sparselizard

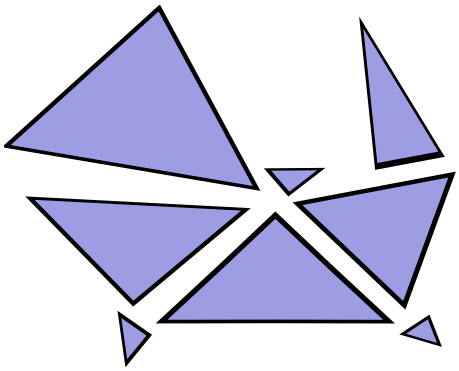
the user friendly

finite element

c++ library

Alexandre Halbach

December 1, 2017



Contents

1 What is sparselizard

Sparselizard (Copyright (C) 2017- Alexandre Halbach and Christophe Geuzaine, University of Liege, Belgium) is an open source C++ finite element library provided under the terms of the GNU General Public License (GPL), version 2 or later.
The library is meant to be user friendly while decently fast and parallelised. It can handle a rather general set of problems in 1D, 2D and 3D such as mechanical, acoustic, thermal, electric and electromagnetic problems (provided in form of a weak formulation as detailed in `https://en.wikipedia.org/wiki/Weak_formulation`). Multiphysics problems, nonlinear problems or nonlinear multiphysics problems can be simulated as well. The problems can be readily solved in time with a time-stepping resolution or with the natively supported multiharmonic resolution method. In the latter case the steady-state solution of a time-periodic problem can be obtained in a single step, for linear as well as for general nonlinear problems. The library comes with hierarchical high order shape functions so that high order interpolations can be used with an interpolation order adapted to every unknown field and geometrical region.
For now sparselizard has been successfully tested on Linux and Mac (but not on Windows). Working examples can be found in the 'examples' folder in the project.

The widely-used open-source GMSH meshing software (`www.gmsh.info`) is recommended to mesh the geometry and generate the .msh file required in the finite element simulation. The result files output by sparselizard are in .pos format supported by GMSH.

We hope you appreciate this library and wish you all the best with it!

2 How to install sparselizard

Sparselizard can be obtained at the following adress:

`https://gitlab.onelab.info/halbux/sparselizard.git`

The files can be either downloaded as an archive or by running in a terminal:

```
git clone https://gitlab.onelab.info/halbux/sparselizard.git
```

Before compiling it, the external libraries listed below must be installed. For that make sure you have the gcc, g++ and the **standard** gfortran compilers. On Ubuntu linux these can be installed with:

```
sudo apt-get install gfortran
sudo apt-get install gcc
sudo apt-get install g++
```

Once the compilers are available the required external libraries must be installed. This can be done easily by running in the provided order all bash scripts in folder 'install_external_libs'. Each script installs with the right options the corresponding external library in the 'SLlibs' folder in the home directory. In case this does not work for a given library, please install it yourself with the configuration options detailed in the bash script. In case you do not want to use the standard installation directory or want to use an already available library do not forget to change the library path accordingly in the makefile and in 'run_sparselizard.sh'.

The external libraries used are the following:

- OpenBLAS: is used for optimised and multithreaded operations on dense matrices and vectors. More information at `www.openblas.net`.
- FFTW: is used for fast Fourier transforms. More information at `www.fftw.org`.
- PETSc: in combination with MUMPS is mainly used to solve the large sparse algebraic problems. More information at `www.mcs.anl.gov/petsc` and `mumps.enseeiht.fr`.
- SLEPc: in combination with PETSc is used to solve eigenvalue problems for large sparse algebraic problems. More information at `slepc.upv.es`.

Once all external libraries are successfully installed sparselizard can be compiled by simply running 'make' or 'make -j4' if you have 4 computing cores.

3 How to use and run sparselizard

One way of using sparselizard is with the following steps:

1. Edit the 'sparselizard' function in the 'main.cpp' file for your simulation.
2. Run make in the terminal. This should be much quicker this time since only the 'main.cpp' file has to be recompiled.
3. Run your simulation by entering './run_sparselizard.sh' in the terminal.

