Annex B. MATLAB and ANSYS scripts used for numerical analysis

```
!Exits processor
FINISH

/CLEAR
!Enter the preprocessor
/PREP7

Height = 0.011                  !Hemisferos aukstis
Width = 0.0015                  !Hemisferos storis
R_inner = 0.0125                !Hemisferos vidinis spindulys
R_outer = R_inner + Width !Hemisferos isorinis spindulys

kampas1=0.0
!--------------Material properties------------

MPTEMP,1,0
MP,DENS,1,7500                  ! Pjezokeramikos tankis (PZT-4, NavyI)
MP,DAMP,1,5.e-8                         ! Slopinimo koeficientas
!MPDATA,EX,1,,8.6e+10           ! Tamprumo modulis isskaiciuotas is garso greicio. EX - x asiai.

!PERX - Electric relative permittivities (also PERY, PERZ).
MP,PERX,1,1475
MP,PERY,1,1475
MP,PERZ,1,1300

!TB - Activates a data table for nonlinear material properties or special element input.
!PIEZ  —  Piezoelectric matrix (SOLID5, PLANE13, SOLID98).
!0 -- Piezoelectric stress matrix [e] (used as supplied)
!1 -- Piezoelectric strain matrix [d] (converted to [e] form before use)


TB,PIEZ,1               ! e konstantos
TBDATA,3,-5.2                   !
TBDATA,6,-5.2                   !
TBDATA,9,15.1                           !
TBDATA,14,12.7
TBDATA,16,12.7

TB,ANEL,1
TBDATA,1,13.9E+10,7.78E+10,7.4E+10
TBDATA,7,13.9E+10,7.4E+10
TBDATA,12,11.5E+10
TBDATA,16,2.56E+10
TBDATA,19,2.56E+10
TBDATA,21,2.56E+10
```

```
ET,1,SOLID98,3  !baigtinio elemento forma. Elemento isdalinimas baigtiniais elemetais

!=================================================================

CYL4,,,R_inner,90
CYL4,,,R_inner + Width,90
BLC4,0,0,R_outer,R_outer-Height
ASBA,2,1
ASBA,4,3
VROTAT,1, , , , , ,2,5,360,24

!=================================================================
!WPROTA, THXY, THYZ, THZX. Rotates the working plane.
WPROTA,,,90                    ! z pasukimas 90 laipsniu
WPROTA,,-45,                   ! y pasukimas 45 laipsniais link neigiamos z asies
WPROTA,,kampas1+7.5          ! Z pasukimas iki pirmojo segmento centro
!CSWPLA, KCN, KCS, PAR1, PAR2. Defines a local coordinate system at the origin of the
working plane.
CSWPLA,11,0,1,1,             ! Pasuktos asies issaugojimas


*DO,I,1,11                     ! WP asiu pasukimas ir issaugojimas

   WPROTA,,15.0
   CSWPLA,I+11,0,1,1,          ! Pasuktu asiu issaugojimas

*ENDDO

WPCSYS,-1,0                  ! Atsukame koordinaciu asis i globalia pozicija

*DO,I,1,11                     ! Uzdedame atributus turiams

  VSEL,S,VOLU,,24-I
  VATT,1, ,1,I+10
  VSEL,ALL

*ENDDO


VSEL,S,VOLU,,1               ! Uzdedame atributa turiui Nr.1 (turiai numeruojami ne is eiles)

VATT,1, ,1,12
VSEL,ALL

!=================================================================
MSHAPE,1,3D
MSHKEY,0
VMESH,ALL

!==============================ELEKTRODAI=========================
```

```
!Kontaktinis taskas: 1690
ASEL,S,AREA,,30,58,4
NSLA,S,0
CP,1,VOLT,ALL
*GET,N1,NODE,,NUM,MIN !
