# SDT & OpenFEM
# A technical overview


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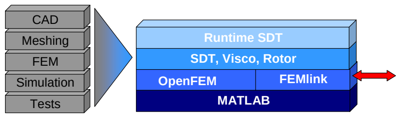
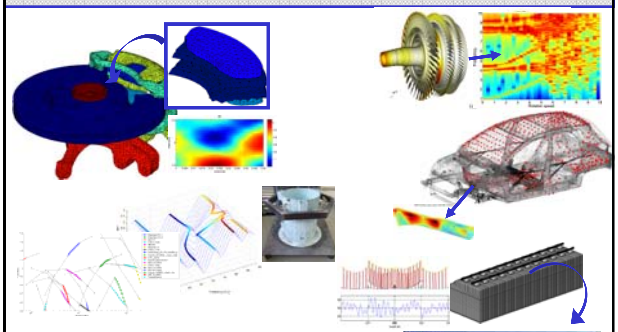
SDTools


## Structural Dynamics Toolbox

- Structural Dynamics Toolbox offers :
  - 3D Finite Element Modeling
  - Experimental Modal Analysis
  - Test / Analysis correlation
- With a modular approach
  - MATLAB environment
  - OpenFEM : Core software for Finite Element Modeling (co-developed with INRIA)
  - FEMlink : Import / export industrial modules
  - Runtime SDT : Customized and standalone compiled applications




## Current SDTools activities



Funding Bosch (squeal), SNECMA (full rotor), PSA (damping design), SNCF (train/track), VALEO (joint non linearities), …

## Why MATLAB ?

Requirements for a long term development environment

| | Matlab | Scilab | Python | Java |
|---|---|---|---|---|
| Ease of development | | | | |
| – Interactive operation on data structures | ☺ | ☺ | ☺ | x |
| – Prior declaration not required (automated memory management) but pre-allocation possible | ☺ | ☺ | 😐 | x |
| – Interactive debugger | ☺ | ☹ | 😐 | ? |
| – Profiler | ☺ | ☹ | 😐 | ? |
| 90 % the code fully portable ⇒ | | | | |
| – virtual machine | ☺ | ☺ | ☺ | ☺ |
| – Performance of interpretation (in-line compiler) | ☺ | ☹ | ? | x |
| Native support of math libraries | ☺ | ☺ | 😐 | x |
| Native support of sparse libraries | ☺ | ☺ | ☹ | x |
| Allow links of few specific libraries to C, C++, Fortran, Java (compile only the small part that needs it) | ☺ | ☺ | ☺ | ☺ |

- MATLAB best (SDT/OpenFEM)
- Python only alternative (ABAQUS, Code_Aster)

Problems

- Memory handling : argument passing without copy often critical (pre-allocation) but user need to pay attention
- MATLAB not perceived as capable of handling large jobs
- NOT FREE : cheap licenses but many users because interactive
- FREE deployment of MATLAB Runtime

## Application areas

Mechanics/dynamics problems are at the interface of many scientific/software areas

| | |
|---|---|
| CATIA, IDEAS, ProEngineer, … | CAD |
| PATRAN, … | Meshing |
| NASTRAN, ABAQUS, ANSYS,... | FEM |
| Adams, Simulink,... | Simulation |
| CADA-X, IDEAS Test, … | Testing |

Simulation ↓ ↑ Validation

## FEM (3) : OpenFEM / SDT architecture

**Preprocessing**
- Mesh manipulations
- Structured meshing
- Property/boundary condition setting

**Import**
- Modulef, GMSH, GID
- NASTRAN, IDEAS, ANSYS, PERMAS, SAMCEF, ABAQUS, MISS, GEFDYN

**FEM core**
- Shape function utilities
- Element functions
- Matrix and load assembly
- Factored matrix object (dynamic selection of sparse library, additional solvers)
- Linear static and time response (linear and non linear)
- Real eigenvalues
- Optimized solvers for large problems, superelements, and system dynamics, model reduction and optimization, vibroacoustics, active control, …
- Drive other software (NASTRAN, MISS)

**Postprocessing**
- Stress computations
- Signal processing
- 3D visualization (major extension , optimized, object based)

**Export**
- VTK, MEDIT
- NASTRAN, IDEAS, SAMCEF
- Ensight, MISS3D, Gefdyn

OpenFEM, SDTools, MSSMat

## OpenFEM

OpenFEM toolbox (Collaboration with INRIA, LGPL license )

