Forces between magnets and multipole arrays of magnets

Will Robertson

November 9, 2009

magnetforces

1. About this file. This is a 'literate programming' approach to writing Matlab code using MATLABWEB[1]. To be honest I don't know if it's any better than simply using the Matlab programming language directly. The big advantage for me is that you have access to the entire LaTeX document environment, which gives you access to vastly better tools for cross-referencing, maths typesetting, structured formatting, bibliography generation, and so on.

The downside is obviously that you miss out on Matlab's IDE with its integrated M-Lint program, debugger, profiler, and so on. Depending on ones work habits, this may be more or less of limiting factor to using 'literate programming' in this way.

2. Calculating forces between magnets. This is the source of some code to calculate the forces and/or stiffnesses and/or torques between two cuboid-shaped magnets with arbitary displacements and magnetisation direction. (A cuboid is like a three dimensional rectangle; its faces are all orthogonal but may have different side lengths.)

[1] http://tug.ctan.org/pkg/matlabweb

3. The main function is *magnetforces*, which takes three mandatory arguments: *magnet_fixed*, *magnet_float*, and *displ*. These will be described in more detail below.

Optional string arguments may be any combination of `'force'`, `'stiffness'`, `'torque'`, or `'angular-stiffness'` to indicate which calculations should be output. If no calculation is specified, `'force'` is the default.

```
⟨magnetforces.m 3⟩ ≡
  function [varargout] = magnetforces(magnet_fixed, magnet_float, displ, varargin)
    ⟨Matlab help text 26⟩
    ⟨Extract input variables 5⟩
    ⟨Parse calculation args 8⟩
    ⟨Precompute rotation matrices 22⟩
    ⟨Decompose orthogonal superpositions 6⟩
    ⟨Calculate all forces 11⟩
    ⟨Combine results and exit 9⟩
    ⟨Functions for calculating forces and stiffnesses 16⟩
    end
```

4. Variables and data structures.

5. First of all, address the data structures required for the input and output. Because displacement of a single magnet has three components, plus sizes of the faces another three, plus magnetisation strength and direction (two) makes nine in total, we use one of Matlab's structures to pass the information into the function. Otherwise we'd have an overwhelming number of input arguments.

We use spherical coordinates to represent magnetisation angle, where *phi* is the angle from the horizontal plane ($-\pi/2 \le \phi \le \pi/2$) and θ is the angle around the horizontal plane ($0 \le \theta \le 2\pi$). This follows Matlab's definition; other conventions are commonly used as well. Remember:

$$\begin{aligned}(1,0,0)_{\text{cartesian}} &\equiv (0,0,1)_{\text{spherical}}\\(0,1,0)_{\text{cartesian}} &\equiv (\pi/2,0,1)_{\text{spherical}}\\(0,0,1)_{\text{cartesian}} &\equiv (0,\pi/2,1)_{\text{spherical}}\end{aligned}$$

⟨ Extract input variables 5 ⟩ ≡

```
a1 = 0.5*magnet_fixed.dim(1);
b1 = 0.5*magnet_fixed.dim(2);
c1 = 0.5*magnet_fixed.dim(3);
size1 = [a1; b1; c1];
a2 = 0.5*magnet_float.dim(1);
b2 = 0.5*magnet_float.dim(2);
c2 = 0.5*magnet_float.dim(3);
size2 = [a2; b2; c2];
J1r = magnet_fixed.magn;
J2r = magnet_float.magn;
J1t = magnet_fixed.magdir(1);
J2t = magnet_float.magdir(1);
J1p = magnet_fixed.magdir(2);
J2p = magnet_float.magdir(2);
if ( J1r < 0 OR J2r < 0 )
error(['By␣convention,␣magnetisation␣must␣be␣positive;␣', ...
    'change␣the␣angle␣to␣reverse␣direction.'])
end
```

This code is used in section 3.

6. Superposition is used to turn an arbitrary magnetisation angle into a set of orthogonal magnetisations.

Each magnet can potentially have three components, which can result in up to nine force calculations for a single magnet.

We don't use Matlab's `sph2cart` here, because it doesn't calculate zero accurately (because it uses radians and `cos`$(\pi/2)$ can only be evaluated to machine precision rather than symbolically).