D,N1,VOLT,100
NSEL,ALL
ASEL,ALL


ASEL,S,AREA,,62,90,4
NSLA,S,0
CP,2,VOLT,ALL
*GET,N2,NODE,,NUM,MIN
D,N2,VOLT,75
NSEL,ALL
ASEL,ALL


!Izeminimas
ASEL,S,AREA,,3,95,4
DA,ALL,VOLT,0
ASEL,ALL

/REPLOT
FINISH
```

```
!Exits processor
FINISH

/CLEAR
!Enter the preprocessor
/PREP7

R_inner = 0.012        !Cilindro vidinis spindulys
R_outer = 0.0145       !Cilindro isorinis spindulys
h = 0.021              !Cilindro aukstis

!--------------Material properties------------
MPTEMP,1,0
MP,DENS,1,7600                  ! Pjezokeramikos tankis (PZT-8, NavyIII)
MP,DAMP,1,5.e-8                      ! Slopinimo koeficientas
!MPDATA,EX,1,,8.6e+10          ! Tamprumo modulis isskaiciuotas is garso greicio. EX - x asiai.

!PERX - Electric relative permittivities (also PERY, PERZ).
MP,PERX,1,1290
MP,PERY,1,1290
MP,PERZ,1,1000

!TB - Activates a data table for nonlinear material properties or special element input.
```

```
!PIEZ  —  Piezoelectric matrix (SOLID5, PLANE13, SOLID98).
TB,PIEZ,1                ! e konstantos
TBDATA,3,-4.1                !
TBDATA,6,-4.1                !
TBDATA,9,14.0                        !
TBDATA,14,10.3
TBDATA,16,10.3

TB,ANEL,1
TBDATA,1,14.6876E+10,8.1087E+10,8.10537E+10
TBDATA,7,14.6876E+10,8.10537E+10
TBDATA,12,13.1712E+10
TBDATA,16,3.28947E+10
TBDATA,19,3.1348E+10
TBDATA,21,3.1348E+10

ET,1,SOLID98,3  !baigtinio elemento forma. Elemento isdalinimas baigtiniais elemetais

!-------------------------------------------------------------------------------------------------!

!-------------------------------------------------------------------------------------------------!
!-------------------------------------------------------------------------------------------------!
!----------------------------------Cilindro formavimas-------------------------------------------!
kampas1=0.0                ! Ispjovos pradinis kampas

*DO,I,1,3
            CYL4,X,Y,R_outer,kampas1,R_inner,(kampas1+120.0),h
            kampas1=kampas1+120.0
*ENDDO

VGLUE,ALL


LDIV,39,,,2
LDIV,37,,,2
!LGEN,2,14,39,0
!ASKIN,26,16
!LDELE,24,,,1
!LDELE,17,,,1
!LDELE,20,,,1
!GEN,1,7,,,,0.005,,,,1
!VEXT,7,,,,-0.01
!VINV,2,4

LDIV,4,,,2
LDIV,5,,,2
!LGEN,2,4,30,0
!ASKIN,31,65
!LDELE,28,,,1
!LDELE,17,,,1
```

```
!LDELE,27,,,1
!LDELE,20,,,1
!LDELE,31,,,1


LDIV,43,,,2
LDIV,42,,,2

LGEN,3,21,,0
KGEN,3,10,,0
KGEN,3,18,,0
LGEN,3,10,,0

LSTR,23,20
LSTR,23,19
LSTR,24,28
LSTR,24,27

AL,22,27,28
AL,25,29,30

AGEN,1,7,,,,0.005,,,,1
VEXT,7,,,,-0.01
AGEN,1,8,,,-0.005,0.0025,,,,1
VEXT,8,,,0.01,-0.005
VADD,2,3
VINV,4,6

LGEN,3,9,,0
KGEN,3,13,,0

