

INTRINSIC SYMMETRY REDUCTION OF SPIRAL AND SCROLL WAVES

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Fitzhugh-Nagumo Dynamics

$$\partial_t u = -u(u - \alpha)(u - 1) + v + D\nabla^2 u$$

$$\partial_t v = \epsilon(\beta u - \gamma v - \delta)$$



Euclidean
Symmetry

What is “a symmetry”?

$$\dot{x} = F(x)$$

$$F(gx) = gF(x)$$

$x(t)$ is a solution

 $gx(t)$ is a solution

Dynamical systems: find the fixed points!

$$\dot{x} = F(x)$$

$$x(t) = g x(0)$$

relative
(Equilibrium)

$$x(t + T) = g x(t)$$

relative
(Periodic)

Continuous symmetries

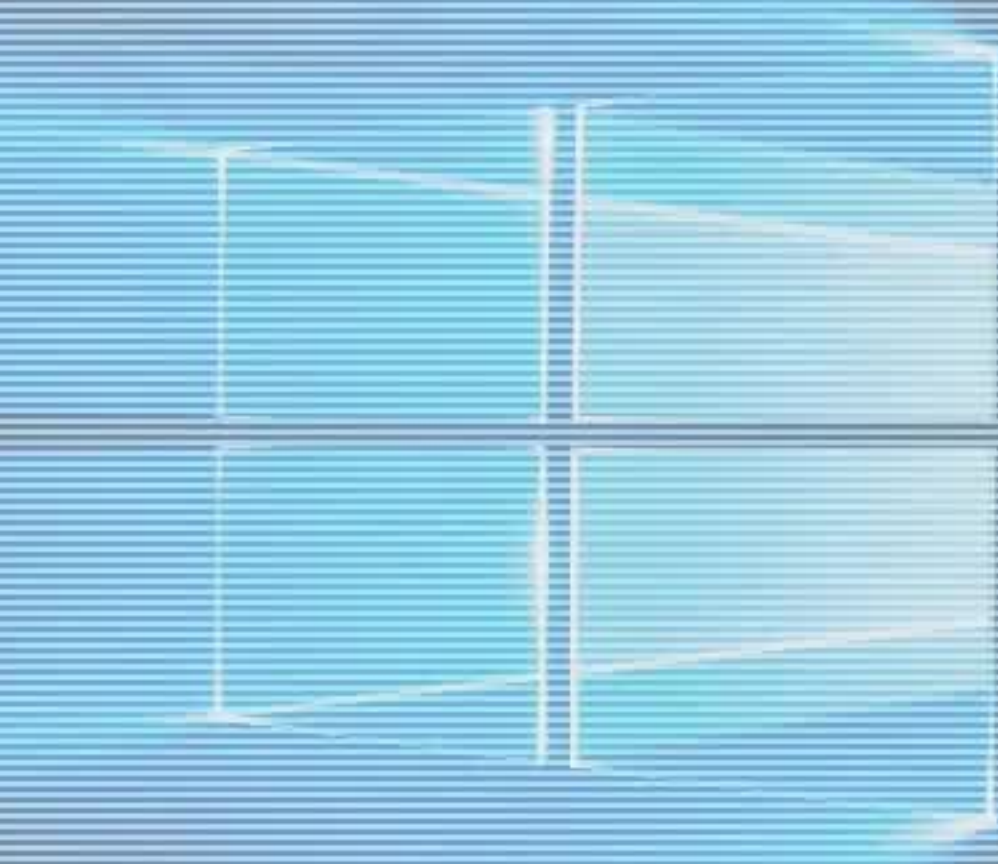
$$e^{x_0 \frac{\partial}{\partial x}} f(x) = f(x + x_0) \quad (\text{translation})$$

$$f(x + \delta x) \approx f(x) + \delta x \frac{\partial f}{\partial x} \quad (\text{generator})$$

$$x(t + \delta t) \approx x(t) + \delta t \frac{\partial x}{\partial t}$$

Familiar example: traveling
waves/alternans

Familiar example: traveling waves/alternans



Clipboard Paste Cut Copy Format Painter New Slide Notion

Layout - Kerset

Font: -32, A, A, A, Text Direction, Align text

Paragraph: B, I, U, S, AV, A, A

Drawing: Shape Fill, Shape Outline, Shape Effects, Find, Replace, Select

Clipboard Slides APPS EDITOR Font Paragraph Drawing Editing

7

8

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11

12

Familiar example: traveling waves/alternans

```

61 convx = zeros(p_totN,p_totN);
62 convy = zeros(p_totN,p_totN);
63
64 x0 = 2.1262;
65 y0 = -3.3179;
66
67 p0 = x0;
68 q0 = y0;
69
70 r0 = norm([p0; q0], 2);
71
72 moving = 0;
73
74 % Initial condition
75 Load('ppp.mat');
76 % Load('ppp.mat');
77 % Load('ppp.mat');
78 p0 = 0.01;
79 q0 = 0.005;

```

Command Window: Operation completed by user starting [alternans](#) (Line 105)

Workspace

Name	Value
axial	1x10000 double
btv	1x100 double
btv	1x100 double
ctd	1x100000 double
mi	498.34
convx	0.0007
cx	0.0451
diff	10.3071
dist	1x100000 double
dt	0.0001
fu	1x100 double
fv	1x100 double
g	92
it	-1.2611e-01
ko	1.3522e-05
m	400
moving	1
p	1x1 double
t	4.4917e+03
T	20000
sig1	16.9937
mp2	60.2121
bu	1x100 double
res0	1x100 double
sv	1x100 double
sv0	1x100 double
u	1x100 double
u	170000x100 double
u0	1x100 double
utemp	1x100 double
v	1x100 double
v0	1x100 double
vtemp	1x100 double

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Current Folder

Name

- Group Talk
- MATLAB Kuramoto
- Old Garbage
- Pattern Formation
- QBIOS
- Symmetry Reduction
- Alternans.m
- Alternans2.m
- alternansdata.mat
- altreq.mat
- altrpo.mat
- filament_tip.m
- Hakim Papers.txt
- Handcart.nb
- Hectorcode.m
- Longdata.csv
- output.mat
- plot2D.m
- plot2DOG.m
- pulse.mat
- respFN.m
- SE2GPU.m
- SE2Reduction.asv
- SE2Reduction.m