As an example let us simulate the static deflection of a mechanical disk with some volume force applied to it. This requires to have the original 'main.cpp' and 'circle.geo' files that are available after having downloaded the sparselizard project. This also requires the binary of the open source GMSH meshing software that can be downloaded at `www.gmsh.info`.
Copy the binary to the sparselizard folder then mesh the 'circle.geo' geometry by running './gmsh circle.geo -3' (3 because it is a 3D problem) or with './gmsh circle.geo' to mesh graphically. This creates a 'circle.msh' file which contains the mesh. Now run './run_sparselizard.sh' in the terminal. This runs the code in 'main.cpp' that has just been compiled.

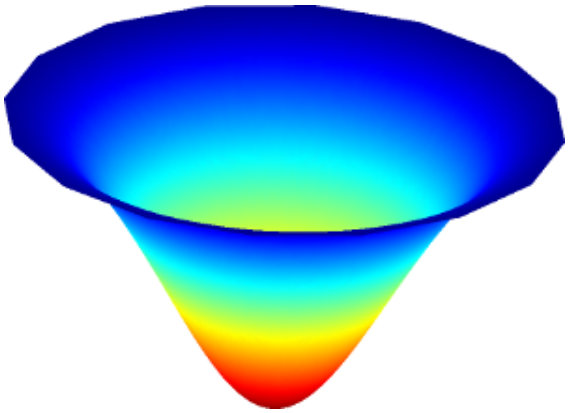


Figure 1: Exaggerated deflection of the 3D disk

The last step has created the 'u.pos' output file, which gives the exaggerated displacement of the top surface in the thin cylinder geometry when the sides are clamped and a volume force is applied downwards. Open it with './gmsh u.pos'. You don't see anything or it looks weird? Don't worry, this is just because the simulation was performed using very few hexahedra in the mesh but with an order 3 interpolation! To visualise high order interpolations in GMSH do this:

- Double click in the middle of the window then select 'All view options' at the bottom of the box that appeared go to the 'General' tab and tick the 'Adapt visualization grid' box.
- Set 'Maximum recursion level' to 3 and 'Target visualization error' to the smallest possible value then press enter. Now you have a finer solution!
- Since the solution is a mechanical displacement you might want to see the (exaggerated) deflection in 3D by double clicking in the middle of the window then selecting 'View vector display' >> 'Displacement' with factor 1.
- In case you see strange lighting effects double click in the middle of the window then select 'All view options' at the bottom of the box that appeared, go to the 'Color' tab and untick the 'Enable lighting' box.

Figure 1 is what you should see. Congratulations for your first simulation with the sparselizard library! In the 'examples' folder you will find more sparselizard examples.

4 Objects and functions available in the library

Much of sparselizard is written in c++ in an object-oriented way. It should thus be no surprise that most of the code you write consists in creating and managing objects. Below is the list of the main objects (as well as the few namespaces) that you can use in your simulations. More objects and functions are available but are not meant to be directly called by the user.

4.1 The *mesh* object (more in /src/mesh/mesh.h):

The mesh object holds the information of the finite element mesh of the geometry.

`mesh(std::string meshname)`

```
mesh mymesh("circle.msh");
```

This creates the mesh object based on the 'circle.msh' mesh file created by GMSH.

`void load(std::string meshname)`

```
mesh mymesh;
mymesh.load("circle.msh");
```

This loads the 'circle.msh' mesh file created by GMSH.

`void write(std::string meshname)`

```
mesh mymesh;
mymesh.write("circle.msh");
```

This writes the mesh in object 'mymesh' to file 'circle.msh'.

`void shift(double x, double y, double z)`

```
mesh mymesh("circle.msh");
mymesh.shift(1.0, 2.0, 3.0);
```

This translates the mesh in object 'mymesh' by 1, 2 and 3 respectively in the x, y and z direction.