⟨ Decompose orthogonal superpositions 6 ⟩ ≡

```
displ = reshape(displ, [3 1]);        % column vector
J1 = [J1r*cosd(J1p)*cosd(J1t); ...
  J1r*cosd(J1p)*sind(J1t); ...
  J1r*sind(J1p)];
J2 = [J2r*cosd(J2p)*cosd(J2t); ...
  J2r*cosd(J2p)*sind(J2t); ...
  J2r*sind(J2p)];
```

This code is used in section 3.

7. Wrangling user input and output.

8. We now have a choice of calculations to take based on the user input. Take the opportunity to bail out in case the user has requested more calculations than provided as outputs to the function.

⟨ Parse calculation args 8 ⟩ ≡

```
Nvargin = length(varargin);
if  ( Nvargin ≠ 0 ∧ ∧ Nvargin ≠ nargout )
error('Must␣have␣as␣many␣outputs␣as␣calculations␣requested.')
end
calc_force_bool = false;
calc_stiffness_bool = false;
calc_torque_bool = false;
calc_angular_stiffness_bool = false;
if Nvargin ≡ 0
  calc_force_bool = true;
else
  for ii = varargin
    switch ii
    case 'force'
      calc_force_bool = true;
    case 'stiffness'
      calc_stiffness_bool = true;
    case 'torque'
      calc_torque_bool = true;
    case 'angular-stiffness'
      calc_angular_stiffness_bool = true;
    otherwise
      error(['Unknown␣calculation␣option␣''', num2str(ii), ''''])
    end
  end
end
```

This code is used in section 3.

9. After all of the calculations have occured, they're placed back into `varargout`.

⟨ Combine results and exit 9 ⟩ ≡

```
for ii = length(varargin)
  switch varargin{ii}
  case 'force'
    varargout{ii} = forces_out;
  case 'stiffness'
    varargout{ii} = stiffnesses_out;
  case 'torque'
    varargout{ii} = torques_out;
  case 'angular-stiffness'
    varargout{ii} = angular_stiffnesses_out;
  end
end
```

This code is used in section 3.

10. The actual mechanics.

11. The expressions we have to calculate the forces assume a fixed magnet with positive z magnetisation only. Secondly, magnetisation direction of the floating magnet may only be in the positive z- or y-directions.

The parallel forces are more easily visualised; if *J1z* is negative, then transform the coordinate system so that up is down and down is up. Then proceed as usual and reverse the vertical forces in the last step.

The orthogonal forces require reflection and/or rotation to get the displacements in a form suitable for calculation.

Initialise a 9×3 array to store each force component in each direction, and then fill 'er up.

```
⟨ Calculate all forces 11 ⟩ ≡
  force_components = repmat(NaN, [9 3]);
  ⟨ Print diagnostics 12 ⟩
  ⟨ Calculate forces x 14 ⟩
  ⟨ Calculate forces y 15 ⟩
  ⟨ Calculate forces z 13 ⟩
  forces_out = sum(force_components);
```

This code is used in section 3.

12. Let's print information to the terminal to aid debugging. This is especially important (for me) when looking at the rotated coordinate systems.

```
⟨ Print diagnostics 12 ⟩ ≡
  debug_disp('␣␣')
  debug_disp('CALCULATING␣FORCES')
  debug_disp('==================')
  debug_disp('Displacement:')
  debug_disp(displ')
  debug_disp('Magnetisations:')
  debug_disp(J1')
  debug_disp(J2')
```

This code is used in section 11.

13. The easy one first, where our magnetisation components align with the direction expected by the force functions.

⟨ Calculate forces z 13 ⟩ ≡

```
debug_disp('Forces␣z-z:')
forces_z_z = forces_calc_z_z(size1, size2, displ, J1, J2);
force_components(7, :) = forces_z_z;

debug_disp('Forces␣z-y:')
forces_z_y = forces_calc_z_y(size1, size2, displ, J1, J2);
force_components(8, :) = forces_z_y;

debug_disp('Forces␣z-x:')
forces_z_x = forces_calc_z_x(size1, size2, displ, J1, J2);
force_components(9, :) = forces_z_x;
```

This code is used in section 11.

14. The other forces (i.e., x and y components) require a rotation to get the magnetisations correctly aligned. In the case of the magnet sizes, the lengths are just flipped rather than rotated (in rotation, sign is important). After the forces are calculated, rotate them back to the original coordinate system.