Editor - C:\Users\ndetal3\Desktop\Alternans2.m

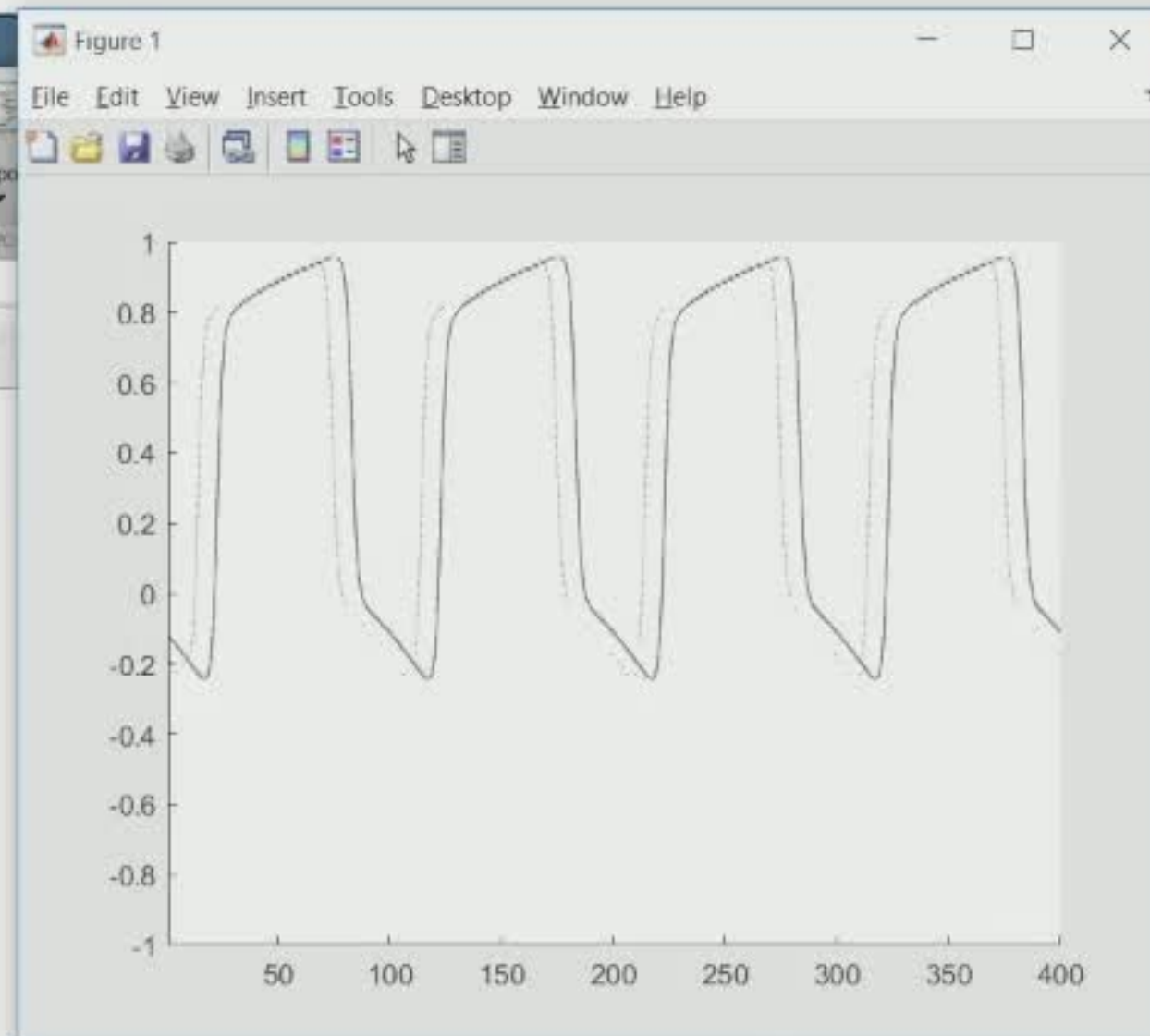
```

49
50 - fu = zeros(1,p.N);
51 - fv = zeros(1,p.N);
52
53 %Initial condition
54 % u(50:60) = .2;
55 % v(40:50) = .2;
56
57 - moving = 0;
58 - load("altreq.mat");
59 % load("altrpo.mat");
60 % load("output.mat");
61 - p.b = 1.1;
62 % p.b = 1.027;
63 - u0 = u;
64 - v0 = v;
65
66
67 - clist = zeros(1, T/dt);
68 - dlist = zeros(1, T/dt);

```

Command Window

Select a file to view details.



Search Documentation

Workspace

Name	Value
apdlist	1x1200000 double
bfu	1x100 double
bfv	1x100 double
clist	1x1200000 double
cnt	89834
convx	0.0867
cx	-0.0451
diff	10.3923
dlist	1x1200000 double
dt	0.0500
fu	1x100 double
fv	1x100 double
i	92
ixf	-5.5614e-07
ixx	1.2322e-05
m	400
moving	1
p	1x1 struct
t	4.4917e+03
T	60000
trig1	36.8927
trig2	60.3127
txu	1x100 double
txu0	1x100 double
txv	1x100 double
txv0	1x100 double
u	1x100 double
U	1200000x100 do...
u0	1x100 double
utemp	1x100 double
v	1x100 double
V	1200000x100 do...
v0	1x100 double
vtemp	1x100 double

script Ln 53 Col 19

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Editor: C:\Users\ndetal3\Desktop\Alternans2.m

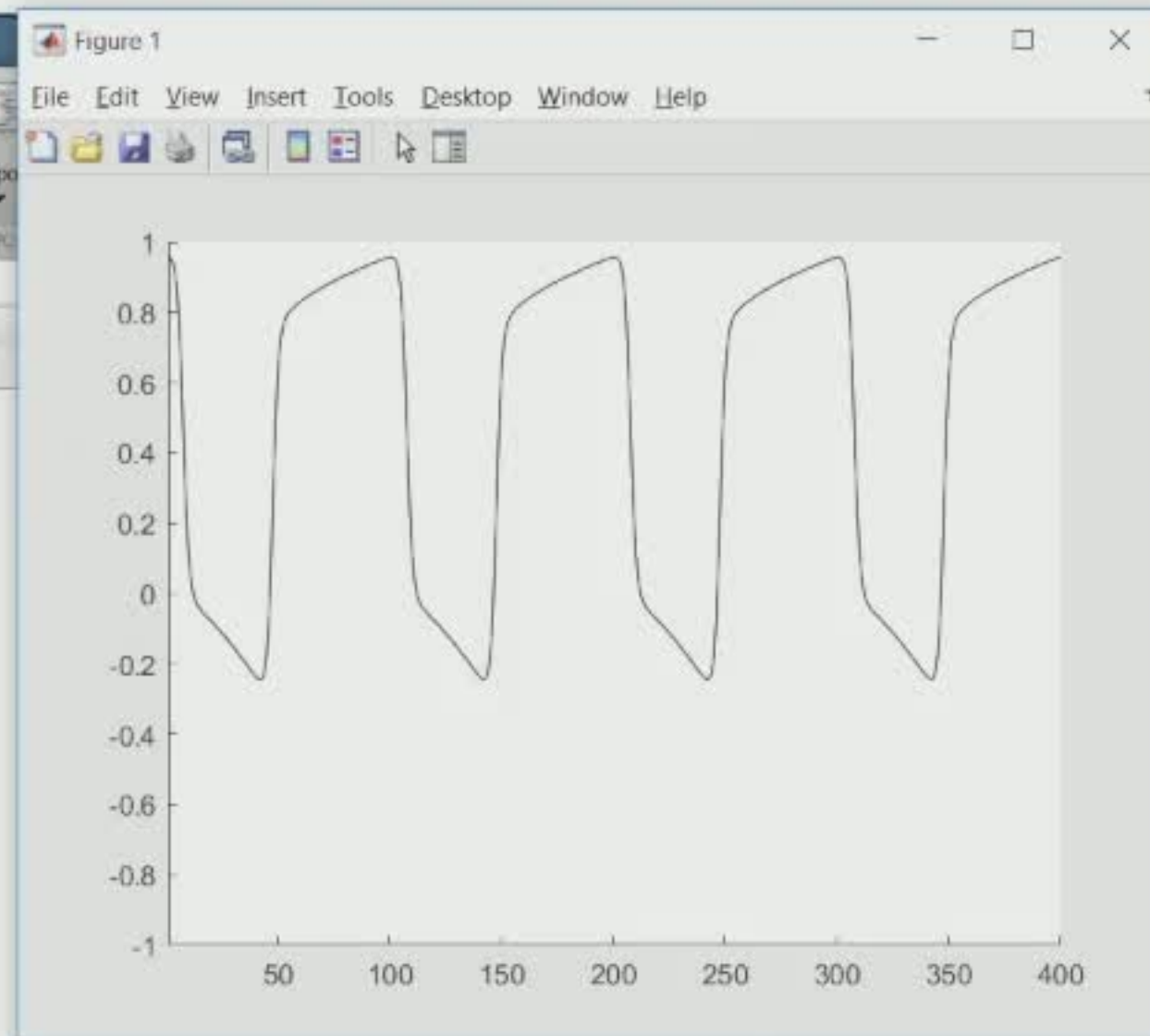
```

49
50 fu = zeros(1,p.N);
51 fv = zeros(1,p.N);
52
53 %Initial condition
54 % u(50:60) = .2;
55 % v(40:50) = .2;
56
57 moving = 1;
58 load("altreq.mat");
59 % load("altrpo.mat");
60 % load("output.mat");
61 p.b = 1.1;
62 % p.b = 1.027;
63 u0 = u;
64 v0 = v;
65
66
67 clist = zeros(1, T/dt);
68 dlist = zeros(1, T/dt);