`void rotate(double ax, double ay, double az)`

```
mesh mymesh("circle.msh");
mymesh.rotate(20, 60, 90);
```

This rotates the mesh in object 'mymesh' by 20, 60 and 90 degrees respectively around the x, y and z axis.

`int getmeshdimension(void)`

```
mesh mymesh("circle.msh");
int dim = mymesh.getmeshdimension();
```

This returns the dimension of the highest dimension element in the mesh in object 'mymesh'.

4.2 The *field* object (more in /src/field/field.h):

The field object holds the information of the finite element fields. The field object itself only holds a pointer to a 'rawfield' object.

`field(std::string fieldtypename)`

```
field v("h1");
```

This creates a field v with nodal (i.e. "h1") shape functions.

The full list of shape functions that are available is:

- Nodal shape functions "h1" e.g. for the electrostatic potential or acoustic pressure field.
- Two-components nodal shape functions "h1xy" e.g. for 2D mechanical displacements.
- Three-components nodal shape functions "h1xyz" e.g. for 3D mechanical displacements.
- Nedelec's edge shape functions "hcurl" e.g. for the electric and magnetic fields in the E-formulation of electromagnetic wave propagation.
- "q6" ("q6xy" or "q6xyz") shape functions (only for rectangular elements) identical to order one "h1" ("h1xy" or "h1xyz") shape functions except that there is an extra bubble mode for more accurate mechanical bending computations.
- "h11" ("h11xy" or "h11xyz") shape functions (only for hexahedral elements) identical to order one "h1" ("h1xy" or "h1xyz") shape functions except that there are three extra bubble modes for more accurate mechanical bending computations.

`field(std::string fieldtypename, const std::vector<int> harmonicnumbers)`

```
field v("h1", {1,4,5,6});
field v4 = v.getharmonic(4);
```

Consider the infinite Fourier series of a field periodic in time:
$v(x,t) = V_1 + V_2\sin(2\pi f_o t) + V_3\cos(2\pi f_o t) + V_4\sin(2\cdot 2\pi f_o t) + V_5\cos(2\cdot 2\pi f_o t) + V_6\sin(3\cdot 2\pi f_o t) + ...$
where t is the time variable, x the space variable and f_0 the fundamental frequency of the periodic field. The V_i coeffcients only depend on the space variable, not on the time variable which has now moved to the sines and cosines.
In the example above field v is a *multiharmonic* "h1" type field that includes 4 monoharmonic fields: the V_1, V_4, V_5 and V_6 fields in the truncated Fourier series above. All other harmonics in the infinite Fourier series are supposed equal zero so that field v can be rewritten as:
$v(x,t) = V_1 + V_4\sin(2\cdot 2\pi f_o t) + V_5\cos(2\cdot 2\pi f_o t) + V_6\sin(3\cdot 2\pi f_o t)$. This is the truncated multiharmonic representation of field v (which must be periodic in time).

The second line in the example gets from field v the 4th harmonic, which can now be used like any other field.

```
int countcomponents(void)
```

```
field E("hcurl");
int numcomp = E.countcomponents();
```

This returns the number of components of field E (3 here).

```
std::vector<int> getharmonics(void)
```

```
field v("h1", {1,4,5,6});
std::vector<int> myharms = v.getharmonics();
```

This returns the harmonics of field v ({1,4,5,6} here).

```
void printharmonics(void)
```

```
field v("h1", {1,4,5,6});
v.printharmonics();
```

Print a string showing the harmonics in the field.

```
void setname(std::string name)
```

```
field v("h1");
v.setname("v");
```

This gives a name to the field (usefull e.g. when printing expressions including fields).

```
void print(void)
```

```
field v("h1");
v.setname("v");
v.print();
```

Print the field name (“v” here).

```
void setorder(int physreg, int interpolorder)
```

```
mesh mymesh("circle.msh");
int vol = 1;
field v("h1");
v.setorder(vol, 3);
```

