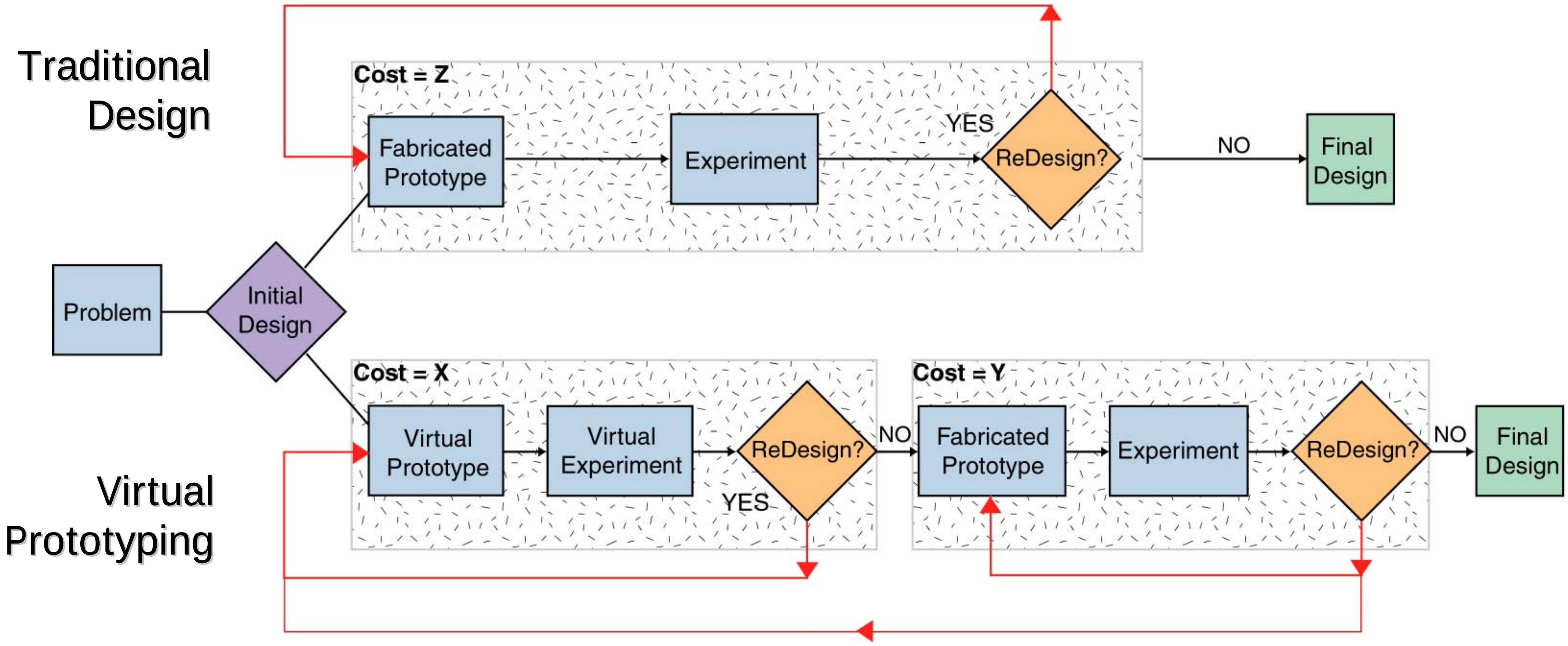
Section 4

Effective Use of FEA

Effective Use of FEA

- Desired outcome - Virtual Prototyping
  - Accurate prediction of system behaviour
  - Economic
    - Faster/cheaper than actual prototyping
  - Combination of modelling system components must be right
    - FE software
    - Hardware
    - User knowledge and approach
      - Material properties often critical

Virtual and Real Prototype



Successful Simulations

- Approaching computer simulations
  - – Identify problem and physical effects
    - Select appropriate simulation tool
  - – Desired data
    - What are the output quantities you wish to know?
    - Qualitative or quantitative?
  - – Input values
    - What is the structure you are interested in (sizes etc)
    - What are the properties of the materials?
    - What are the driving conditions? (pressure, voltage etc)

Successful Simulations

- Approaching computer simulations
  - Simplify, then make more complex
    - Solve smallest model possible
      - 1D, 2D, 2D axisymmetric, simple 3D
        - FE may be overkill
      - Much can be learned from simple models
        - Make more mistakes, faster
  - Solve one step at a time – validate
    - Experimental validation <u>essential</u>
  - Make good notes on previous simulations
    - Input file comments
  - Several focused models better than one ‘all-encompassing’ model

Successful Simulations

- User
  - All FE packages have steep learning curve
    - Particularly for nonlinear
    - Learning a second FE package faster
      - If good habits developed with first
      - Like programming language
  - Requires regular use to maintain skill
    - Occasional use difficult
  - Ideally understands FE and ultrasound
    - Or has access to knowledgeable support
  - Justify <u>all</u> assumptions

Writing FEA Software

- Identify Problem
  - Select appropriate equations to solve
    - Too simple? Too complex?
    - Basic assumptions?
  - Implement into FE software
    - Adapt existing software, or start anew?
    - Does programmer understand the physics?
      - Tight teamwork required
- Does it work?