```

Command Window

Select a file to view details

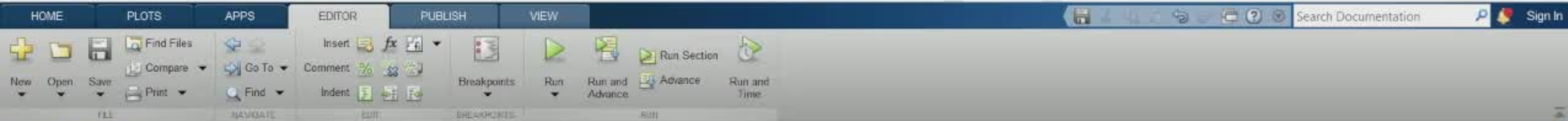


Search Documentation Sign In

Workspace

Name	Value
apdlist	1x1200000 double
bfu	1x100 double
bfv	1x100 double
clist	1x1200000 double
cnt	52692
convx	0.1116
cx	-0.1116
diff	20.6141
dlist	1x1200000 double
dt	0.0500
fu	1x100 double
fv	1x100 double
i	30
ixf	-0.1253
ixx	1.1228
m	400
moving	0
p	1x1 struct
t	2.6346e+03
T	60000
trig1	63.7419
trig2	98.0376
txu	1x100 double
txu0	1x100 double
txv	1x100 double
txv0	1x100 double
u	1x100 double
U	1200000x100 do...
u0	1x100 double
utemp	1x100 double
v	1x100 double
V	1200000x100 do...
v0	1x100 double
vtemp	1x100 double

script Ln 57 Col 11



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Editor: C:\Users\ndetal3\Desktop\Alternans2.m

```

49
50 - fu = zeros(1,p.N);
51 - fv = zeros(1,p.N);
52
53 %Initial condition
54 % u(50:60) = .2;
55 % v(40:50) = .2;
56
57 - moving = 1;
58 - load("altreq.mat");
59 % load("altrpo.mat");
60 % load("output.mat");
61 - p.b = 1.1;
62 % p.b = 1.027;
63 - u0 = u;
64 - v0 = v;
65
66
67 - clist = zeros(1, T/dt);
68 - dlist = zeros(1, T/dt);

```

Command Window

Operation terminated by user during **Alternans2** (line 219)

Workspace

Name	Value
apdlist	1x1200000 double
bfu	1x100 double
bfv	1x100 double
clist	1x1200000 double
cnt	145805
convx	0.1152
cx	-0.1093
diff	0.0021
dlist	1x1200000 double
dt	0.0500
fu	1x100 double
fv	1x100 double
i	85
ixf	-2.6622e-06
ixx	2.4361e-05
m	400
moving	1
p	1x1 struct
t	7.2902e+03
T	60000
trig1	12.2236
trig2	46.4846
txu	1x100 double
txu0	1x100 double
txv	1x100 double
txv0	1x100 double
u	1x100 double
U	1200000x100 do...
u0	1x100 double
utemp	1x100 double
v	1x100 double
V	1200000x100 do...
v0	1x100 double
vtemp	1x100 double

Figure 1

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```

49
50 fu = zeros(1,p.N);
51 fv = zeros(1,p.N);
52
53 %Initial condition
54 % u(50:60) = .2;
55 % v(40:50) = .2;
56
57 moving = 1;
58 load("altreq.mat");
59 % load("altrpo.mat");
60 % load("output.mat");
61 p.b = 1.1;
62 % p.b = 1.027;
63 u0 = u;
64 v0 = v;
65
66
67 clist = zeros(1, T/dt);
68 dlist = zeros(1, T/dt);
    
```

Workspace:

Name	Value
apdlist	1x1200000 double
bfu	1x100 double
bfv	1x100 double
clist	1x1200000 double
cnt	145805
convx	0.1152
cx	-0.1093
diff	0.0021
dlist	1x1200000 double
dt	0.0500
fu	1x100 double
fv	1x100 double
i	85
ixf	-2.6622e-06
ixx	2.4361e-05
m	400
moving	1
p	1x1 struct
t	7.2902e+03
T	60000
trig1	12.2236
trig2	46.4846
txu	1x100 double
txu0	1x100 double
txv	1x100 double
txv0	1x100 double
u	1x100 double
U	1200000x100 do...
u0	1x100 double
utemp	1x100 double
v	1x100 double
V	1200000x100 do...
v0	1x100 double
vtemp	1x100 double

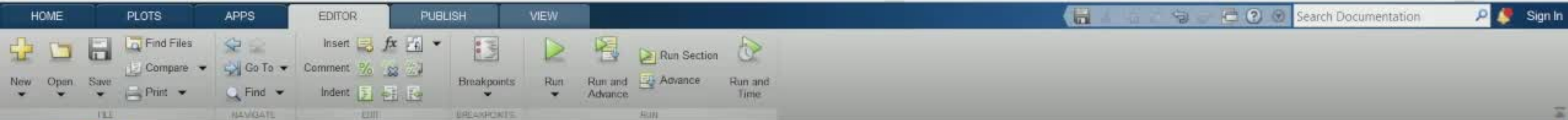
Command Window

Operation terminated by user during Alternans2 (line 219)

fx >>

Figure 1

Figure 1 displays a plot of a signal, likely representing the output of the Alternans2 simulation. The plot shows a series of oscillations, characteristic of an alternans phenomenon, with a regular period and amplitude. The x-axis represents time or iteration, and the y-axis represents the signal value.



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```

49
50 - fu = zeros(1,p.N);
51 - fv = zeros(1,p.N);
52
53 %Initial condition
54 % u(50:60) = .2;
55 % v(40:50) = .2;
56
57 - moving = 1;
58 % load("altreq.mat");
59 - load("altrpo.mat");
60 % load("output.mat");
61 % p.b = 1.1;
62 - p.b = 1.027;
63 - u0 = u;
64 - v0 = v;
65
66
67 - clist = zeros(1, T/dt);
68 - dlist = zeros(1, T/dt);

```

Workspace:

Name	Value
apdlist	1x1200000 double
bfu	1x100 double
bfv	1x100 double
clist	1x1200000 double
cnt	56892
convx	0.0668
cx	-0.0619
diff	8.0718
dlist	1x1200000 double
dt	0.0500
fu	1x100 double
fv	1x100 double
i	43
ixf	-3.4699e-05
ixx	5.6044e-04
m	400
moving	0
p	1x1 struct
t	2.8446e+03
T	60000
trig1	82.9148
trig2	96.5453
txu	1x100 double
txu0	1x100 double
txv	1x100 double
txv0	1x100 double
u	1x100 double
U	1200000x100 do...
u0	1x100 double
utemp	1x100 double
v	1x100 double
V	1200000x100 do...
v0	1x100 double
vtemp	1x100 double

Command Window

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fx >>

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SE2Reduction.m Alternans2.m

```

49
50 - fu = zeros(1,p.N);
51 - fv = zeros(1,p.N);
52
53 %Initial condition
54 % u(50:60) = .2;
55 % v(40:50) = .2;
56
57 - moving = 1;
58 % load("altreq.mat");
59 - load("altrpo.mat");
60 % load("output.mat");
61 % p.b = 1.1;
62 - p.b = 1.027;
63 - u0 = u;
64 - v0 = v;
65
66
67 - clist = zeros(1, T/dt);
68 - dlist = zeros(1, T/dt);

```

Command Window

Operation terminated by user during Alternans2 (line 188)

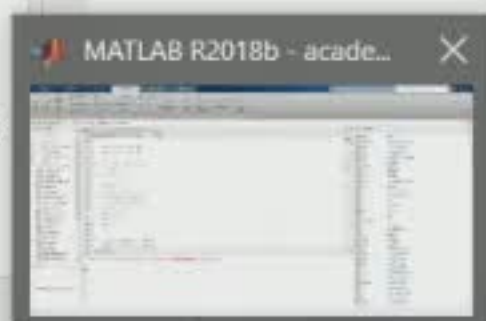
fx >>

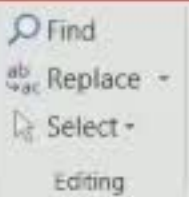
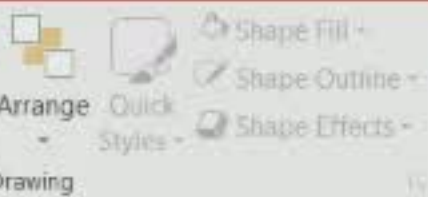
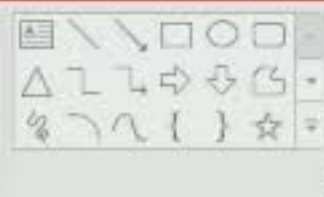
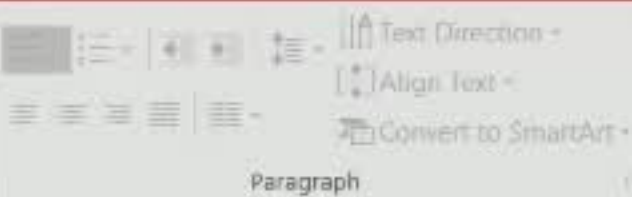
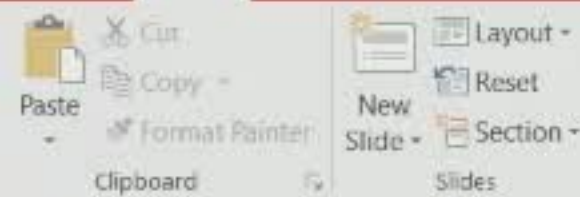
Workspace