Sets interpolation order 3 on region number 1. The default interpolation order is 1.

```
void setvalue(int physreg, expression input, int extraintegrationdegree = 0)
```

```
mesh mymesh("circle.msh");
int vol = 1;
field v("h1");
v.setvalue(vol, 12 );
```

Sets the field value on region 1 to expression "12". An extra int argument (e.g. +2) can be used to increase (or decrease) the default integration order when computing the projection of the expression on field v. Increasing it can give a more accurate computation of the expression but might take longer. The default integration order is the v field order + 2.

```
void setvalue(int physreg)
```

```
mesh mymesh("circle.msh");
int vol = 1;
field v("h1");
v.setvalue(vol);
```

Sets the field value on region 1 to 0.

```
void setconstraint(int physreg, expression input, int extraintegrationdegree = 0)
```

```
mesh mymesh("circle.msh");
int vol = 1;
field v("h1"), w("h1");
v.setconstraint(vol, 12*w*w );
```

Forces the field value (i.e. Dirichlet condition) on region 1 to expression "12*w*w" (this gives 0 untill w is set to a non-zero value). An extra int argument (e.g. +2) can be used to increase (or decrease) the default integration order when computing the projection of the expression on field v. Increasing it can give a more accurate computation of the expression but might take longer. The default integration order is the v field order + 2.

```
void setconstraint(int physreg)
```

```
mesh mymesh("circle.msh");
int vol = 1;
field v("h1");
v.setconstraint(vol);
```

Forces the field value (i.e. Dirichlet condition) on region 1 to value 0.

```
void getdata(int physreg, vectorfieldselect myvec)
```

```
mesh mymesh("circle.msh");
int vol = 1;
field v("h1"), w("h1");
formulation projection;
projection += integral(vol, dof(v)*tf(v) - 2*tf(v) );
projection.generate();
vec sol = solve(projection.A(), projection.b());

w.getdata(vol, sol|v);
```

The last line transfers the data corresponding to field v in the solution vector 'sol' to field w on the region number 1.
This only works if v and w are of the same type (here they are both "h1" type). In case v has a higher interpolation order than w the higher order dofs are not transferred to w. In the opposite case the higher order dofs of w are zeroed.

```
void getdata(int physreg, vec myvec)
```

```
...
v.getdata(vol, sol);
```

This function does the same as the above except that data from field v in the 'sol' vector is transferred to field v, not to an other field.

```
field comp(int component)
```

```
field u("h1xyz");
field ux = u.comp(0);
field uy = u.comp(1);
field uz = u.comp(2);
```

This function gets the x, y or z component of a field with subfields.

```
field compx(void)
```

```
field u("h1xyz");
field ux = u.compx();
```

This function gets the x component of a field with multiple subfields.

```
field compy(void)
```

```
field u("h1xyz");
field uy = u.compy();
```

This function gets the y component of a field with multiple subfields.

`field compz(void)`

```
field u("h1xyz");
field uz = u.compz();
```

This function gets the z component of a field with multiple subfields.

`field harmonic(int harmonicnumber)`

```
field u("h1xyz", {1,2,3});
field u2 = u.harmonic(2);
```

This function gets a "h1xyz" type field that is the harmonic 2 of field u.

`field harmonic(const std::vector<int> harmonicnumbers)`

```
field u("h1xyz");
field u23 = u.harmonic({2,3});
```

This function gets a "h1xyz" type field that includes the harmonics 2 and 3 of field u.

`field sin(int freqindex)`

```
field u("h1xyz", {1,2,3,4,5});
field us = u.sin(2);
```

This function gets a "h1xyz" type field that is the sin harmonic at 2 times the fundamental frequency in field u, i.e. it is harmonic 4.

`field cos(int freqindex)`

```
field u("h1xyz", {1,2,3,4,5});
field uc = u.cos(0);
```

This function gets a "h1xyz" type field that is the cos harmonic at 0 times the fundamental frequency in field u, i.e. it is harmonic 1.

`integrate and write`: please refer to the expression object

`operators + - * /` : please refer to the expression object