⟨ Calculate forces x 14 ⟩ ≡

```
size1_rot = swap_x_z(size1);
size2_rot = swap_x_z(size2);
d_rot = rotate_x_to_z(displ);
J1_rot = rotate_x_to_z(J1);
J2_rot = rotate_x_to_z(J2);

debug_disp('Forces␣x-x:')
forces_x_x = forces_calc_z_z(size1_rot, size2_rot, d_rot, J1_rot, J2_rot);
force_components(1, :) = rotate_z_to_x(forces_x_x);

debug_disp('Forces␣x-y:')
forces_x_y = forces_calc_z_y(size1_rot, size2_rot, d_rot, J1_rot, J2_rot);
force_components(2, :) = rotate_z_to_x(forces_x_y);

debug_disp('Forces␣x-z:')
forces_x_z = forces_calc_z_y(size1_rot, size2_rot, d_rot, J1_rot, J2_rot);
force_components(3, :) = rotate_z_to_x(forces_x_z);
```

This code is used in section 11.

15. Same again, this time making y the 'up' direction.

⟨ Calculate forces y 15 ⟩ ≡

```
size1_rot = swap_y_z(size1);
size2_rot = swap_y_z(size2);
d_rot = rotate_y_to_z(displ);
J1_rot = rotate_y_to_z(J1);
J2_rot = rotate_y_to_z(J2);

debug_disp('Forces␣y-x:')
forces_y_x = forces_calc_z_x(size1_rot, size2_rot, d_rot, J1_rot, J2_rot);
force_components(4, :) = rotate_z_to_y(forces_y_x);

debug_disp('Forces␣y-y:')
forces_y_y = forces_calc_z_z(size1_rot, size2_rot, d_rot, J1_rot, J2_rot);
force_components(5, :) = rotate_z_to_y(forces_y_y);

debug_disp('Forces␣y-z:')
forces_y_z = forces_calc_z_y(size1_rot, size2_rot, d_rot, J1_rot, J2_rot);
force_components(6, :) = rotate_z_to_y(forces_y_z);
```

This code is used in section 11.

16. Functions for calculating forces and stiffnesses. The calculations for forces between differently-oriented cuboid magnets are all directly from the literature. The stiffnesses have been derived by differentiating the force expressions, but that's the easy part.

⟨ Functions for calculating forces and stiffnesses 16 ⟩ ≡

  ⟨ Parallel magnets force calculation 17 ⟩
  ⟨ Orthogonal magnets force calculation 18 ⟩
  ⟨ Helper functions 23 ⟩

This code is used in section 3.

17. The expressions here follow directly from Akoun and Yonnet [1].

Inputs:	*size1*=(a, b, c)	the half dimensions of the fixed magnet
	size2=(A, B, C)	the half dimensions of the floating magnet
	displ=(*dx*, *dy*, *dz*)	distance between magnet centres
	$(J, J2)$	magnetisations of the magnet in the z-direction
Outputs:	*forces_xyz*=(*Fx*, *Fy*, *Fz*)	Forces of the second magnet

⟨ Parallel magnets force calculation 17 ⟩ ≡

```
function forces_xyz = forces_calc_z_z(size1, size2, offset, J1, J2)
    J1 = J1(3);
    J2 = J2(3);
    if ( J1 ≡ 0 OR J2 ≡ 0 )
    debug_disp('Zero␣magnetisation.')
    forces_xyz = [0;  0;  0];
    return;
    end
    ⟨ Forces initialise variables 20 ⟩
    f_x = ...
    +0.5*(v .^ 2 − w .^ 2) .* log(r − u) ...
    +u .* v .* log(r − v) ...
    +v .* w .* atan2(u .* v, r .* w) ...
    +0.5*r .* u;
    f_y = ...
    +0.5*(u .^ 2 − w .^ 2) .* log(r − v) ...
    +u .* v .* log(r − u) ...
    +u .* w .* atan2(u .* v, r .* w) ...
    +0.5*r .* v;
    f_z = ...
    −u .* w .* log(r − u) ...
    −v .* w .* log(r − v) ...
    +u .* v .* atan2(u .* v, r .* w) ...
    −r .* w;
    fx = index_sum .* f_x;
    fy = index_sum .* f_y;
    fz = index_sum .* f_z;
    magconst = J1*J2/(4*π*(4*π*1 · 10^−7));
    forces_xyz = magconst .* [sum(fx(:));  sum(fy(:));  sum(fz(:))];
    debug_disp(forces_xyz')
    end
```

This code is used in section 16.