Name	Value
apdlist	1x1200000 double
bfu	1x100 double
bfv	1x100 double
clist	1x1200000 double
cnt	147488
convx	0.0696
cx	-0.0696
diff	1.1655
dlist	1x1200000 double
dt	0.0500
fu	1x100 double
fv	1x100 double
i	45
ixf	-0.0851
ixx	1.2230
m	400
moving	1
p	1x1 struct
t	7.3744e+03
T	60000
trig1	22.9864
trig2	36.9815
txu	1x100 double
txu0	1x100 double
txv	1x100 double
txv0	1x100 double
u	1x100 double
U	1200000x100 do...
u0	1x100 double
utemp	1x100 double
v	1x100 double
V	1200000x100 do...
v0	1x100 double
vtemp	1x100 double

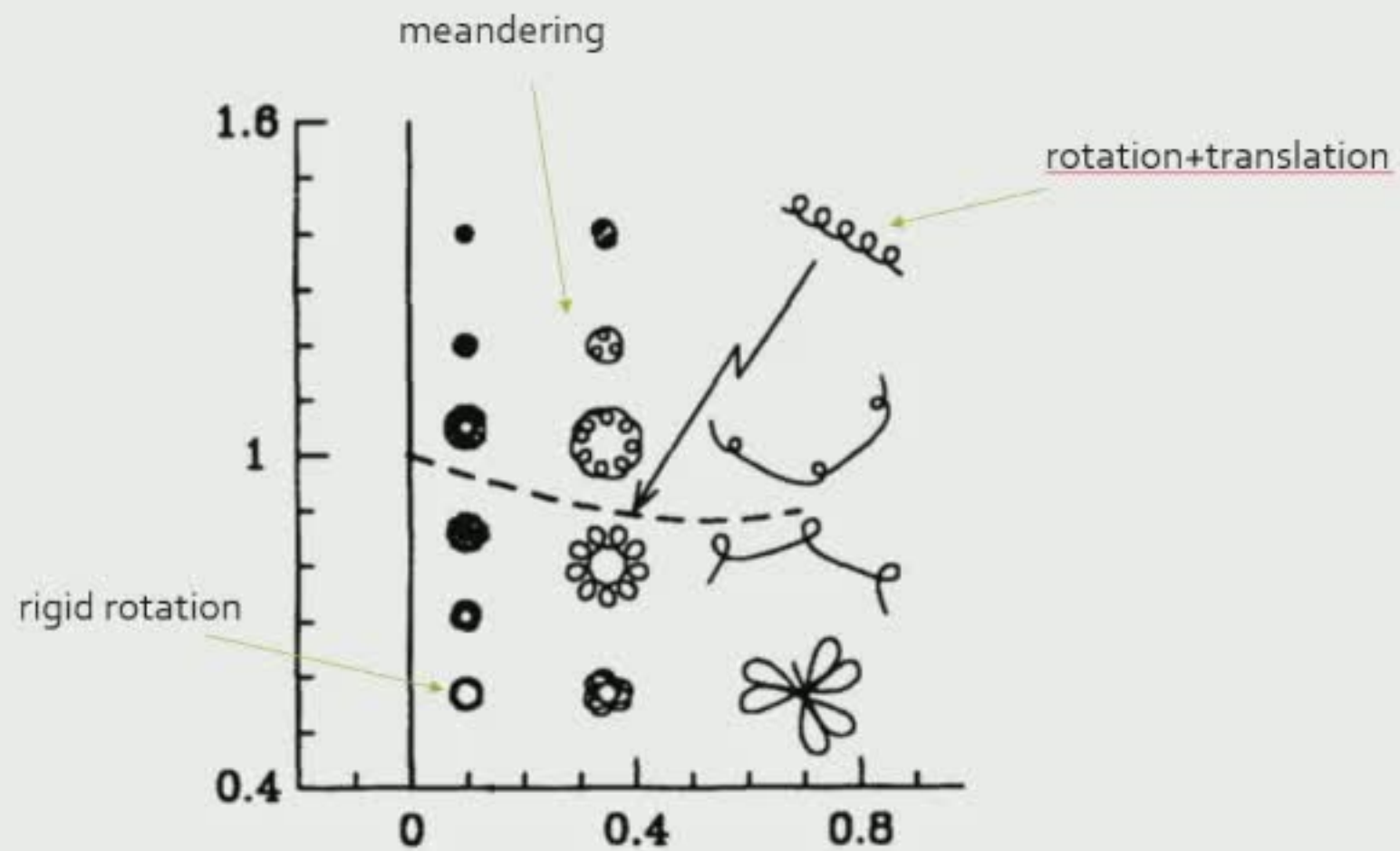
Details

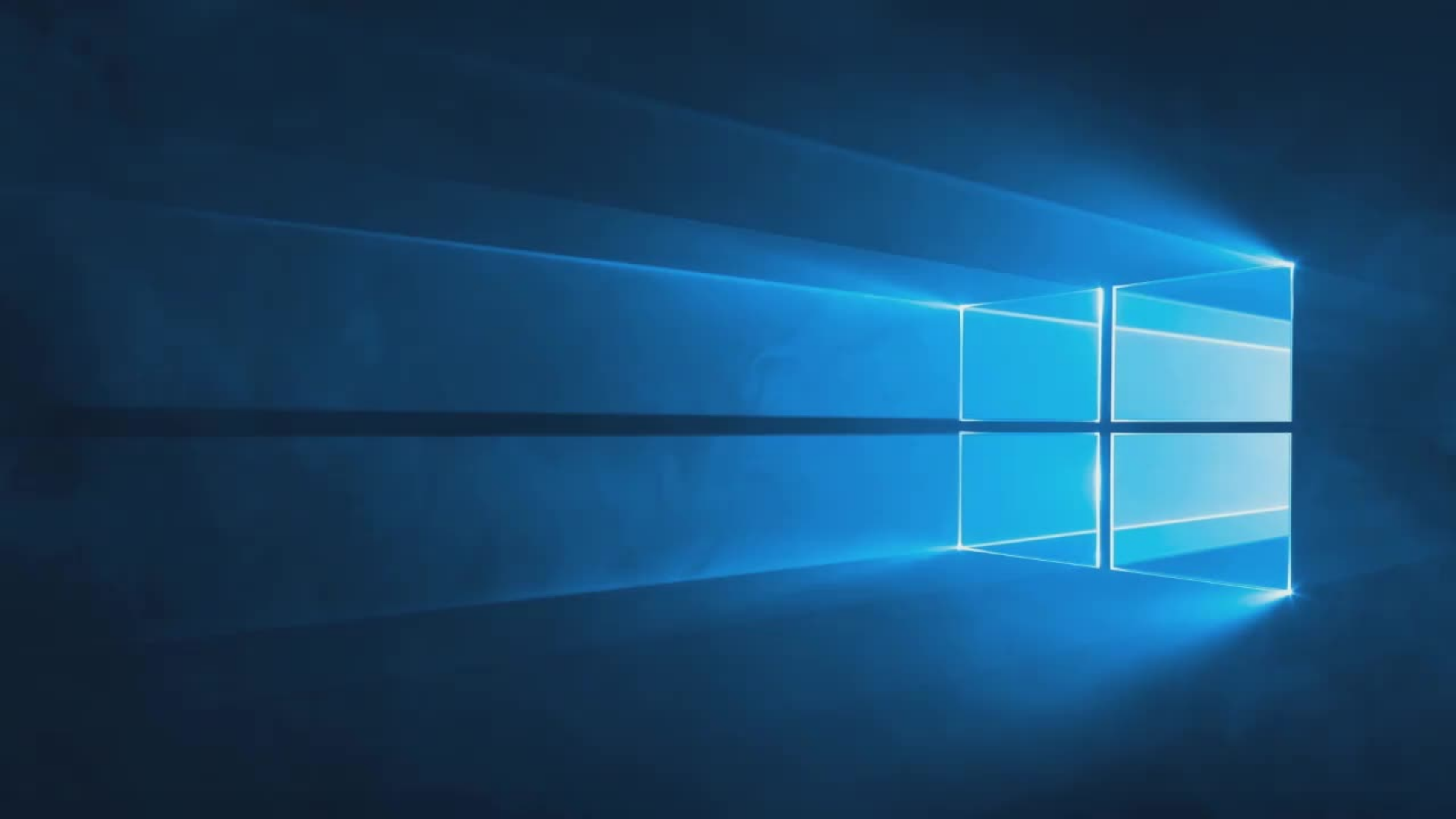
Select a file to view details



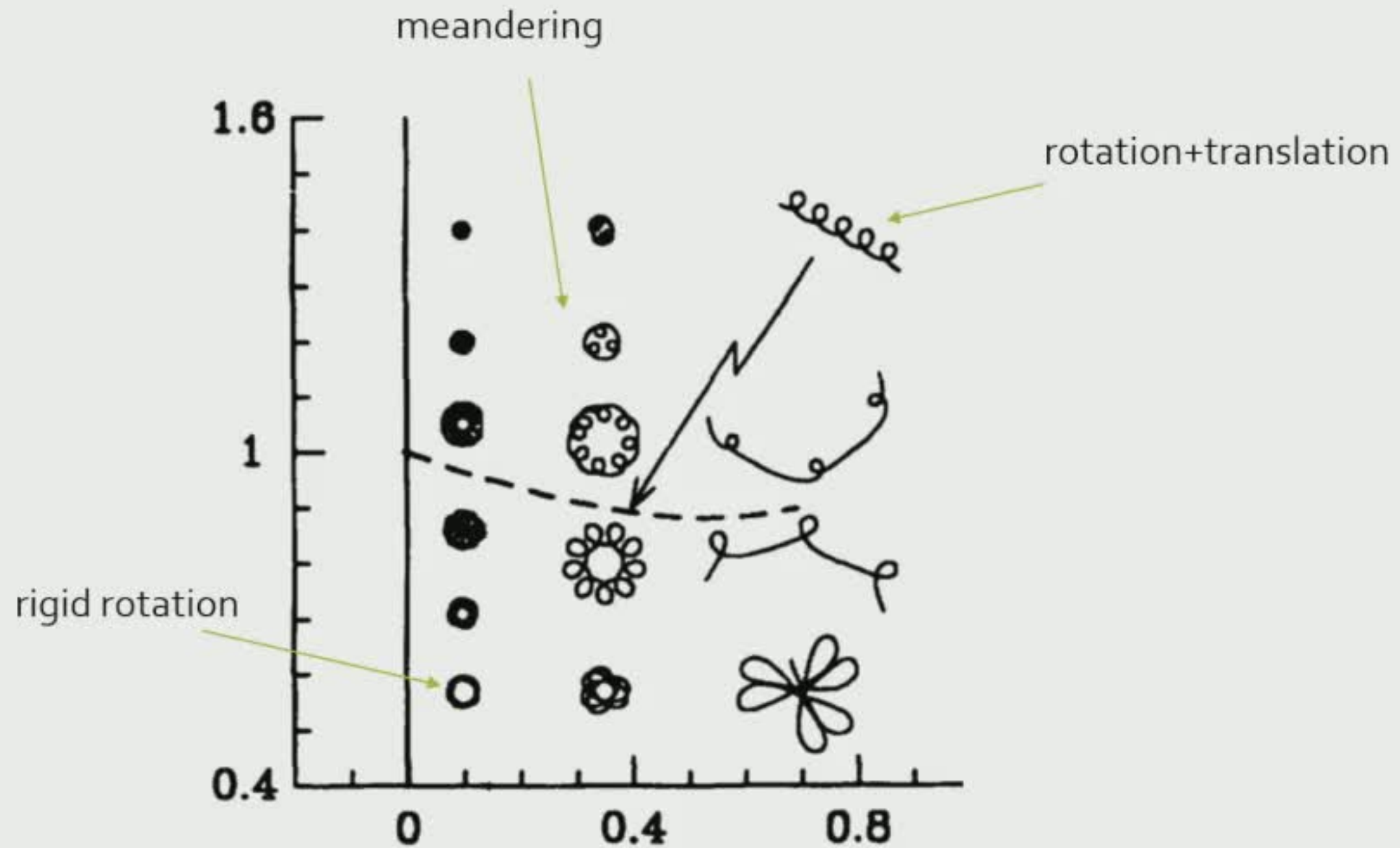


Spiral 2D Symmetries





Spiral 2D Symmetries



Symmetry Reduction by Slicing

2D: Translation in x, y rotation in θ

$$F(u') - \dot{\varphi}_x \partial_x u' - \dot{\varphi}_y \partial_y u' - \dot{\varphi}_\theta [(x - \varphi_x) \partial_y u' - (y - \varphi_y) \partial_x u']$$

$$\langle \partial_x u' | \partial_t u' \rangle = \langle \partial_y u' | \partial_t u' \rangle = \langle \partial_\theta u' | \partial_t u' \rangle = 0$$

$$\vec{A} \cdot \dot{\vec{\varphi}} = \vec{F}$$

Symmetry Reduction by Slicing

2D: Translation in x,y rotation in θ

$$\overleftrightarrow{A} \cdot \dot{\vec{\varphi}} = \vec{F}$$

$$\dot{\vec{\varphi}} = \overleftrightarrow{A}^{-1} \cdot \vec{F}$$

$$\begin{pmatrix} \dot{\varphi}_x \\ \dot{\varphi}_y \\ \dot{\varphi}_\theta \end{pmatrix} = \begin{pmatrix} \dots \\ 0 \\ 0 \end{pmatrix} \varphi_y + \begin{pmatrix} 0 \\ \dots \\ 0 \end{pmatrix} \varphi_x + \begin{pmatrix} \dots \\ \dots \\ \dots \end{pmatrix}$$