- Element library (2-D & 3-D, linear & non-linear, mechanics, acoustics, heat, …), load generation, stress evaluations
- Time and non-linear solvers
- Pre- and post-processing tools

Objectives for the partners:

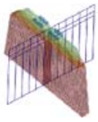
- augment use of general purpose FEM in the MATLAB environment
- INRIA : prototyping environment, demonstrate viability of MATLAB/Scilab type environment for FEM computations
- SDTools : share development costs for non core applications (2-D, non-linear mechanics, …)

## Meshing 1: unstructured

Meshing is a serious business that needs to be integrated in a CAD environment.

OpenFEM is a computing environment.

- IMPORT (MODULEF, GMSH, GID, NASTRAN, ANSYS, SAMCEF, PERMAS, IDEAS)
- Structured meshing
- Run meshing software : GMSH Driver
- 2D quad meshing, 2D Delaunay

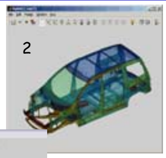


OpenFEM, SDTools

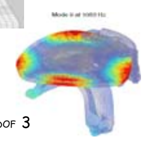
## SDT/FEMLink

- NASTRAN : read/write/drive
- ABAQUS read/write model and results (.fil)
- ANSYS : read model and element matrices, partial write model
- UFF : read/write model
- PERMAS : read/write model and matrices
- SAMCEF read model and matrices, write topology …

- Focus on very large model and matrix support







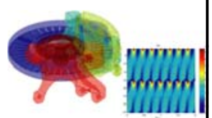
1. ESA ESTEC, 2e6 DOF, 8 GB modal base
2. PSA Peugeot Citroen : body with partial trim 1.2 MDOF
3. Bosch : brake model with contact for squeal

3

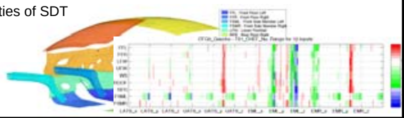
## Why NASTRAN, ANSYS … and SDT ?

Typical reasons to use your FEM and SDT

- Post-processing
  ⇒ extract response from full model output, generate state-space models, visualize, …
- Pre-processing
  ⇒ generate parts of your job, for example in a shape optimization process
- Serve as base for your in-house developments (example Bosch time simulation of squeal)
- Integrate pre- and post-processing in an optimization process (example PSA topology optimization for vibroacoustic response)



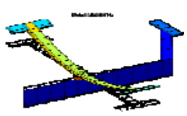
- Model reduction capabilities of SDT



## Meshing 1 : structured example

```
femesh

FEelt=[];
FEnode = [1 0 0 0  0 0 0;2 0 0 0  0 0 .15;
        3 0 0 0 0.4 1.0 .176;4 0 0 0 0.4 0.9 0.176];
% fuselage
femesh('objectbeamline 1 2');
femesh('extrude 0  1.0 0.0 0.0', …
  [linspace(0,.55,5) linspace(.65,1.4,6) 1.5]);
femesh('addsel;');

% vertical tail
femesh('objectbeamline',femesh('findnode z==.15 & x>=1.4'));
femesh(';extrude 3 0 0 .1;addsel;');
% vertical horizontal tail
femesh('objectbeamline',femesh('findnode z==.45'));
femesh('extrude 0  0.0 0.2 0.0',[-1 -.5 0 .5 1]);
femesh('addsel;');

% right drum
femesh(';objectbeamline 3 4;extrude 1 .4 0 0');
femesh('divide',[0 2/40 15/40 25/40 1],[0 .7 1]);
femesh('addsel;');

% left drum
femesh(';symsel 1 0 1 0;addsel;');
```

- Structured meshing
- Mapped divisions
- Objects (beam, circle, tube, …)



```
  Node: [144x7 double]
   Elt: [100x9 double]
    pl: [2x6 double]
    il: [4x6 double]
   bas: []
 Stack: {}
```