Writing FEA Software

- FE Software must be Verified and Validated
- Verify
  - Can it solve the appropriate equations accurately?
- Validate
  - Does the model match reality?
    - Under all reasonable states
- Is it usable?
  - Algorithms and their encoding < 10% of development time

Writing FEA Software

- Verify
  - One component at a time
  - Compare to exact solution
  - Errors with grid size
  - Monitor values such as energy, momentum etc
  - Benchmark against other codes?
  - Skeptical of results
  - Peer review
  - IEEE estimates 7 bugs per 1000 lines of code

Writing FEA Software

- Validate
  - Confirm modelled results
    - Compare to experiments
    - Model first, then compare
  - Too many combinations to cover every case
  - Peer review often not practical
- Almost impossible to be 100% accurate, 100% of the time

Writing FEA Software

- How long to solve?
  - Are practical problems solvable economically?
  - Simplify to increase speed/reduce memory?
    - Still sufficiently accurate?
- Implement more efficiently, new algorithms?
- Other considerations
  - Fit within existing framework
    - May require to work with sub-optimal approach
  - Manageable within time/cost frame?
  - Difficulty of use

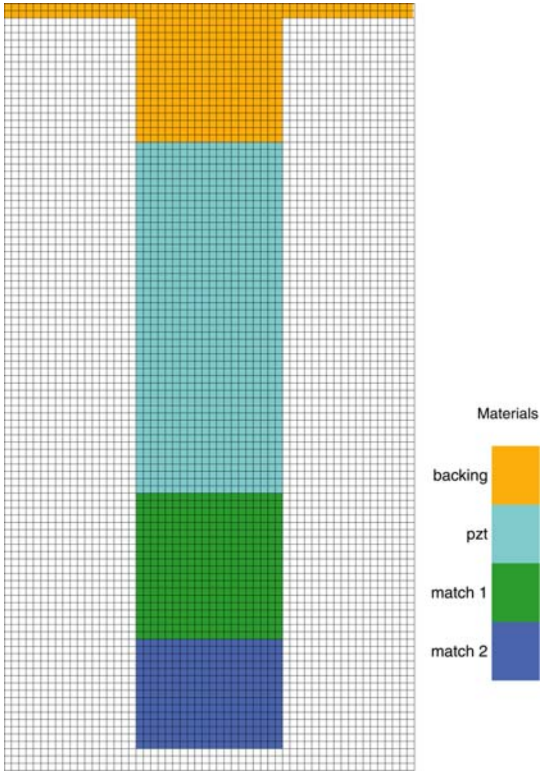
Accurate FEA

- Discrepancies
  - Basic equations/assumptions valid?
  - Incorrect implementation?
  - Fair experimental comparison?
  - Material properties
  - External components/circuits
- Material properties are the single largest cause of discrepancy to any FE results after Verification and Validation

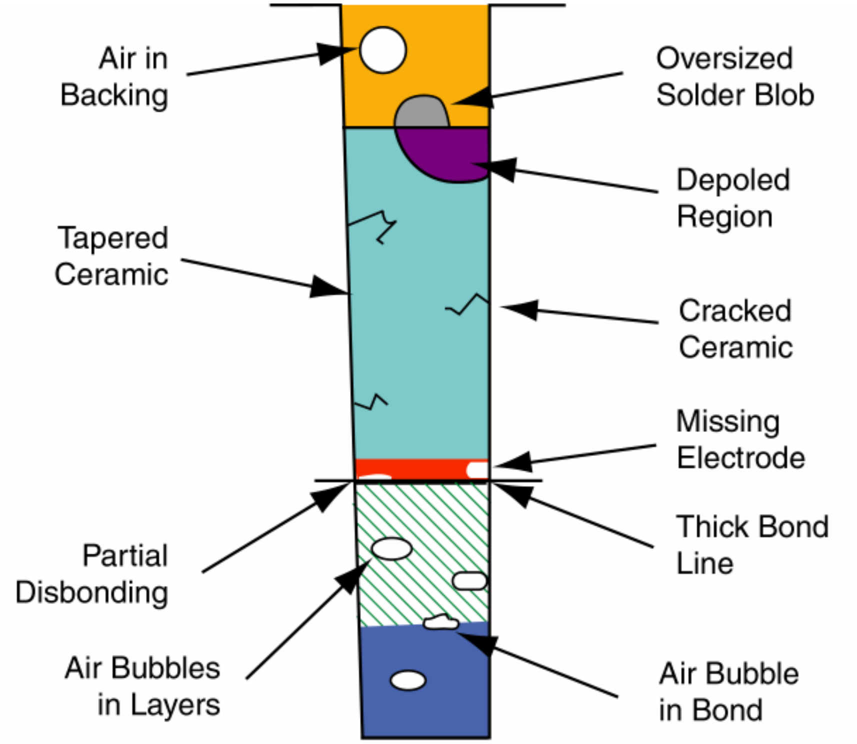
Accurate FEA

- Depends upon entire FEA ‘system’
  - Accurate representation of physical structure
  - Accurate material properties
  - Accurate driving signals
  - Appropriate boundary conditions and assumptions
  - Appropriate post-processing of data
  - Sufficient meshing to represent data