18. Don't bother with rotation matrices for the z–x case; just reflect the coordinate system by swapping the components.

⟨ Orthogonal magnets force calculation 18 ⟩ ≡

```
function forces_xyz = forces_calc_z_x(size1, size2, offset, J1, J2)
    forces_xyz = forces_calc_z_y(...
      swap_x_y(size1), swap_x_y(size2), swap_x_y(offset), ...
      J1, swap_x_y(J2));
    forces_xyz = swap_x_y(forces_xyz);
    end
```

See also section 19.

This code is used in section 16.

19. Orthogonal magnets forces given by Yonnet and Allag [2].

⟨ Orthogonal magnets force calculation 18 ⟩ +≡

```
function forces_xyz = forces_calc_z_y(size1, size2, offset, J1, J2)
    J1 = J1(3);
    J2 = J2(2);
    if ( J1 ≡ 0 OR J2 ≡ 0 )
    debug_disp('Zero␣magnetisation.')
    forces_xyz = [0;  0;  0];
    return;
    end
    ⟨ Forces initialise variables 20 ⟩
    f_x = ...
    −multiply_x_log_y(v .∗ w, r − u) ...
    +multiply_x_log_y(v .∗ u, r + w) ...
    +multiply_x_log_y(u .∗ w, r + v) ...
    −0.5∗u .^ 2 .∗ atan1(v .∗ w, u .∗ r) ...
    −0.5∗v .^ 2 .∗ atan1(u .∗ w, v .∗ r) ...
    −0.5∗w .^ 2 .∗ atan1(u .∗ v, w .∗ r);
    f_y = ...
    0.5∗multiply_x_log_y(u .^ 2 − v .^ 2, r + w) ...
    −multiply_x_log_y(u .∗ w, r − u) ...
    −u .∗ v .∗ atan1(u .∗ w, v .∗ r) ...
    −0.5∗w .∗ r;
    f_z = ...
    0.5∗multiply_x_log_y(u .^ 2 − w .^ 2, r + v) ...
    −multiply_x_log_y(u .∗ v, r − u) ...
    −u .∗ w .∗ atan1(u .∗ v, w .∗ r) ...
    −0.5∗v .∗ r;
    f_x = index_sum .∗ f_x;
    f_y = index_sum .∗ f_y;
    f_z = index_sum .∗ f_z;
    forces_xyz = J1∗J2/(4∗π∗(4∗π∗1 · 10^−7)) .∗ ...
    [sum(f_x(:));  sum(f_y(:));  sum(f_z(:))];
    debug_disp(forces_xyz')
    end
```

20. Some shared setup code. First **return** early if either of the magnetisations are zero — that's the trivial solution. Assume that the magnetisation has already been rounded down to zero if necessary; i.e., that we don't need to check for *J1* or *J2* are less than $1 \cdot 10^{-12}$ or whatever.

⟨ Forces initialise variables 20 ⟩ ≡

```
dx = offset(1);
dy = offset(2);
dz = offset(3);
a = size1(1);
b = size1(2);
c = size1(3);
A = size2(1);
B = size2(2);
C = size2(3);
[index_h, index_j, index_k, index_l, index_p, index_q] = ndgrid([0 1]);
index_sum = (-1) .^ (index_h + index_j + index_k + index_l + index_p +
        index_q);
        % (Using this vectorised method is less efficient than using six for
        % loops over [0, 1]. To be addressed.)
u = dx + A*(-1) .^ index_j - a*(-1) .^ index_h;
v = dy + B*(-1) .^ index_l - b*(-1) .^ index_k;
w = dz + C*(-1) .^ index_q - c*(-1) .^ index_p;
r = sqrt(u .^ 2 + v .^ 2 + w .^ 2);
```

This code is used in sections 17 and 19.

21. Setup code.

22. When the forces are rotated we use these rotation matrices to avoid having to think too hard. Use degrees in order to compute $\sin(\pi/2)$ exactly!