## Meshing 2 : femesh/feutil

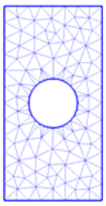
- Add FEeli FEelj, AddSel
- AddNode [,New] [, From i]
- AddTest [,NodeShift,Merge]
- Divide div1 div2 div3
- DivideInGroups
- DivideGroup i ElementSelectors
- EltId
- Extrude nRep tx ty tz
- FindDof ElementSelectors
- GetDof
- Find [Elt,El0] ElementSelectors
- FindNode Selectors
- GetEdge[Line,Patch]
- GetElemF
- GetLine
- GetNode Selectors
- GetNormal[Elt,Node][,Map]
- GetPatch
- Info [ ,FEeli, Nodei]
- Join [,el0] [group i, EName]
- model [,0]
- Matid,ProId,MPID

- ObjectBeamLine i, ObjectMass i
- ObjectHoleInPlate
- Object[Quad,Beam,Hexa] MatId ProId
- Object[Circle,Cylinder,Disk]
- Optim [Model, NodeNum, EltCheck]
- Orient, Orient i [ , n nx ny nz] [,-neg]
- Plot [Elt, El0]
- Quad2Tria, quad42quadb, etc.
- RefineBeam
- Remove[Elt,El0] ElementSelectors
- Renumber
- RepeatSel nITE tx ty tz
- Rev nDiv OrigID Ang nx ny nz
- RotateSel OrigID Ang nx ny nz
- Sel [Elt,El0] ElementSelectors
- SelGroup i, SelNode i
- SetGroup [i,name] [Mat j, Pro k, EGID e, Name s]
- StringDOF
- SymSel OrigID nx ny nz
- TransSel tx ty tz
- UnJoin Gp1 Gp2

Generation, Selection, …

## Meshing 4: fe_gmsh

```
FEnode = [1 0 0 0  0 0 0; 2 0 0 0  1 0 0; 3 0 0 0  0 2 0];
femesh('objectholeinplate 1 2 3 .5 .5 3 4 4');
FEelt=FEel0;femesh('selelt seledge');model=femesh('model0');
model.Node=feutil('getnode groupall',model);

model=fe_gmsh('addline',model,'groupall');
mo1=fe_gmsh('write temp.msh -lc .3 -run -2 -v 0',model);
feplot(mo1); delete('temp.msh')
```



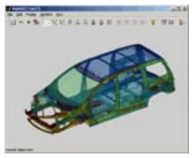
Default element size
GMSH options

- Good functionality for 2D and 3D
- Limited handling of complex surfaces
- Extensions for TETGEN and NETGEN

## Meshing 5: selection

Recursive node and element selections

| | |
|---|---|
| GID ~=i | EltId i |
| Group ~=i | EltInd i |
| Groupa i | EltName ~=s |
| InElt{sel} | EGID == i |
| NodeId > i | Facing > cos x y z |
| NotIn{sel} | Group i |
| Plane == i nx ny nz | InNode i |
| rad <=r x y z | MatId i |
| cyl <=*r i nx ny nz* | ProId i |
| Setname name | SelEdge type |
| x >a | SelFace type |
| x y z | Setname name |
| | WithNode i |
| | WithoutNode i |



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OpenFEM, SDTools, MSSMat

## FEM (1) : why MATLAB ?

MATLAB can be an efficient driver for all of FEM applications
- Very useful versatility in manipulating input to FEM
- Many steps can be performed in MATLAB itself
- MATLAB can be efficiently linked against external libraries (compile only the small part that needs it)
- Debugger and profiler allow quality and optimization

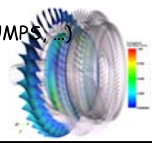
- Easy to manipulate
- Lower development costs
- No loss of performance

But
- Element level computations need to be compiled
- Argument passing without copy often critical
- MATLAB not perceived as capable of handling large jobs
- A different pricing strategy : cheap licenses but many users because interactive (need for SDT Runtime)

## FEM (2) : How big ?

- 64 bit OS no particular limitation : 2000e6 (int32) nodes/DOFs, typical failure for very large dataset : matrix factor (no out-of-core solver), very long time response, …
- 32 bit OS : models that have run 400.000 DOF car body, 150.000 engine blade, generally fails due to memory segmentation (largest block becomes small)

Current SDT trends out-of-core routines
- matrix read/multiply 52 bit (4096 TB)
- storage of datasets (v_handle pointer to data in file) for matrices, time responses, …
- coupling with external solvers (NASTRAN, MUMPS, …)
- Java3D rendering considered



*Multistage rotor with 21e6 nodes, SNECMA*

## ofact : gateway to sparse libraries

Kq=F is central to most FEM problems. Optimal is case/machine dependent. ofact object allows library independent code.