Symmetry reduction of rigid and meandering spirals



Symmetry reduction of rigid and meandering spirals

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SE2Reduction.m Alternans2.m

```

7
8     % x -> M, j
9     % y -> N, i
10
11     %--dimensions.....
12 -   p.N = 100;
13 -   p.M = 100;
14 -   p.totN = p.N+2;
15 -   p.totM = p.M+2;
16 -   p.Lx = 6;
17 -   p.Ly = 6;
18
19 -   t = 0;
20 -   T = 12000;
21 -   p.dt = 0.1;
22
23 -   p.dx = p.Lx / (p.M-1);
24 -   p.dy = p.Ly / (p.N-1);
25

```

Workspace

Name	Value
apdlist	1x1200000 double
bfu	1x100 double
bfv	1x100 double
clist	1x1200000 double
cnt	147488
convx	0.0696
cx	-0.0696
diff	1.1655
dlist	1x1200000 double
dt	0.0500
fu	1x100 double
fv	1x100 double
i	45
ixf	-0.0851
ixx	1.2230
m	400
moving	1
p	1x1 struct
t	7.3744e+03
T	60000
trig1	22.9864
trig2	36.9815
txu	1x100 double
txu0	1x100 double
txv	1x100 double
txv0	1x100 double
u	1x100 double
U	1200000x100 do...
u0	1x100 double
utemp	1x100 double
v	1x100 double
V	1200000x100 do...
v0	1x100 double
vtemp	1x100 double

Command Window

script Ln 77 Col 11

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SE2Reduction.m x Altemans2.m x +

```

64 - x0 = 2.7262;
65 - y0 = 3.3179;
66 - phix = x0;
67 - phiy = y0;
68
69 - clist = zeros(T/p.dt, 3);
70
71 - moving = 1;
72 %Initial condition
73 - load("spreq.mat");
74 % load("sprpo.mat");
75 % load("output.mat");
76 - p.epsilon = 0.012;
77 % p.epsilon = 0.005;
78
79
80 % Filament trajectory array index
81 - Xtx = [];
82 - Yty = [];