LSTR,24,30
LSTR,24,29
LSTR,27,19
LSTR,27,9

AL,26,25,31
AL,13,32,33

AGEN,1,9,,,-0.005,-0.0025,,,,1
VEXT,9,,,0.01,0.005
AGEN,1,10,,,0.00,-0.005,,,,1
VEXT,10,,,,0.01
VADD,3,4
VINV,1,6

LSTR,20,25
LSTR,26,21
LSTR,26,22
LSTR,25,23
```

```
AL,22,2,8
AL,5,7,24

AGEN,1,1,,,0.005,-0.0025,,,,1
VEXT,1,,,-0.01,0.005
AGEN,1,2,,,0.005,0.0025,,,,1
VEXT,2,,,-0.01,-0.005
VADD,1,4
VINV,5,6

VDELE,ALL,,1
ADELE,5,,,1
ADELE,11,,,1
ADELE,22,,,1
ADELE,13,14,,1
ADELE,16,20,1,1
ADELE,27,28,,1
ADELE,33,36,1,1
ADELE,39,42,1,1
ADELE,44,47,1,1

!=====================================================================

kampas1=0.0                ! Ispjovos pradinis kampas

*DO,I,1,24

   CYL4,X,Y,R_outer,kampas1,R_inner,(kampas1+15.0),h
   kampas1=kampas1+15.0

*ENDDO

VGLUE,ALL

!=====================================================================
!WPROTA, THXY, THYZ, THZX. Rotates the working plane.
WPROTA,,,90                    ! z pasukimas 90 laipsniu
WPROTA,,kampas1+7.5        ! Z pasukimas iki pirmojo segmento centro
!CSWPLA, KCN, KCS, PAR1, PAR2. Defines a local coordinate system at the origin of the
working plane.
CSWPLA,11,0,1,1,           ! Pasuktos asies issaugojimas


*DO,I,1,23                     ! WP asiu pasukimas ir issaugojimas

   WPROTA,,15.0
   CSWPLA,I+11,0,1,1,        ! Pasuktu asiu issaugojimas

*ENDDO
```

```
WPCSYS,-1,0                ! Atsukame koordinaciu asis i globalia pozicija

*DO,I,1,23                       ! Uzdedame atributus turiams

  VSEL,S,VOLU,,48-I
  VATT,1, ,1,I+10
  VSEL,ALL

*ENDDO


VSEL,S,VOLU,,1             ! Uzdedame atributa turiui Nr.1 (turiai numeruojami ne is eiles)

VATT,1, ,1,24
VSEL,ALL
!=============================================================

LCSL,28,216,228,240
LCSL,27,264,276,288
LCSL,25,15,34,48
LCSL,31,96,84,72
LCSL,5,168,180,192
LCSL,2,144,132,120

LSEL,S,,,23
ASBL,217,ALL
LSEL,S,,,40
ASBL,221,ALL
LSEL,S,,,39
ASBL,225,ALL
LSEL,S,,,43
ASBL,233,ALL
LSEL,S,,,55
ASBL,237,ALL
LSEL,S,,,53
ASBL,241,ALL
LSEL,S,,,28
ASBL,153,ALL
LSEL,S,,,27
ASBL,5,ALL
LSEL,S,,,68
ASBL,157,ALL
LSEL,S,,,67
ASBL,161,ALL
LSEL,S,,,22
ASBL,229,ALL
LSEL,S,,,25
ASBL,169,ALL
LSEL,S,,,77
```

```
ASBL,173,ALL
LSEL,S,,,76
ASBL,177,ALL
LSEL,S,,,15
ASBL,181,ALL
LSEL,S,,,5
ASBL,185,ALL
LSEL,S,,,99
ASBL,189,ALL
LSEL,S,,,100
ASBL,193,ALL
LSEL,S,,,59
ASBL,165,ALL
LSEL,S,,,89
ASBL,197,ALL
LSEL,S,,,72
ASBL,201,ALL
LSEL,S,,,88
ASBL,205,ALL
LSEL,S,,,87
ASBL,209,ALL
LSEL,S,,,31
ASBL,213,ALL
ADELE,8,,,1
ADELE,9,,,1
ADELE,10,,,1

MSHAPE,1,3D
MSHKEY,0
VMESH,ALL

NSEL, ALL
!D,ALL,UX,0
!D,ALL,UY,0
/REPLOT