- Method : dynamic selection of method (OpenFEM, SDTools)

```
      lu : MATLAB sparse LU solver
    chol : MATLAB sparse Cholesky solver
 pardiso : PARDISO sparse solver
*umfpack : UMFPACK solver (NOT AVAILABLE ON THIS MACHINE)
->  spfmex : SDT sparse LDLt solver
  mtaucs : TAUCS sparse solver
 sp_util : SDT skyline solver
 *psldlt : SGI sparse solver (NOT AVAILABLE ON THIS MACHINE)
```

- Symfact : symbolic factorization (renumbering, allocation)
- Fact : numeric factorization (possibly multiple for single symfact)
- Solve : forward backward solve (possibly multiple for single fact)
- Clear : free memory

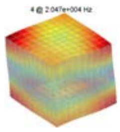
- Not tried : MUMPS, BCS-Lib, …

## ofact : performance test

| 10x10x100 elt<br>36 663 DOF | 10x20x100 elt<br>69 993 DOF | 10x40x100 elt<br>136 653 DOF | |
|---|---|---|---|
| 83 (0.8) | 363 (2.6) | 1706 (5.8) | SPOOLES, PIII 1 Ghz, Linux |
| 10 (0.2) | 90 (2.3) | 262 (6.0) | TAUCS snll + metis, PIII 1GHz Linux |
| | 39 (2.6) | | SPOOLES, AMD 64 4000+ Linux |
| 28 (0.17) | 99 (0.4) | | SPOOLES, Xeon 2.6 GHz, Windows |
| 6.8 (0.48) | 16 (1.1) | | MKL-Pardiso, Xeon 2.6 GHz, Windows |
| 32 (0.64) | | | CHOL Matlab 7.1 (R13SP3) Xeon 2.6 GHz, Windows |
| 56 (0.69) | | | LU Matlab 7.1 (R13SP3) Xeon 2.6 GHz, Windows |

*Fact (solve) CPU seconds*

- *All libraries can be accessible (OpenFEM, SDTools), best is application/machine dependent.*
- *Memory usage and fragmentation is another issue that may drive library selection*




## OpenFEM history

Start in 2001 from

- *Structural dynamics toolbox* .m file elements limited library
- *MODULEF* large library but no longer a convenient prototyping environment

Phase I -> OpenFEM 1.0 & 2.0

- Port of MODULEF elements (2D and 3D volumes, MITC4)
- Translation to SCILAB (stopped in 2006)

Phase II (current)

- Efficient non-linear operation (generic compiled elements, geometric non-linear mechanics, … )

## Design criteria

- Be a toolbox (easy to develop, debug, optimization only should take time)
- Optimize ability to be extended by users
- Performance identical to good fully compiled code
- Solve very general multi-physics FE problems
- Be suitable for application deployment

## Easy user extensions

- Object oriented concepts (specify data structures and methods)
- But non typed data structures (avoid need to declare inheritance properties)

Example user element

- Element name of .m file (beam1.m)
- Must provide basic methods (node, DOF, face, parent, …)
- Self provide calling format. Eg : beam1('call')
  [k1,m1]=beam1(nodeE, elt(cEGI(jElt),:), pointers(:,jElt), integ, constit, elmap, node);

Other self extensions

- Material functions
- Property functions (problem formulations)
- Non-standard topology definitions

## Shape function utilities (integrules)

Supported topologies are

- node1 (0 d topology)
- bar1 (1D linear)
- beam1,beam3 (1D cubic)
- quad4 (2D bi-linear), quadb (2d quadratic)
- tria3 (2D affine), tria6 (2D quadratic)
- tetra4, tetra10
- penta6, penta15
- hexa8, 20, 21, 27