```

Command Window

fx

Workspace

Name	Value
amat	[26.0914, -0.5201, ...]
bfu	102x102 double
bfv	102x102 double
clist	120000x3 double
cnt	3750
convx	102x102 double
convy	102x102 double
ct	0.0193
cvec	[-0.0012; 0.0029, ...]
cx	-0.0012
cy	-0.0029
fu	102x102 double
fv	102x102 double
ii	1x100 double
iii	1x98 double
iiii	1x64 double
iim	102x102 double
itf	1.6420
itt	532.9585
ixf	-0.2384
ixt	-94.1225
ixx	26.0914
ixy	-0.5201
iyf	0.2062
iyt	59.2821
iyy	17.6443
jj	1x100 double
jjj	1x98 double
jjjj	1x64 double
jjm	102x102 double
m	250
moving	0
offset	20
p	1x1 struct
phix	2.5156

script Ln 71 Col 11

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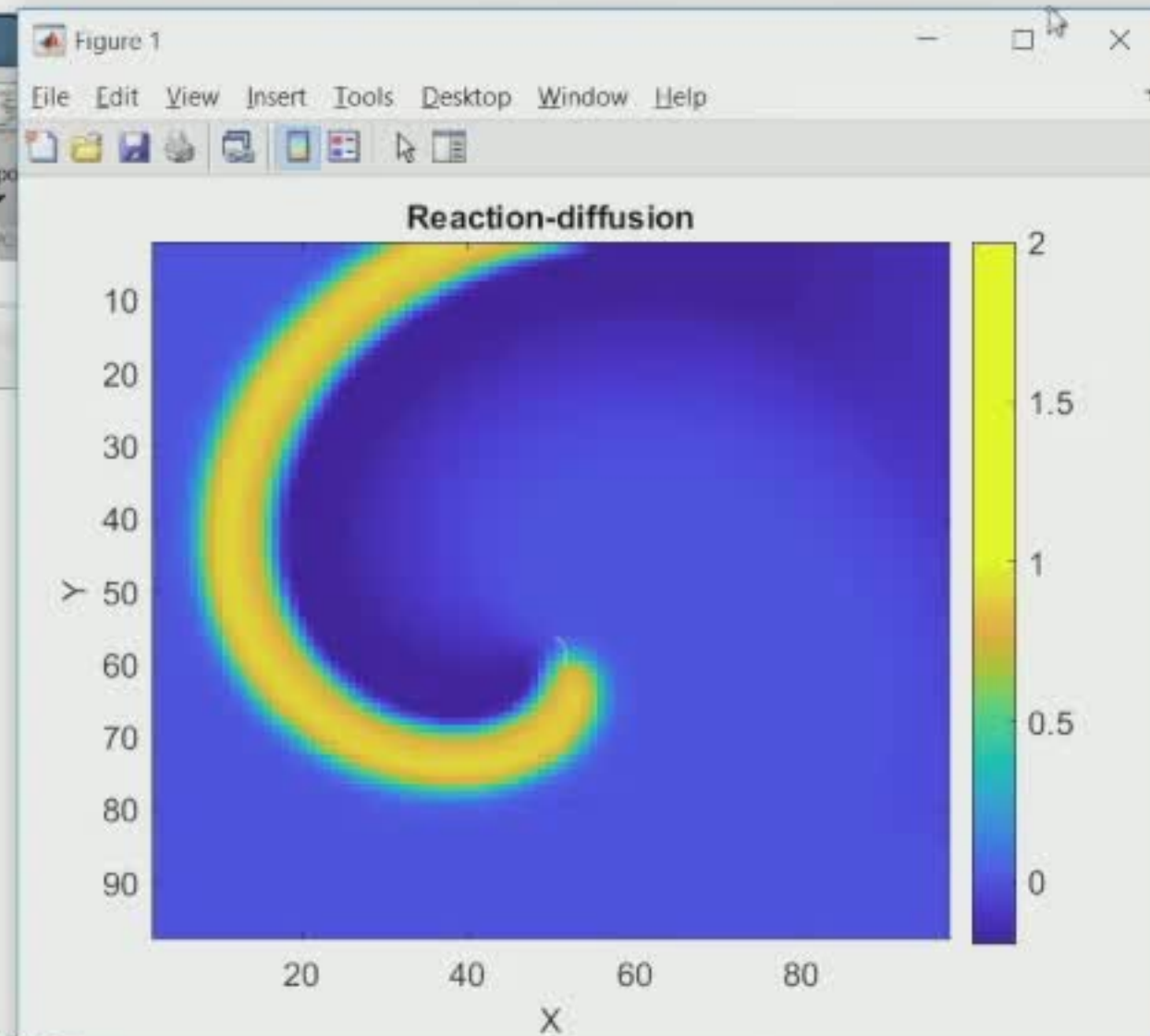
Editor: C:\Users\ndetal3\Desktop\SE2Reduction.m

```

64 - x0 = 2.7262;
65 - y0 = 3.3179;
66 - phix = x0;
67 - phiy = y0;
68
69 - clist = zeros(T/p.dt, 3);
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71 - moving = 1;
72 %Initial condition
73 - load("spreq.mat");
74 % load("sprpo.mat");
75 % load("output.mat");
76 - p.epsilon = 0.012;
77 % p.epsilon = 0.005;
78
79
80 % Filament trajectory array index
81 - Xtx = [];
82 - Yty = [];

```

Command Window



Search Documentation Sign In

Workspace

Name	Value
amat	[26.0914, -0.5201, ...
bfu	102x102 double
bfv	102x102 double
clist	120000x3 double
cnt	3750
convx	102x102 double
convy	102x102 double
ct	0.0193
cvec	[-0.0012; 0.0029; ...
cx	-0.0012
cy	-0.0029
fu	102x102 double
fv	102x102 double
ii	1x100 double
iii	1x98 double
iiii	1x64 double
iim	102x102 double
itf	1.6420
itt	532.9585
ixf	-0.2384
ixt	-94.1225
ixx	26.0914
ixy	-0.5201
iyf	0.2062
iyt	59.2821
iyy	17.6443
jj	1x100 double
jjj	1x98 double
jjjj	1x64 double
jjm	102x102 double
m	250
moving	0
offset	20
p	1x1 struct
phix	2.5156

script Ln 71 Col 11

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C:\Users\ndetal3\Desktop

Current Folder Editor - C:\Users\ndetal3\Desktop\SE2Reduction.m

SE2Reduction.m Alternans2.m

```

64 - x0 = 2.7262;
65 - y0 = 3.3179;
66 - phix = x0;
67 - phiy = y0;
68
69 - clist = zeros(T/p.dt, 3);
70
71 - moving = 1;
72 %Initial condition
73 % load("spreq.mat");
74 - load("sprpo.mat");
75 % load("output.mat");
76 % p.epsilon = 0.012;
77 - p.epsilon = 0.005;
78
79
80 % Filament trajectory array index
81 - Xtx = [];
82 - Yty = [];

```

Command Window

fx

Workspace

Name	Value
amat	[33.5010, -1.5888, ...
bfu	102x102 double
bfv	102x102 double
clist	120000x3 double
cnt	5250
convx	102x102 double
convy	102x102 double
ct	-0.0192
cvec	[-0.0197; -6.9073...
cx	-0.0197
cy	-6.9073e-04
fu	102x102 double
fv	102x102 double
ii	1x100 double
iii	1x98 double
iiii	1x64 double
iim	102x102 double
itf	-0.5709
itt	517.0668
ixf	0.0962
ixt	-91.1771
ixx	33.5010
ixy	-1.5888
iyf	-0.0157
iyt	85.1181
iyy	25.7129
jj	1x100 double
jjj	1x98 double
jjjj	1x64 double
jjm	102x102 double
m	250
moving	0
offset	20
p	1x1 struct
phix	3.1628

script Ln 71 Col 11

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Insert Comment Indent Breakpoint