Accurate FEA



PZFlex Finite Element Model Compared to Possible Experimental Structure



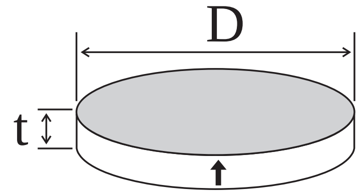
Ceramic and layers also taper in elevation. Layers and backing are inhomogenous on a scale large with respect to an element.

From original by C. Oakley

Active Materials Characterisation

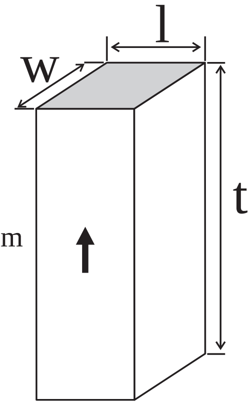
- IEEE Standard
- Standard Resonators
  - Isolate resonances
  - Extract properties using electrical impedances
  - Multiple samples required
  - Assumes consistency
- Material properties from manufacturers
  - Often incomplete
  - May vary between and within batches
- Method implemented in software, e.g. PRAP

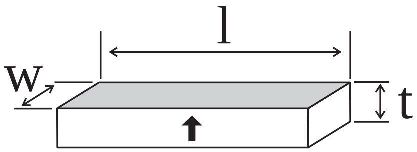
Active Material Characterisation



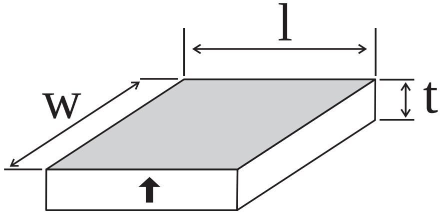
D>20t
t=0.5mm, D=10mm

t>5w, t>5l
w=l=0.1mm, t=0.5mm

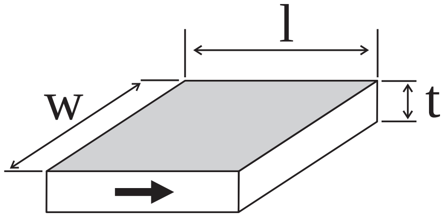




w<3t, l>10t, l>3w
w=1.0mm, l=7.5mm, t=0.5mm



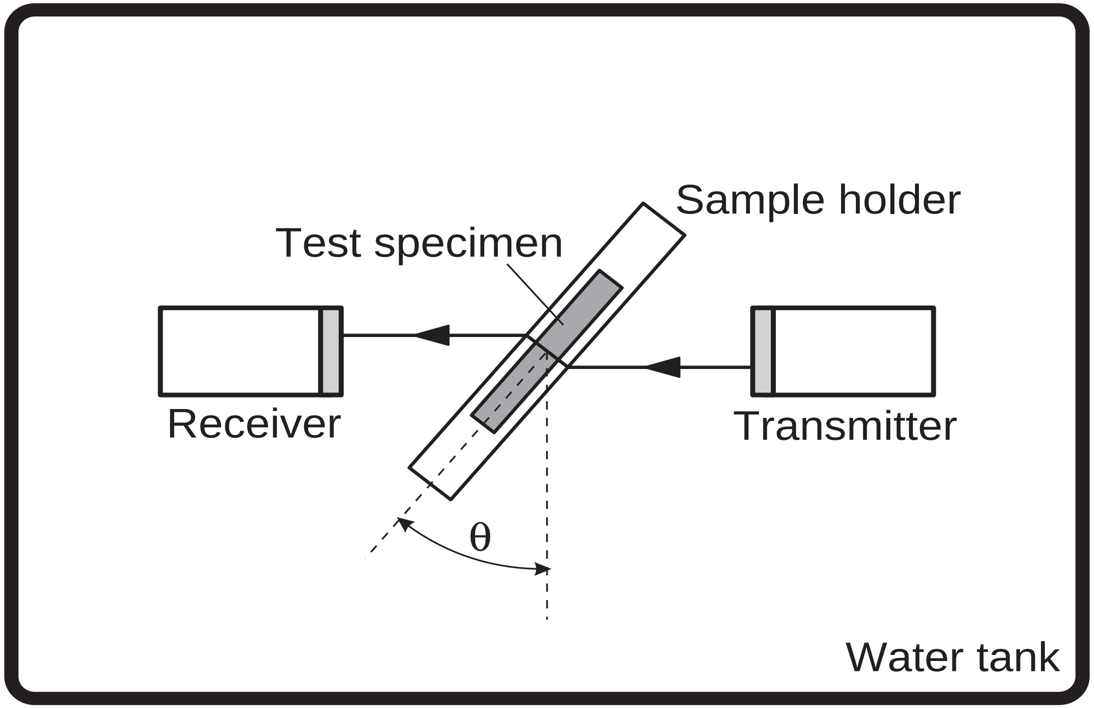
w>10t, l>10t
w=l=7.5mm, t=0.5mm



w>10t, l>10t
w=l=7.5mm, t=0.5mm

IEEE standard resonators, used to extract piezoelectric material parameters.