Standard quadrature rules

```
» integrules('hexa8',3)
          N: [27x8 double]
         Nr: [27x8 double]
         Ns: [27x8 double]
         Nt: [27x8 double]
         Nw: 27
        NDN: [8x108 double]
  NDNLabels: {'' ',x' ',y' ',z'}
       jdet: [27x1 double]
          w: [27x4 double]
      Nnode: 8
         xi: [8x3 double]
       type: 'hexa8'
```

```
>> integrules('gauss q2d')
    [ -3]               []    'order default'
    [ -2]    [ 0x1 double]    'node'
    [ -1]    [ 1x4 double]    'center'
    [102]    [ 4x4 double]    'gefdyn 2x2'
    [  2]    [ 4x4 double]    'standard 2x2'
    [109]    [ 9x4 double]    'Q4WT'
    [  9]    [ 9x4 double]    '9 point'
    [  3]    [ 9x4 double]    'standard 3x3'
    [  2]    [ 4x4 double]    'standard 2x2'
    [ 13]    [13x4 double]    '2x2 and 3x3'
```

## Formulation library

Generic compiled elements

- Support any linear element without recompilation
- 3D elasticity with full anisotropy, 2D plane stress/strain
- 2 & 3D acoustic fluids, fluid/structure coupling
- Heat equation
- Piezo-electric volumes, poro-elasticity
- Gyroscopic effects

Other compiled families

- geometrically non-linear mechanics, mechanical or thermal pre-stress
- Hyper-elasticity, follower pressure

*Other elements*

- Shells. Laminated plate theory. Piezoelectric shells.
- 3D lines/points : Bar, Beam, Pre-stressed beam, spring, bush, mass

The OpenFEM specification is designed for multiphysics applications

99 DOF/node
999 internal DOF/element

SDT

# User elements


```
elseif  comstr(Cam,'node');  out = [1 2];
elseif  comstr(Cam,'prop');  out = [3 4 5];
elseif  comstr(Cam,'dof');   out=[1.01 1.02 1.03 2.01 2.02 2.03]';
elseif  comstr(Cam,'line');  out = [1 2];
elseif  comstr(Cam,'face');  out =[];
elseif  comstr(Cam,'sci_face'); out = [1 2 2];
elseif  comstr(Cam,'edge');  out =[1 2];
elseif  comstr(Cam,'patch');  out = [1 2];
elseif  comstr(Cam,'parent');   out = 'beam1';
```

```
[k1,m1]=beam1(nodeE, elt(cEGI(jElt),:),
pointers(:,jElt), integ, constit, elmap, node);
```

```
[ID,pl,il]=deal(varargin);
pe=pe(find(pe(:,1)==ID(1),3:end); % material properties
ie=ie(find(ie(:,1)==ID(2),3:end);

%          E*A nu      eta  rho*A       A lump
constit = [pe(1)*ie(4)  0    pe(3)*ie(4) ie(4) ie(7)];
integ=ID;%matid proid
Elmap=[];

out=constit(:); out1=integ(:); out2=ElMap;
```

# Generic compiled elements

Objective ease implementation of

- linear element families
- arbitrary multi-physic
- good compiled speed
- provisions for non linear extensions

Assumptions

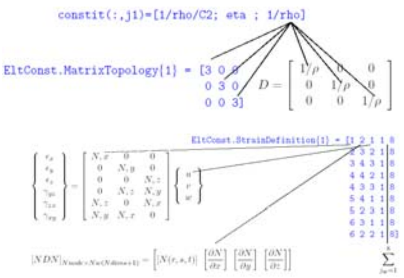
- Strain ε=[B]{q} linear function of N and ∇N
- Element matrix quadratic function of strain

$$k^{(e)} = \sum_{ji,jj} \sum_{jw} \left[ \{B_{ji}\} D_{ji\,jk}(w(jw)) \{B_{jj}\}^T \right] J(w(jw)) W((jw))$$

# Generic compiled elements

During assembly init define

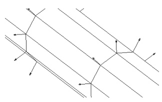
- D ↔ constit
- ε ↔ EltConst.NDN
- $K_e$ ↔ D,e (EltConst. MatrixIntegrationRule built in integrules MatrixRule)




EltConst=p_solid('constsolid','hexa8',[],[])
p_solid('constsolid','hexa8',[],[])
p_solid('constfluid','hexa8',[],[])

# OpenFEM current developments

- Support shape function tricks (MITC, average strain, …)
- Extend FieldAtNode interpolation
- 3D material orientation maps
- Better support of analytic expressions for loads



Waiting for real need

- Improve ease of development of NL constitutive laws
- Extend parallel operations beyond assembly

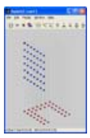
*INRIA MACS Simplified modeling of cardiac contraction with OpenFEM*

# Boundary conditions

Cases define :

boundary conditions, point and distributed loads, physical parameters, ...