⟨ Precompute rotation matrices 22 ⟩ ≡

```
swap_x_y =@(vec) vec([2 1 3]);
swap_x_z =@(vec) vec([3 2 1]);
swap_y_z =@(vec) vec([1 3 2]);
Rx =@(θ) [1 0 0;  0 cosd(θ) − sind(θ);  0 sind(θ) cosd(θ)];
Ry =@(θ) [cosd(θ) 0 sind(θ);  0 1 0;  −sind(θ) 0 cosd(θ)];
Rz =@(θ) [cosd(θ) − sind(θ) 0;  sind(θ) cosd(θ) 0;  0 0 1];
Rx_180 = Rx(180);
Rx_090 = Rx(90);
Rx_270 = Rx(−90);
Ry_180 = Ry(180);
Ry_090 = Ry(90);
Ry_270 = Ry(−90);
Rz_180 = Rz(180);
identity_function =@(inp) inp;
rotate_round_x =@(vec) Rx_180∗vec;
rotate_round_y =@(vec) Ry_180∗vec;
rotate_round_z =@(vec) Rz_180∗vec;
rotate_none = identity_function;
rotate_z_to_x =@(vec) Ry_090∗vec;
rotate_x_to_z =@(vec) Ry_270∗vec;
rotate_z_to_y =@(vec) Rx_090∗vec;
rotate_y_to_z =@(vec) Rx_270∗vec;
```

This code is used in section 3.

23. The equations contain some odd singularities. Specifically, the equations contain terms of the form $x\log(y)$, which becomes `NaN` when both x and y are zero since $\log(0)$ is negative infinity.

This function computes $x\log(y)$, special-casing the singularity to output zero, instead.

⟨ Helper functions 23 ⟩ ≡

```
function out = multiply_x_log_y(x, y)
    out = x .∗ log(y);
    out(isnan(out)) = 0;
    end
```

See also sections 24 and 25.

This code is used in section 16.

24. Also, we're using `atan` instead of `atan2` (otherwise the wrong results are calculated. I guess I don't totally understand that), which becomes a problem when trying to compute `atan`(0/0) since 0/0 is `NaN`.

This function computes `atan` but takes two arguments.

⟨ Helper functions 23 ⟩ +≡

```
function out = atan1(x, y)
    out = zeros(size(x));
    ind = x ≠ 0 ∧ y ≠ 0;
    out(ind) = atan(x(ind) ./ y(ind));
    end
```

25. This function is for easy debugging; in normal use it gobbles its argument but will print diagnostics when required.

⟨ Helper functions 23 ⟩ +≡

```
function debug_disp(str)
      %disp(str)
  end
```

26. When users type `help magnetforces` this is what they see.

⟨ Matlab help text 26 ⟩ ≡

```
%% MAGNETFORCES  Calculate forces between two cuboid magnets
%
% Finish this off later.
%
```

This code is used in section 3.

27. Test files. The chunks that follow are designed to be saved into individual files and executed automatically to check for (a) correctness and (b) regression problems as the code evolves.

How do I know if the code produces the correct forces? Well, for many cases I can compare with published values in the literature. Beyond that, I'll be setting up some tests that I can logically infer should produce the same results (such as mirror-image displacements) and test that.

There are many Matlab unit test frameworks but I'll be using a fairly low-tech method. In time this test suite should be (somehow) useable for all implementations of `magnetocode`, not just Matlab. But I haven't thought about doing anything like that, yet.

28. Because I'm lazy, just run the tests manually for now. This script must be run twice if it updates itself.

⟨`testall.m` 28⟩ ≡

```
clc;
unix('~/bin/mtangle␣magnetforces');
magforce_test001a
magforce_test001b
magforce_test001c
magforce_test001d
```

29. This test checks that square magnets produce the same forces in the each direction when displaced in positive and negative x, y, and z directions, respectively. In other words, this tests the function *forces_calc_z_y* directly. Both positive and negative magnetisations are used.

⟨`magforce_test001a.m` 29⟩ ≡

```
disp('=================')
fprintf('TEST␣001a:␣')
magnet_fixed.dim = [0.04 0.04 0.04];
magnet_float.dim = magnet_fixed.dim;
magnet_fixed.magn = 1.3;
magnet_float.magn = 1.3;
offset = 0.1;
⟨Test z–z magnetisations 30⟩
⟨Assert magnetisations tests 38⟩
⟨Test x–x magnetisations 31⟩
⟨Assert magnetisations tests 38⟩
⟨Test y–y magnetisations 32⟩
⟨Assert magnetisations tests 38⟩
fprintf('passed\n')
disp('=================')
```

30. Testing vertical forces.

⟨ Test z–z magnetisations 30 ⟩ ≡

```
f = [];
for ii = [1, −1]
  magnet_fixed.magdir = [0 ii*90];      % ±z
  for jj = [1, −1]
    magnet_float.magdir = [0 jj*90];
    for kk = [1, −1]
      displ = kk*[0 0 offset];
      f(:, end + 1) = magnetforces(magnet_fixed, magnet_float, displ);
    end
  end
end
dirforces = chop(f(3, :), 8);
otherforces = f([1 2], :);
```

This code is used in section 29.