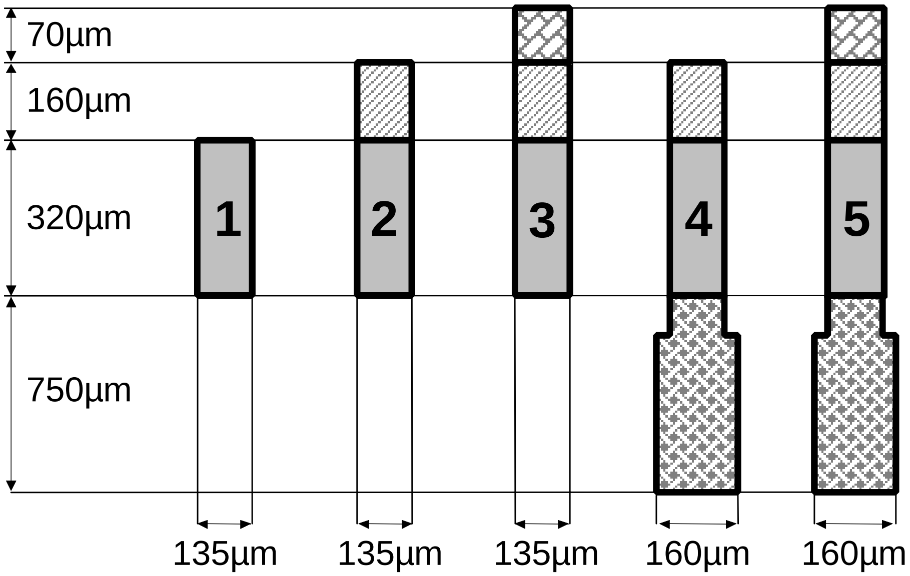
Passive Material Characterisation



Accurate FEA

- Treat like a ‘Virtual Experiment’
  - Isolate variables
- Characterise Materials
- Model – Build – Test (at first)
  - Validate each step
  - Confidence in Model
- Build database of materials
- Fewer steps with experience

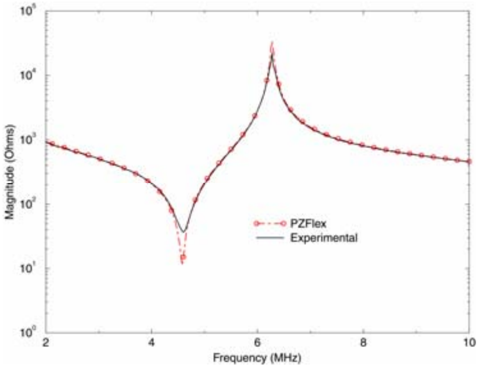
Model-Build-Test Array Components

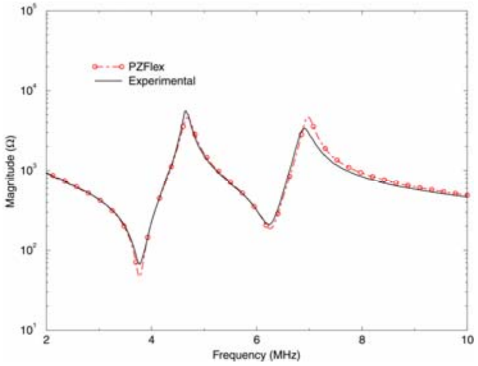


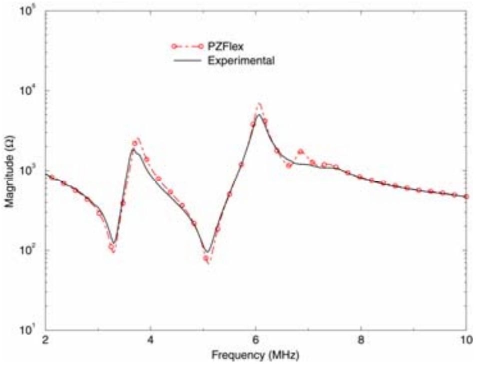
▩ 3203HD PLZT
▨ Inner matching layer - ML#107
▧ Outer matching layer - ML#103
▦ Backing