Current Folder: C:\Users\ndetal3\Desktop

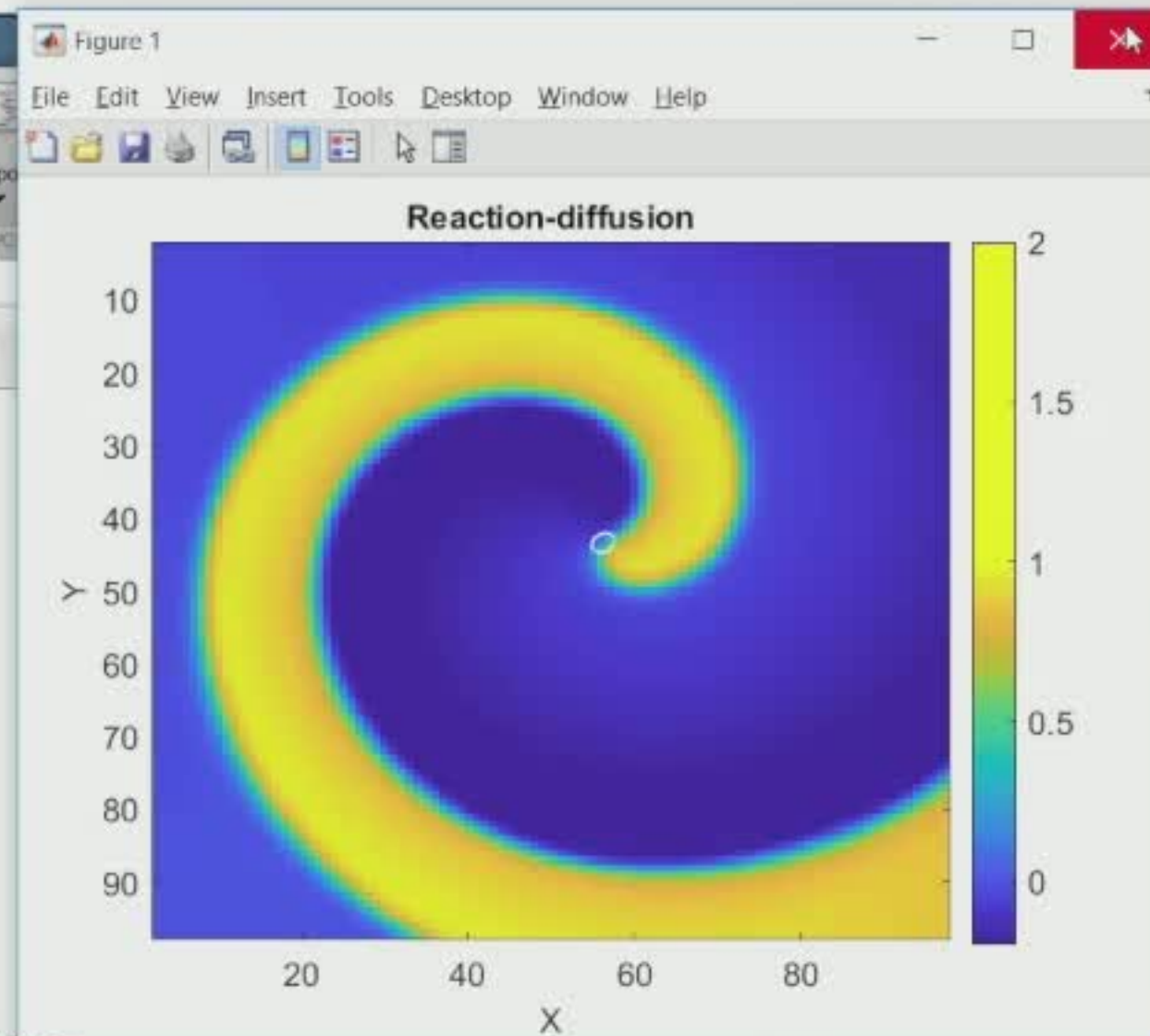
Editor: C:\Users\ndetal3\Desktop\SE2Reduction.m

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Search Documentation Sign In

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script Ln 71 Col 11

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Run Section Advance Run and Time

Search Documentation Sign In

C:\Users\ndetal3\Desktop

Current Folder Editor - C:\Users\ndetal3\Desktop\SE2Reduction.m

SE2Reduction.m Alternans2.m

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script Ln 71 Col 11

Clipboard: Paste, Copy, Format Painter, New Slide, Section

Slides: Layout, Reset, Section

Font: Font size (32), Bold (B), Italic (I), Underline (U), Strikethrough (ABC), Font color (Aa), Background color (A)

Paragraph: Text Direction, Align Text, Convert to SmartArt

Drawing: Drawing tools (lines, shapes, arrows, text boxes, etc.), Arrange, Quick Styles, Shape Fill, Shape Outline, Shape Effects

Editing: Find, Replace, Select

14

Symmetry reduction by string

$$F(x) = A_1 x^2 + A_2 x + A_3$$

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15

Symmetry reduction by string

$$F(x) = A_1 x^2 + A_2 x + A_3$$

$$F(x) = A_1 x^2 + A_2 x + A_3$$

$$\begin{pmatrix} x \\ y \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \end{pmatrix} + \begin{pmatrix} 1 \\ 0 \end{pmatrix} x + \begin{pmatrix} 0 \\ 1 \end{pmatrix} y + \begin{pmatrix} 0 \\ 0 \end{pmatrix}$$

16

Symmetry reduction by string

$$F(x) = A_1 x^2 + A_2 x + A_3$$

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$$F(x) = A_1 x^2 + A_2 x + A_3$$

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Symmetry reduction of rigid and meandering spirals

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Symmetry reduction of rigid and meandering spirals

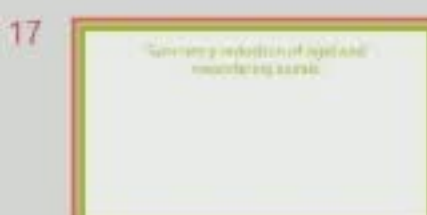
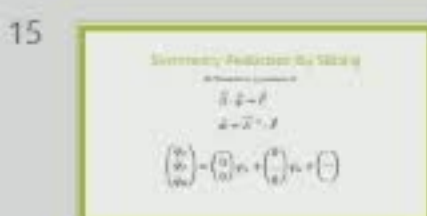
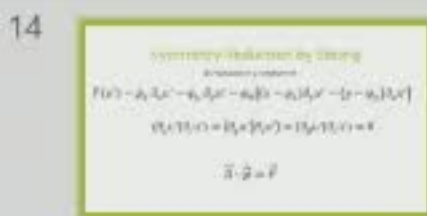
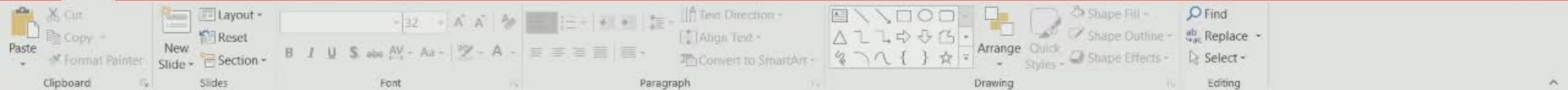


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Symmetry reduction of rigid and meandering spirals



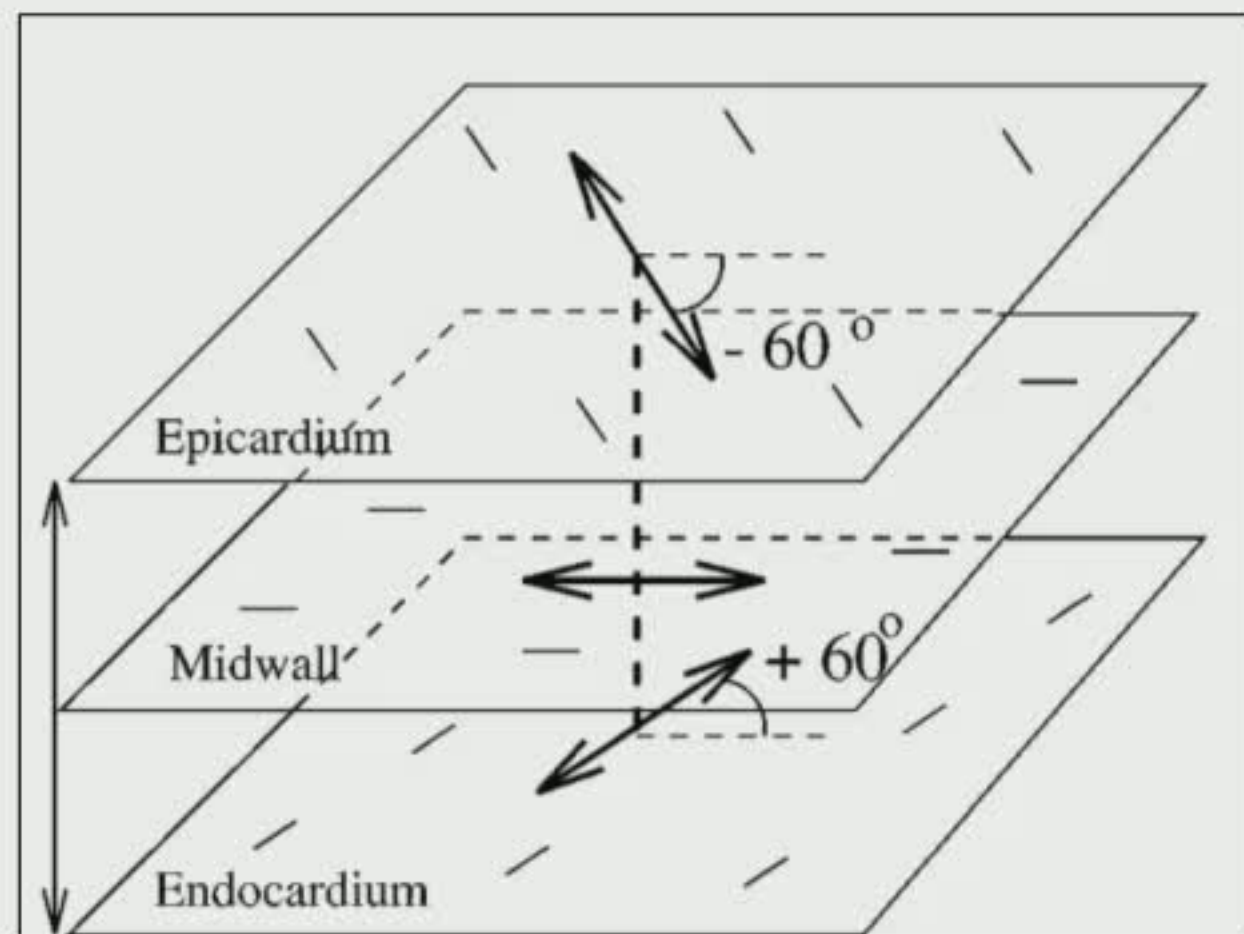
Symmetry reduction of rigid and meandering spirals