31. Testing horizontal x forces.

⟨ Test x–x magnetisations 31 ⟩ ≡

```
f = [];
for ii = [1, −1]
  magnet_fixed.magdir = [90 + ii*90 0];      % ±x
  for jj = [1, −1]
    magnet_float.magdir = [90 + jj*90 0];
    for kk = [1, −1]
      displ = kk*[offset 0 0];
      f(:, end + 1) = magnetforces(magnet_fixed, magnet_float, displ);
    end
  end
end
dirforces = chop(f(1, :), 8);
otherforces = f([2 3], :);
```

This code is used in section 29.

32. Testing horizontal y forces.

⟨ Test y–y magnetisations 32 ⟩ ≡

```
f = [];
for ii = [1, −1]
  magnet_fixed.magdir = [ii∗90 0];        % ±y
  for jj = [1, −1]
    magnet_float.magdir = [jj∗90 0];
    for kk = [1, −1]
      displ = kk∗[0 offset 0];
      f(:, end + 1) = magnetforces(magnet_fixed, magnet_float, displ);
    end
  end
end
dirforces = chop(f(2, :), 8);
otherforces = f([1 3], :);
```

This code is used in section 29.

33. This test does the same thing but for orthogonally magnetised magnets.

⟨ magforce_test001b.m 33 ⟩ ≡

```
disp('=================')
fprintf('TEST␣001b:␣')
magnet_fixed.dim = [0.04 0.04 0.04];
magnet_float.dim = magnet_fixed.dim;
magnet_fixed.magn = 1.3;
magnet_float.magn = 1.3;
⟨ Test ZYZ 34 ⟩
⟨ Assert magnetisations tests 38 ⟩
⟨ Test ZXZ 35 ⟩
⟨ Assert magnetisations tests 38 ⟩
⟨ Test ZXX 37 ⟩
⟨ Assert magnetisations tests 38 ⟩
⟨ Test ZYY 36 ⟩
⟨ Assert magnetisations tests 38 ⟩
fprintf('passed\n')
disp('=================')
```

34. z–y magnetisations, z displacement.

⟨ Test ZYZ 34 ⟩ ≡

```
fzyz = [ ];
for ii = [1, −1]
  for jj = [1, −1]
    for kk = [1, −1]
      magnet_fixed.magdir = ii∗[0 90];      % ±z
      magnet_float.magdir = jj∗[90 0];      % ±y
      displ = kk∗[0 0 0.1];      % ±z
      fzyz(:, end + 1) = magnetforces(magnet_fixed, magnet_float, displ);
    end
  end
end
dirforces = chop(fzyz(2, :), 8);
otherforces = fzyz([1 3], :);
```

This code is used in section 33.

35. z–x magnetisations, z displacement.

⟨ Test ZXZ 35 ⟩ ≡

```
fzxz = [ ];
for ii = [1, −1]
  for jj = [1, −1]
    for kk = [1, −1]
      magnet_fixed.magdir = ii∗[0 90];      % ±z
      magnet_float.magdir = [90 + jj∗90 0];      % ±x
      displ = kk∗[0.1 0 0];      % ±x
      fzxz(:, end + 1) = magnetforces(magnet_fixed, magnet_float, displ);
    end
  end
end
dirforces = chop(fzxz(3, :), 8);
otherforces = fzxz([1 2], :);
```

This code is used in section 33.

36. z–y magnetisations, y displacement.

⟨ Test ZYY 36 ⟩ ≡

```
fzyy = [];
for ii = [1, −1]
  for jj = [1, −1]
    for kk = [1, −1]
      magnet_fixed.magdir = ii∗[0 90];      % ±z
      magnet_float.magdir = jj∗[90 0];      % ±y
      displ = kk∗[0 0.1 0];      % ±y
      fzyy(:, end + 1) = magnetforces(magnet_fixed, magnet_float,
          displ);
    end
  end
end
dirforces = chop(fzyy(3, :), 8);
otherforces = fzyy([1 2], :);
```

This code is used in section 33.