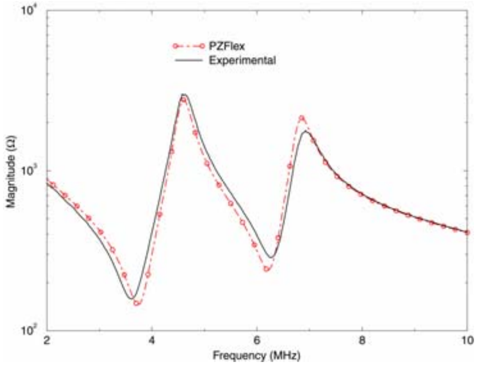
Element length = 8mm

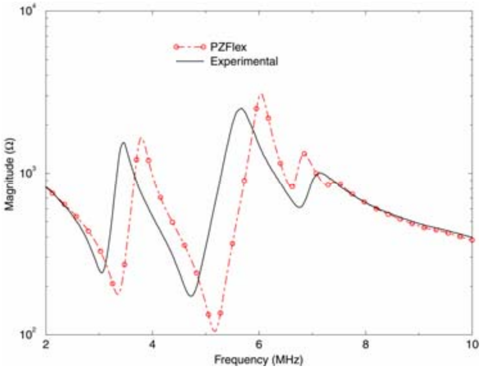
MBT - Electrical Impedance











- Experimental and PZFlex Impedance profiles for samples 1 through 5

Hardware

- FE requires computer system to run
  - Important to understand some basic concepts
- Traditionally 2 ‘classes’ of systems
  - Supercomputer
  - Desktop PC
    - Inexpensive, reasonably powerful since mid-90s
    - Beowulf clusters
      - Collections of inexpensive PC type systems
      - Can rival smaller supercomputers at lower costs
      - Require specialised software

Definitions

- Single Precision, 4 bytes (32 bits)
  - Integer: 4,294,967,296 ($4x10^{9}$)
  - Floating Point: $\pm10^{-38}$, $\pm10^{-38}$
  - 6 to 9 significant figures (usually ~7)
- Double Precision, 8 bytes (64 bits)
  - Integer: 18,446,744,073,709,551,616 ($18x10^{18}$)
  - Floating Point: $\pm10^{308}$, $\pm10^{-308}$
  - 15 to17 significant figures (usually ~16)

Precision

- Single precision usually sufficiently accurate
  - Larger errors exist elsewhere
  - Commodity hardware of 1990s struggles with double precision
- Double precision needed in some calculations
  - High accuracy required
  - Some non-linear problems
- Performance difference disappearing between single/double precision
  - On commodity hardware

Memory

- RAM required to store FE data during computation
  - Ideally RAM > problem size – disk impractical
- Must ensure CPU is ‘fed’ with data
  - Balance memory bandwidth, size with processor
- Integer values used for memory allocation
  - 32 bit systems limited to 4GB RAM
  - 64 bit systems needed for large memory
  - Intel, AMD, now have <u>commodity</u> 64 bit CPUs
  - 64 bit OS now available (Linux, 64 bit Windows)
    - >4GB systems practical and affordable

Parallel Computing

- Multi-core processors now available/affordable
    - Parallel computing becoming more common
- FE codes need to parallelise
    - Single system multiple processors
        - Open MP (SMP)
    - Multiple systems
        - Message Passing (MPI)
        - Data sent between multiple running programmes
        - Split problem into pieces
        - ‘Beowulf’, Linux

Optimization Driven by Simulation

- Large scale multiphysics simulations common
- Optimization problems
  - goal functions calculated through simulation
- Optimal design and material characterization are two central applications in this area

Modeling and Design Driven by Optimization

- FEA now sufficiently accurate and powerful
- Current design methodologies
  - Engineer directed iterations to existing designs,
  - Device parameter sweeps
- To help engineer need
  - Design goals, design parameters, parameterized models
  - Non-trivial with several design variables
  - Optimization can help to automate much of this process