Symmetry reduction of rigid and meandering spirals

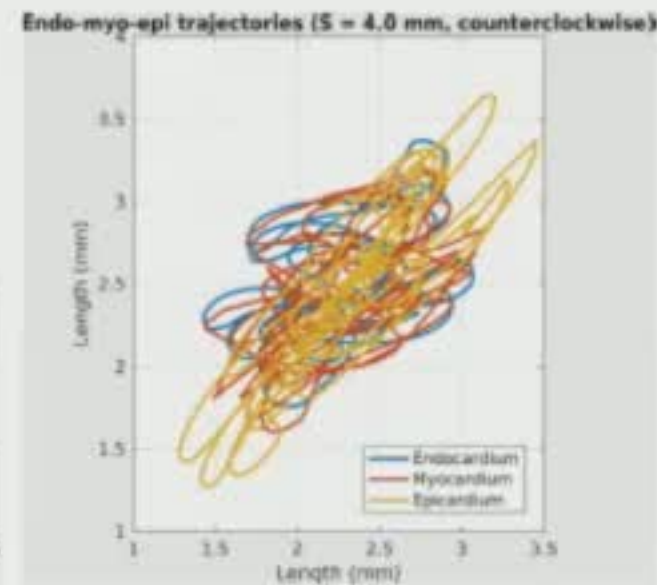
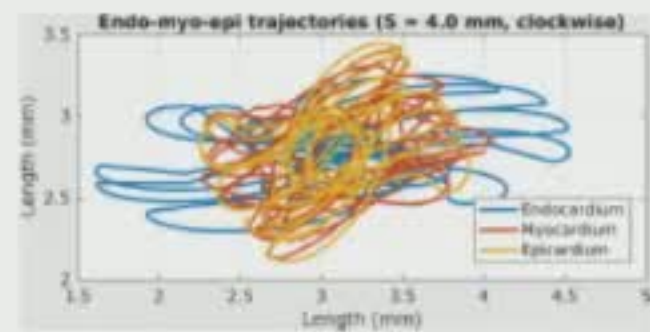
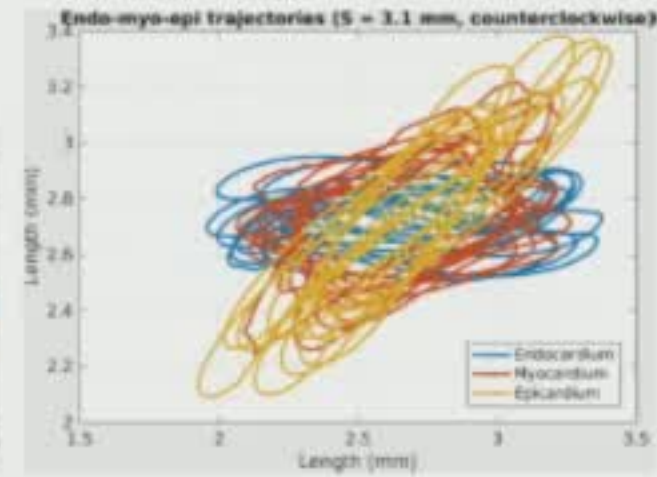
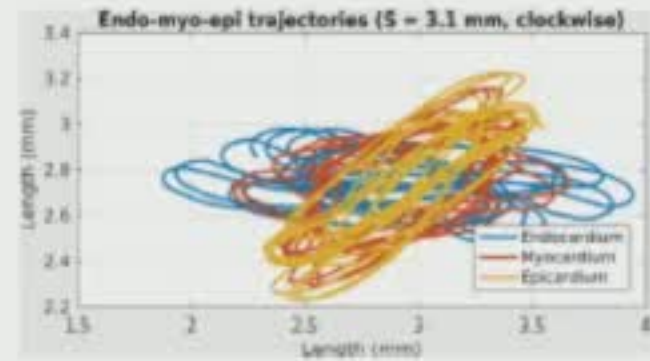
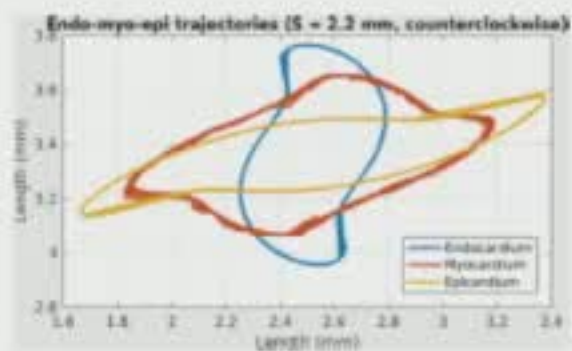
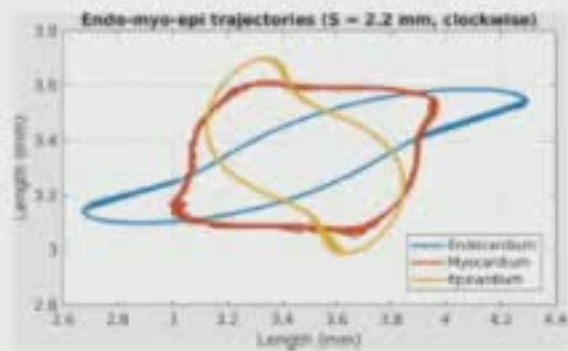
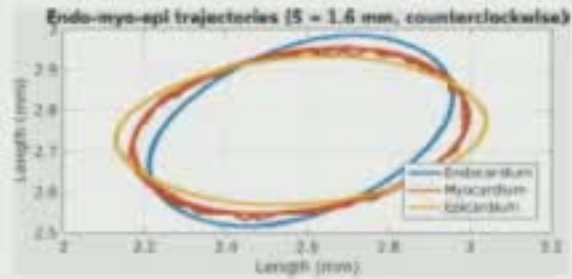
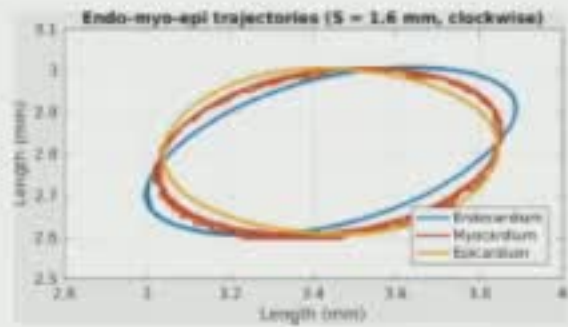
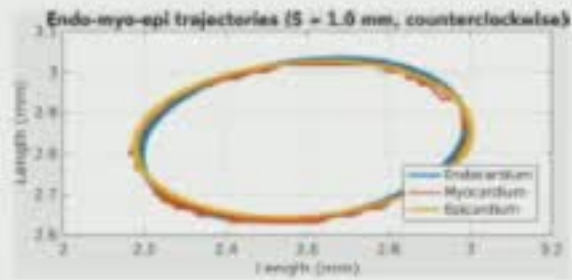
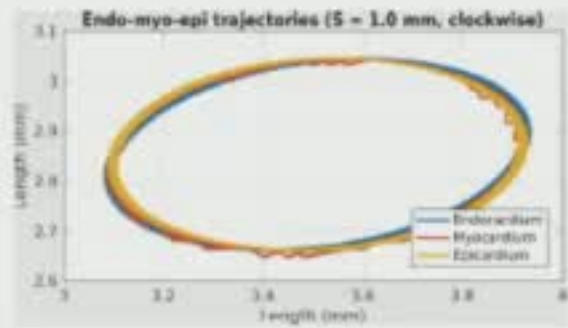
Symmetry reduction of rigid and meandering spirals

Fiber twist anisotropy...is easier?



- Rotation + translation in z
- x-y translation

Fiber twist symmetry solutions



Relative equilibria (?)

Relative periodic orbits (?)