37. z–x magnetisations, x displacement.

⟨ Test ZXX 37 ⟩ ≡

```
fzxx = [];
for ii = [1, −1]
  for jj = [1, −1]
    for kk = [1, −1]
      magnet_fixed.magdir = ii∗[0 90];      % ±z
      magnet_float.magdir = [90 + jj∗90 0];      % ±x
      displ = kk∗[0 0 0.1];      % ±z
      fzxx(:, end+1) = magnetforces(magnet_fixed, magnet_float, displ);
    end
  end
end
dirforces = chop(fzxx(1, :), 8);
otherforces = fzxx([2 3], :);
```

This code is used in section 33.

38. The assertions, common between directions.

⟨ Assert magnetisations tests 38 ⟩ ≡

```
assert(...
  all(abs(otherforces(:)) < 1 · 10^{-11}), ...
  'Orthogonal␣forces␣should␣be␣zero' ...
  )
assert(...
  all(abs(dirforces) ≡ abs(dirforces(1))), ...
  'Force␣magnitudes␣should␣be␣equal' ...
  )
assert(...
  all(dirforces(1 : 4) ≡ −dirforces(5 : 8)), ...
  'Forces␣should␣be␣opposite␣with␣reversed␣fixed␣magnet␣magnetisation' ...
  )
assert(...
  all(dirforces([1 3 5 7]) ≡ −dirforces([2 4 6 8])), ...
  'Forces␣should␣be␣opposite␣with␣reversed␣float␣magnet␣magnetisation' ...
  )
```

This code is used in sections 29 and 33.

39. Now try combinations of displacements.

⟨ magforce_test001c.m 39 ⟩ ≡

```
disp('=================')
fprintf('TEST␣001c:␣')
magnet_fixed.dim = [0.04 0.04 0.04];
magnet_float.dim = magnet_fixed.dim;
magnet_fixed.magn = 1.3;
magnet_float.magn = 1.3;
⟨ Test combinations ZZ 40 ⟩
⟨ Assert combinations tests 42 ⟩
⟨ Test combinations ZY 41 ⟩
⟨ Assert combinations tests 42 ⟩
fprintf('passed\n')
disp('=================')
```

40. Tests.

⟨ Test combinations ZZ 40 ⟩ ≡

```
f = [];
for ii = [−1 1]
  for jj = [−1 1]
    for xx = 0.12∗[−1, 1]
      for yy = 0.12∗[−1, 1]
        for zz = 0.12∗[−1, 1]
          magnet_fixed.magdir = [0 ii∗90];        % z
          magnet_float.magdir = [0 jj∗90];        % z
          displ = [xx yy zz];
          f(:, end + 1) = magnetforces(magnet_fixed, magnet_float,
                displ);
        end
      end
    end
  end
end
f = chop(f, 8);
uniquedir = f(3, :);
otherdir = f([1 2], :);
```

This code is used in section 39.

41. Tests.

⟨ Test combinations ZY 41 ⟩ ≡

```
f = [];
for ii = [−1 1]
  for jj = [−1 1]
    for xx = 0.12∗[−1, 1]
      for yy = 0.12∗[−1, 1]
        for zz = 0.12∗[−1, 1]
          magnet_fixed.magdir = [0 ii∗90];        % ±z
          magnet_float.magdir = [jj∗90 0];        % ±y
          displ = [xx yy zz];
          f(:, end + 1) = magnetforces(magnet_fixed, magnet_float,
              displ);
        end
      end
    end
  end
end
f = chop(f, 8);
uniquedir = f(1, :);
otherdir = f([2 3], :);
```

This code is used in section 39.

42. Shared tests, again.

⟨ Assert combinations tests 42 ⟩ ≡

```
test1 = abs(diff(abs(f(1, :)))) < 1 · 10^−10;
test2 = abs(diff(abs(f(2, :)))) < 1 · 10^−10;
test3 = abs(diff(abs(f(3, :)))) < 1 · 10^−10;
assert( all(test1) ∧ ∧ all(test2) ∧ ∧ all(test3), ...
  'All␣forces␣in␣a␣single␣direction␣should␣be␣equal' )
test = abs(diff(abs(otherdir))) < 1 · 10^−11;
assert(all(test), 'Orthogonal␣forces␣should␣be␣equal')
test1 = f(:, 1 : 8) ≡ f(:, 25 : 32);
test2 = f(:, 9 : 16) ≡ f(:, 17 : 24);
assert( all(test1(:)) ∧ ∧ all(test2(:)), ...
  'Reverse␣magnetisation␣shouldn''t␣make␣a␣difference' )
```

This code is used in section 39.