Optimizer Choice

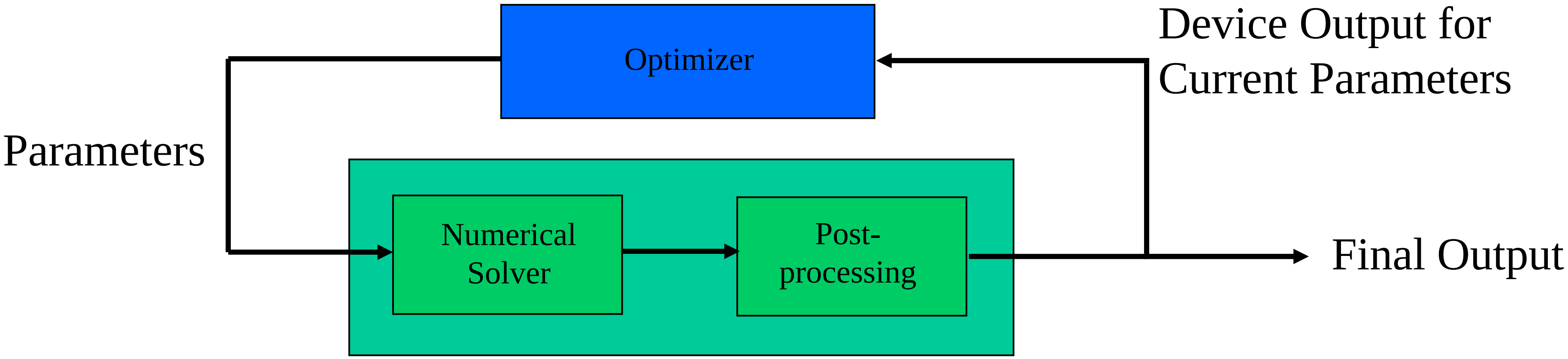
- Optimizer steers process towards stated goal
  - Variation of parameters
  - Updated parameters produce new output
  - Optimizer adjusts parameters accordingly
- Iterative technique
- Derivatives sometimes used
  - Not always available
  - Speed rapidly decreases with increasing number of parameters
  - Can lead to instability

Impact on Optimization Methods

- Individual iterations can be computationally expensive
- Effective optimization requires
  - Moderate number of iterations for convergence
  - No derivatives required
  - Amenable to block partition and parallelization
  - Global optimization capabilities

Optimization Method

- Model must be parameterised
  - Important design consideration must be variable
  - e.g. thickness, diameters, drive conditions, material properties
- Goal must be clearly defined
  - Must be numerical function
  - e.g. pressure amplitude, bandwidth, resonant frequency

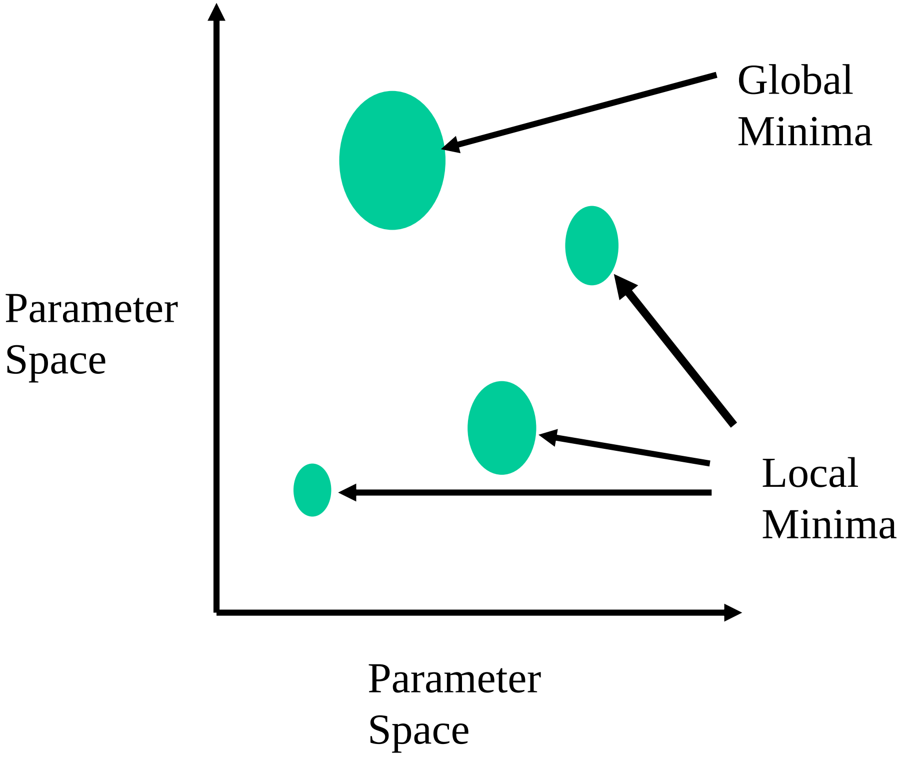


Optimization Method

- Initial steps
  - Small perturbations around initial parameter values
  - Then larger steps around parameter space
- Optimizations may need hundreds of iterations
  - Model runtime significant factor
  - Runtime of minutes is good, seconds is better!
  - Parallel simulations on commodity hardware reduce solve time economically

Optimization Method

- Several function minima (or maxima) may exist within parameter search space
- Optimizer may become ‘trapped’ in local minima
- Multiple start points in parallel approach reduce chance of this occurring
  - Keep database of previous searches



