - **Biomedical**: multiphysics effects, deeper pockets for advanced technology.

Computational Structural Acoustics

The Near Horizon

- Structural acoustics workflows
  - Increased acceptance of computations by acousticians (Asia & Europe are ahead of the US here).
    - This is partially driven by the retirement of the generation which can perform complex analytical studies without FEM.
  - Closer integration of structural acoustics into the offerings of large vendors.
  - Assimilation of structural acoustics education and practice into finite element workflows.
  - Increased innovation in structural-acoustics multiphysics: heating, piezoelectric, etc. effects.

Computational Structural Acoustics

Conclusion

Computational Structural Acoustics

Final Comments

- Structural acoustics has benefited greatly from the overall progress of FEM.
- The finite element method dominates computational structural acoustics and is the technology with the most momentum.
- Niche markets are retained by SEA, FD and BEM.
- New technology particular to structural acoustics is being introduced.
- Industrial usage of computations in acoustics will increase, as the quality of the competition / threat increases.

Computational Structural Acoustics

Questions?