FINISH
```

```
==========================================================================
plot(FREQ, UX1, 'DisplayName','UX');
xlabel('FREQ, Hz');
ylabel('Amplitude, nm');
grid on;
set(gca,'YMinorGrid','on');
hold on;
plot(FREQ, UY1, 'DisplayName','UY');
hold on;
plot(FREQ, UZ1, 'DisplayName','UZ');
legend show
%-----------------------------------

%Krypties vektoriai
```

```
%NODE1(6.066861769 138.3114028) NODE2(-19.77418966 147.7635969)
node_x1 = 6.066861769;
node_y1 = 138.3114028;
node_x2 = -19.77418966;
node_y2 = 147.7635969;
v1 = node_x1 + node_x2;
v2 = node_y1 + node_y2;
quiver(0,0,node_x1,node_y1);
hold on;
quiver(0,0,node_x2,node_y2);
hold on;
quiver(0,0,v1,v2);
hold on;
axis equal
grid on;
set(gca,'YMinorGrid','on');
set(gca, 'YMinorGrid','on', 'Color','w', 'XColor','k','YColor','k','ZColor','k');
set(get(gca,'Title'),'Color','k')
set(get(gca,'XLabel'),'Color','k')
set(get(gca,'YLabel'),'Color','k')
set(get(gca,'ZLabel'),'Color','k')
set(gcf,'Color','w')
xL = xlim;
yL = ylim;
line([0 0], yL, 'Color', 'k');
line(xL, [0 0], 'Color', 'k');
annotation('arrow',[0.905 0.905], [0.11 0.11]);
annotation('arrow',[0.532 0.532], [0.924 0.925]);
legend('Force vector of node 1', 'Force vector of node 2', 'Resultant force vector');

ang_1 = radtodeg(atan2(abs(det([Resultant_1;[278.9804011 - 70.74499235, 0]])),dot(Resultant_1,
[278.9804011 - 70.74499235, 0])));
r_1 = norm(Resultant_1);
ang_2 = radtodeg(atan2(abs(det([Resultant_2;[85.40501308 + 302.8072211, 0]])),dot(Resultant_2,
[85.40501308 + 302.8072211, 0])));
r_2 = norm(Resultant_2);
ang_3 = radtodeg(atan2(abs(det([Resultant_3;[704.3268666 + 45.92756691, 0]])),dot(Resultant_3,
[704.3268666 + 45.92756691, 0])));



Resultant_1 = [6.066861769 - 19.77418966, 138.3114028 + 147.7635969];
Resultant_2 = [-667.1436711 + 106.3488348, 494.2714161 + 646.7608151];
Resultant_3 = [808.0760869 - 138.8282967, 596.1630203 + 745.7605096];

ang_1 = atan2(abs(det([Resultant_1;[539.4384218 + 227.8549141, 0]])),dot(Resultant_1,
[539.4384218 + 227.8549141, 0]));
r_1 = norm(Resultant_1);
ang_2 = atan2(abs(det([Resultant_2;[-667.1436711 + 106.3488348, 0]])),dot(Resultant_2, [-
667.1436711 + 106.3488348, 0]));
```

```
r_2 = norm(Resultant_2);
ang_3 = atan2(abs(det([Resultant_3;[808.0760869 - 138.8282967, 0]])),dot(Resultant_3,
[808.0760869 - 138.8282967, 0]));
r_3 = norm(Resultant_3);

polarplot([0 ang_1], [0 r_1], [0 ang_2], [0 r_2], [0 ang_3], [0 r_3]);
legend('Resultant force vector 100V/50V', 'Resultant force vector 100V/75V', 'Resultant force
vector 100V/100V');
```