Modeling + Optimization

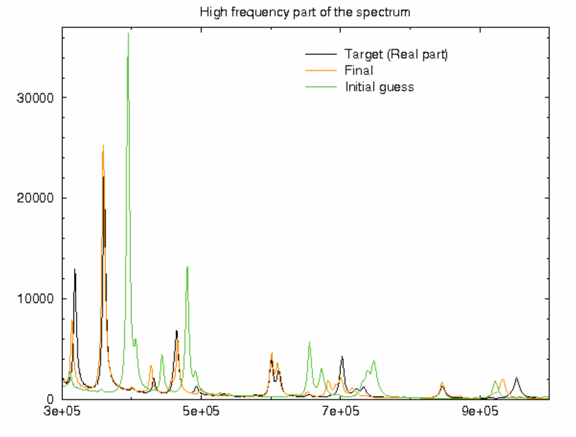
- Optimizer can aid in improving device design
  - In conjunction with FE
  - Speed of solution significant factor
- Variety of optimization options
  - Several considerations
    - Stability
    - Speed
    - Number of parameters
    - Learning capability
    - Parallel capability

Modeling + Optimization

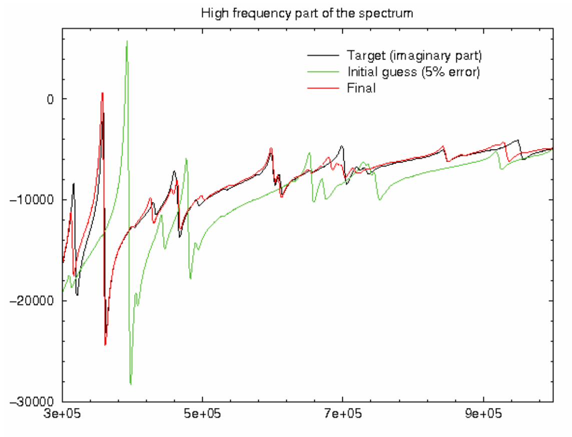
- Optimizer may get stuck in local minima
- Target function choice can significantly affect final outcome
- Highly parallel approach attractive

Material Characterisation and Optimization

Real



Imaginary



- Optimizer may be used to ‘back-out’ material properties from experimental results
- Multi-mode structures result in almost all parameters found
- Accuracy dependant upon piezoelectric sample

Summary

Summary

- Effective modelling
  - Start simple and keep it simple
    - component models - 1D, 2D, 2D axisymmetric
    - smaller, run faster and are easier to understand
  - Investigate meshing issues, parameter variations on small models before starting on larger models
  - Don’t make models more detailed or complicated than they have to be
  - Return to small component models to investigate anomolies
    - run parameter studies

Summary

- Effective modelling
  - Try new ideas and features on a small scale before putting them in large calculations
  - Check your material properties
  - Compare to experiment
  - Be skeptical
  - Detailed comments/notes
  - Justify all assumptions

Summary

- Hardware
  - Commodity hardware most economical
  - 64 bit hardware and OS now available
  - Balance processor and memory
  - >4GB now manageable
  - Multi-core CPUs becoming common
    - Parallel models
  - Numerical optimization offers benefits
    - Field of study in itself

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References

- Basic FEA of Piezoelectrics

  - H.Allick and T.J.R Hughes, “Finite Element Method for Piezoelectric Vibration”, Int. J. Num. Meth. Eng, vol 2, 1970, pp151-157
  - Y. Kagawa and T. Yamabuchi, “Finite Element Simulation of Two-Dimensional Electromechanical Resonators”, IEEE Sonics and Ultrasonics, vol su-21, 4, Oct 1970, pp 275-283
  - D. Boucher, M. Lagier and C. Maerfeld, “Computation of the Vibrational Modes for Piezoelectric Array Transducers using a Mixed Finite Element-Perturbation Method”, IEEE Sonics and Ultrasonics, vol su-28, 5, Sept 1981, 318-330
  - R. Lerch and H. Kaarmann, “Three-Dimensional Finite Element Analysis of Piezoelectric Media”, IEEE Symposium on Ultrasonics, 1987, pp853-858
  - J.J. Jeng, X.Q.Bao, V.V. Varadan and V.K. Varadan, “A Complete Finite Element-Eigenmode Analysis for a 1-3 Type of Piezoelectric Composite Transducer Including the Effect of Fluid Loading and Internal Losses”, IEEE Symposium on Ultrasonics, 1988, pp 685-688
  - J.A.Hossack and G.Hayward, “Finite-Element Analysis of 1-3 Composite Transducers”, IEEE Transactions on UFFC, Vol. 38, 6, Nov 1991, pp618-629
  - A.C. Hladky-Hennion and J.N. Decarpigny, “Finite Element Modeling of Active Periodic Structures: Application to 1-3 Piezocomposites”, J.Acoust.Soc.Am. 94 (2), Pt. 1, Aug 1993, pp621-635
  - G.L. Wojcik, D.K. Vaughan, N. Abboud, J. Mould, “Electromechanical Modeling using Explicit Time-Domain Finite Elements”, IEEE Symposium on Ultrasonics, 1993, pp 1107-1112
  - D.F. Ostergaard and T.P. Pawlak, "Three-dimensional finite elements for analyzing piezoelectric structures," 1986, IEEE Ultrasonics Symposium, pp 639-642