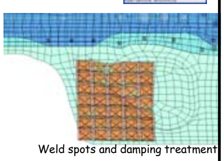
```
data=struct('sel','x==-.5', ...
          'eltsel','withnode {z>1.25}', ...
          'def',1,'DOF',.19);
model = fe_case(femesh('testubeam'),...
     'FSurf','Pressure load',data, ...
     'FixDof','Fixed boundary condition','x==0');
```



Supported boundary conditions

- KeepDOF, FixDOF
- Rigid
- MPC, Un=0

Typical handling by elimination



Weld spots and damping treatment

$$\left[Ms^2 + Cs + K\right]\{q(s)\} = [b]\{u(s)\}$$
$$\{y(s)\} = [c]\{q(s)\}$$
$$[c_{int}]\{q(s)\} = 0$$

$$\left[T^T M T s^2 + T^T C T s + T^T K T\right]\{q_R(s)\} = \left[T^T b\right]\{u(s)\}$$
$$\{y(s)\} = [cT]\{q_R(s)\}$$

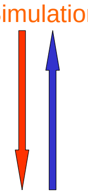
$$\text{range}([T]_{N\times(N-NC)}) = \ker([c_{int}]_{NS\times N})$$

# Application areas

Mechanics/dynamics problems are at the interface of many scientific/software areas

| | |
|---|---|
| CATIA, IDEAS, ProEngineer, … | CAD |
| PATRAN, … | Meshing |
| NASTRAN, ABAQUS, ANSYS,... | FEM |
| Adams, Simulink,... | Simulation |
| CADA-X, IDEAS Test, … | Testing |

Simulation

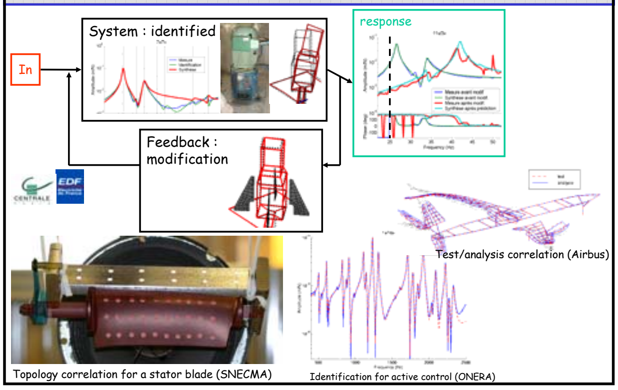


Validation

## SDT & not OpenFEM

- Large model optimization
- feplot (interactive mesh viewer), iiplot (curve viewer)
- Model reduction & superelements
- Sensors
- Experimental modal analysis
- Cyclic symmetry
- Active control with piezoelectric
- Parametric model analysis
- Non-conform mesh matching

## SDT & Vibration testing/EMA



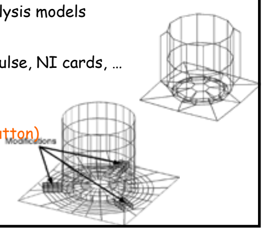

## SDT & Vibration testing/EMA

MATLAB is perfectly adapted for Experimental Modal Analysis

SDT provides
Frequency domain identification
Test / analysis correlation (topology, expansion, correlation, …)
GUI based ODS analysis

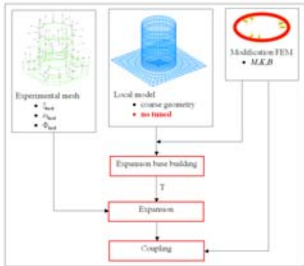
Current development in the following areas
Structural modification, hybrid test/analysis models
Model updating
In operation identification
Improved links with acquisition Photon, Pulse, NI cards, …

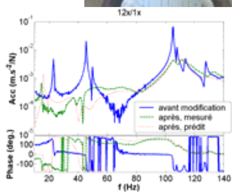
Main limitation (target audience)
Matlab based Toolbox
rather than GUI application (full push-button)




## SDM, operational loads

- Objective predict the effect of highly dissipative modifications on structures known from experiment
- In operation loads (injectors for PSA)