43. Now we want to try non-orthogonal magnetisation.

```
⟨magforce_test001d.m 43⟩ ≡
  disp('=================')
  fprintf('TEST␣001d:␣')
  magnet_fixed.dim = [0.04 0.04 0.04];
  magnet_float.dim = magnet_fixed.dim;
      % Fixed parameters:
  magnet_fixed.magn = 1.3;
  magnet_float.magn = 1.3;
  magnet_fixed.magdir = [0 90];        % z
  displ = 0.12*[1 1 1];
  ⟨Test XY superposition 44⟩
  ⟨Assert superposition 47⟩
  ⟨Test XZ superposition 45⟩
  ⟨Assert superposition 47⟩
  ⟨Test planar superposition 46⟩
  ⟨Assert superposition 47⟩
  fprintf('passed\n')
  disp('=================')
```

44. Test with a magnetisation unit vector of $(1, 1, 0)$.

```
⟨Test XY superposition 44⟩ ≡
  magnet_float.magdir = [45 0];        % e_x + e_y
  f1 = magnetforces(magnet_fixed, magnet_float, displ);
      % Components:
  magnet_float.magdir = [0 0];        % e_x
  fc1 = magnetforces(magnet_fixed, magnet_float, displ);
  magnet_float.magdir = [90 0];        % e_y
  fc2 = magnetforces(magnet_fixed, magnet_float, displ);
  f2 = (fc1 + fc2)/sqrt(2);
```

This code is used in section 43.

45. Test with a magnetisation unit vector of $(1, 0, 1)$.

⟨ Test XZ superposition 45 ⟩ ≡

```
magnet_float.magdir = [0 45];      % e_y + e_z
f1 = magnetforces(magnet_fixed, magnet_float, displ);
    % Components:
magnet_float.magdir = [0 0];       % e_x
fc1 = magnetforces(magnet_fixed, magnet_float, displ);
magnet_float.magdir = [0 90];      % e_z
fc2 = magnetforces(magnet_fixed, magnet_float, displ);
f2 = (fc1 + fc2)/sqrt(2);
```

This code is used in section 43.

46. Test with a magnetisation unit vector of $(1, 1, 1)$. This is about as much as I can be bothered testing for now. Things seem to be working.

⟨ Test planar superposition 46 ⟩ ≡

```
[t p r] = cart2sph(1/sqrt(3), 1/sqrt(3), 1/sqrt(3));
magnet_float.magdir = [t p]*180/π;      % e_y + e_z + e_z
f1 = magnetforces(magnet_fixed, magnet_float, displ);
    % Components:
magnet_float.magdir = [0 0];       % e_x
fc1 = magnetforces(magnet_fixed, magnet_float, displ);
magnet_float.magdir = [90 0];      % e_y
fc2 = magnetforces(magnet_fixed, magnet_float, displ);
magnet_float.magdir = [0 90];      % e_z
fc3 = magnetforces(magnet_fixed, magnet_float, displ);
f2 = (fc1 + fc2 + fc3)/sqrt(3);
```

This code is used in section 43.

47. The assertion is the same each time.

⟨ Assert superposition 47 ⟩ ≡

```
assert(...
  isequal(chop(f1, 6), chop(f2, 6)), ...
  'Components␣should␣sum␣due␣to␣superposition' ...
  )
```

This code is used in section 43.

48. These are MATLABWEB declarations to improve the formatting of this document. Ignore unless you're editing `magnetforces.web`.

define end ≡ **end**
format *END* *TeX*

Index of `magnetforces`

List of Refinements in `magnetforces`

References

[1] Gilles Akoun and Jean-Paul Yonnet. "3D analytical calculation of the forces exerted between two cuboidal magnets". In: *IEEE Transactions on Magnetics* MAG-20.5 (Sept. 1984), pp. 1962–1964. DOI: `10.1109/TMAG.1984.1063554`.

[2] Jean-Paul Yonnet and Hicham Allag. "Analytical Calculation of Cubodal Magnet Interactions in 3D". In: *The 7th International Symposium on Linear Drives for Industry Application.* 2009.