References

- FEA of Electromechanical Systems
  - M. Kaltenbacher, “Numerical Simulation of Mechatronic Sensors and Actuators”, Springer, 2004, ISBN-3-540-20458-X
- Acoustics and Materials
  - B.A. Auld, “Acoustic Fields in Waves and Solids”, Krieger, Vols I and II, ISBN 0-89874-784-X, 1st ed 1973, 2nd 1990
  - G.S. Kino, “Acoustic Waves: Devices, Imaging and Analog Signal Processing”, Prentice-Hall, 1987, ISBN 0-13-003047-3
  - W.P. Mason, “Electro-mechanical Transducers and Wave Filters”, Van Nostrand, 1942
- PseudoSpectral Methods
  - B. Fornberg, “A Practical Guide to Pseudospectral Methods”, Cambridge, 1996, ISBN 0-521-49582-2
  - G. Wojcik, B. Fornberg, R. Waag, L. Carcione, J. Mould, L. Nikodym, T.Driscol, “Pseudospectral Methods for Large-Scale Bioacoustic Models”, IEEE Sympisium on Ultrasonics
- Nonlinear Waves
  - R.T. Beyer, “Nonlinear Acoustics”, Acoustical Society of America, 1997, ISBN 1-56396-724-3

References

- Materials Characterisation and Properties
  - F. A. Duck, “Physical Properties of Tissue:A Comprehensive Reference Book”, Academic Press, 1990, ISBN 0-12-222800-6 and Properties
  - A.R. Selfridge, “Approximate Material Properties in Isotropic Materials”, IEEE Transactions on Sonics and Ultrasonics, su-32,3, May 1985
  - J. Wu, “Determination of Velocity and Attenuation of Shear Waves using Ultrasonic Spectroscopy”, J. Acoust.Soc.Am, 99 (5), May 1996, pp 2871-2875
  - S. Sherrit, H.D. Wiederick, B.K. Mukherjee, “ A Complete Characterization of the Piezoelectric, Dielectric and Elastic Properties of Motorola PZT 3203 HD including Losses and Dispersion”, Proceeding SPIE Medical Imaging, Feb 1997, Vol 3037
- Inverse Methods (Time Reversal)
  - M. Fink, F.Wu, J. Thomas, D. Cassereau, “Time-Reversal of Ultrasonic Fields – Parts I, II, and III”, IEEE UFFC, Vol 39, No. 5, Sept 1992, pp 555-592
  - M. Fink, G. Montaldo, M. Tanter, “Time-Reversal Acoustics in Biomedical Engineering”, *Annu. Rev. Biomed Eng..”,* 5, 2003, pp. 465-497.
- Attenuation and Dispersion
  - T.L. Szabo and J. Wu, “A Model for Longitudinal and Shear Wave Propagation in Viscoelastic Media”, J. Acoust. Soc. Am, 107 (5), Pt. 1., May 2000, pp 24372446

References

- FEA and NDT
  - W. Hassan, W. Veronesi, “Finite Element Analysis of Rayleigh Wave Interaction with Finite-size, Surface-breaking Cracks”, Ultrasonics, 41, 2003, pp 41-52
  - A. Gachagn, A. McNab, P.Reynolds, “Analysis of Ultrasonic Wave Propagation in Pipe Structures Using Finite Element Modeling Techniques” , IEEE Ultrasonics Symposium, 2004
- HIFU
  - G. ter Haar, “Ultrasound Focal Beam Surgery”, Ultrasound Med Biology, No. 21, No 9, 1995, pp. 1089-1100.
  - D.R. Daum, K. Hynynen,”A 256-Element Ultrasonic Phased Array System for the Treatment of Large Volumes of Deep Seated Tissue” IEEE UFFC, Vol 46, No 5, September 1999, pp11254-1268
  - G. Wojcik, J. Mould, Jr., F. Lizzi, N. Abboud, M. Ostromogilsky, and D. Vaughan, “Nonlinear Modeling of Therapeutic Ultrasound”, IEEE Symposium on Ultrasonics, 1995, pp1617-1622

References

- Model-Build-Test
  - D.J. Powell, G.L. Wojcik, C.S. DeSilets, T.R. Gururaja, K. Guggenberger, S. Sherrit, B.K. Muckheriee, “Incremental ”Model-Build-Test Validation Exercise for a 1-D Biomedical Ultrasound Imaging Array”, IEEE Ultrasonics Symposium, 1997
- Ultrasound Imaging
  - T.Szabo, “Diagnostic Ultrasound Imaging: Inside Out”, Academic Press, 2004 ISBN 0126801452
- Optimisation
  - L. Carcione, J. Mould, V. Pereyra, D. Powell, G. Wojcik, “Nonlinear Inversion of Piezoelectrical Transducer Impedance Data”, Journal of Computational Acoustics, 2001, Vol. 9, 3
- Numerical Precision
  - D. Goldberg, “What Every Computer Scientist Should Know About Floating-Point Arithmetic”, Computing Surveys, March, 1991