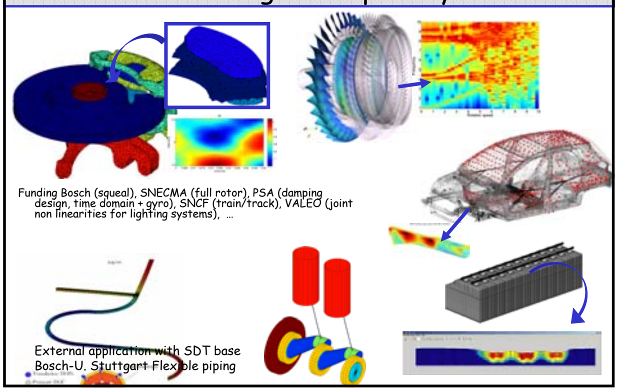




## SDT & Superelements

Superelement :
- group of elements identified by a name
- stored as a sub-model
- possibly reduced $\{q\}=[T]\{q_r\}$
- Possibly reused (sectors, slices, …)

SDT provided utilities
- Select in model (and dispatch constraints)
- Display full and partial
- Partial recovery for reduced, support reduced sensors
- Reduction (Craig-bampton, free modes, many variants, possibly parameterized)
- Node renumbering

## Substructuring & complex systems



# Model reduction

Substructuring and complex structures

Established
- Multi-level substructuring, Parametric analysis

Current trends
- Component design within whole
- Time domain, contact/friction
- Thermo-elastic coupling
- Time domain damping, self-heating, …

- Stabilize procedures for several million DOFs

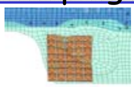
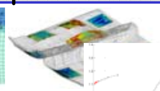
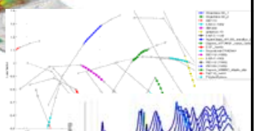
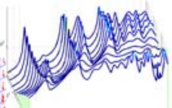
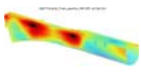
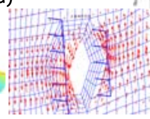
Vibroacoustics

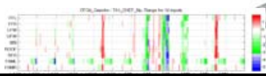
**Established techniques**
- Acoustic FEM modeling
- Coupling matrices
- Coupled predictions
- Reduction methodology (critical for heavy fluids)

Current trends
- Lining materials (poroelasticity)
- Design & robustness
- Industrial process automation

# Damping procedures

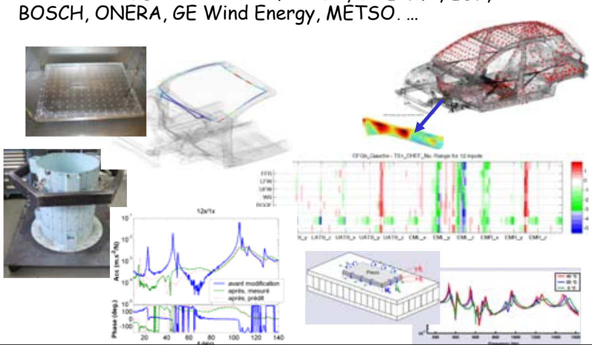
- Meshing
- Material handling
- Response predictions (huge challenge, but well established)
- Analysis tools
- Vibroacoustic optimization



# Damping projects

- In this area SDTools worked for PSA, SNECMA, EDF, BOSCH, ONERA, GE Wind Energy, METSO. …



# Damping issues

Established techniques undergoing refinement
- Damping device (re)-meshing
- Reduction methods for direct FRF & modal

Opened issues
- Device placement & shape optimization techniques
- Design methodologies (initial evaluation & validation)
- Viscoelastic behavior & non linearities (time domain simulation, brake lining, engine supports, suspensions, …).
- Thermally challenging environments & self heating, thermoelasticity
- Rethinking the use of piezoelectric shunts to damp vibrations above 150C

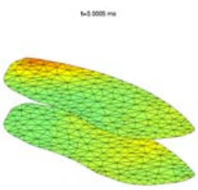
- Improve material knowledge
- Help building convincing prototypes

# Vibration & surface contact

Established
- Optimized time integration of small displacement contact/friction coupled with superelement reduction

Current trends
- Design methodologies for time based simulations (application : squeal with BOSCH)
- Equivalent linear design parameters for systems with gaps & friction (probable EDF)
- Weld spot, rivet, bolt, … dissipation (unfunded)

Possible (seen as related)
- Lubricated joints, high velocity abrasion or machining,



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