Team Problem 9

Velocity Effects and Low Level Fields in Axisymmetric Geometries

GENERAL DESCRIPTION

The problem described here relates to computation of velocity effects and low level electromagnetic fields in axisymmetric geometries. Two specific problems are considered. One is the computation of velocity effects on the field generated by the current loop at different velocities. The loop is moving inside a bore in a magnetic or nonmagnetic material. The second is the computation of fields and induced voltages due to a coil inside a magnetic or nonmagnetic tube. The fields inside and outside the tube and at large distances from the coil, are calculated and compared. The computation of low level fields relates to a particular method of testing called the remote field effect in which, the field due to an exciting coil is picked up by a second coil at a distance of over two probe diameters away where the flux density is very low. It has been found experimentally that in this regime, the pickup signal is more sensitive to defects on the outer diameter of the tube than on the inner diameter. This allows the testing of relatively thick tubes from the inside for corrosion effects on the outside. The induced voltage in the pickup coil is of the order of a few microvolts and the fields producing them is of the order of a few milliGauss.

GEOMETRIES AND MATERIAL PROPERTIES

The first geometry to be considered is shown in Fig. 1. It consists of a large ferromagnetic piece (essentially infinite in extent) with a cylindrical bore in it. A single loop moves inside the bore and carries a current I=1A. The bore is 28 mm in diameter and the loop is 24mm in diameter. Assume μ_r=50 for the ferromagnetic material. The conductivity of either material is $\sigma=5.0\times10^6$ S/m. The quantity of interest is the flux density at various velocities of the loop.

The second geometry considered is shown in Fig. 2. It consists of a long tube, 28 mm in diameter (inner) and 6 mm wall thickness. The tube is made of steel. Assume μ_r=50 and $\sigma=5.0\times10^6$ S/m. Two coils, identical in size are located 112 mm from each other (center to center) and physically connected together to allow them to move as one. Each coil is 4 mm thick and 10 mm long, as shown in Fig. 2. One coil is driven (Coil A) with an AC current at 50 Hz and a current density of 3.0×10^6 Amp/m^2. Each coil consists of 400 turns. The second coil (Coil B) is used as a pickup coil, connected to a voltmeter. This induced voltage and its phase are commonly used for detection and analysis of defects.

MESH

The mesh itself is not specified and should be chosen to minimize errors. Because of the large solution domain needed to calculate the fields far from the driving coil and the need for correct modeling of velocity effects, it is anticipated that a relatively large, dense mesh will be required. Upwinding of elements for computation of velocity effects and any other means of improving accuracy or reducing the mesh size are encouraged.

RESULTS

The following results should be calculated for comparison. Calculation of results as required here will facilitate comparison.

1. Calculation of the normal and tangential (to the surface of the bore) flux densities inside the bore, 1mm from the surface of the bore. This is shown in Fig. 1 as line la. Use Tables 1 and la for tabulation of results. The flux density is compared at distances of 0.1, 0.5, 1.0, 1.5, 2.0, 3.0, 4.0, 5.0 and 6.0 loop diameters away from the center of the driving loop.
2. Calculation of normal and tangential (to the tube) flux densities outside the conducting tube shown in Fig. 2 and 3, 0.3 mm from the inner surface and 0.3 mm from the outer surface, for the ferromagnetic material. The two lines on which the flux density is calculated are marked as L_l and L_2 in Fig. 2. The flux density is compared at distances of 0.1, 0.5, 1.0, 1.5, 2.0, 3.0, 4.0, 5.0 and 6.0 coil diameters away from the center of the driving coil. Tables 2 and 2a are suggested for tabulation.
3. Same as in 2 but for the nonmagnetic material. Table 3 and 3a are suggested for tabulation.
4. Repeat 2 and 3 with a probe velocity of 1, 10, and 100 m/sec. Enter the results in Tables 2 or 3 as appropriate.
5. For the pickup coil shown in Fig. 2 calculate the induced voltage at different velocities. Use Table 4 and 4a for these results.

An analytic solution to the geometries described above is available and the data for comparison has been incorporated directly below the tables mentioned above.

Note: In all cases, plotting of results is suggested although not required for comparison.

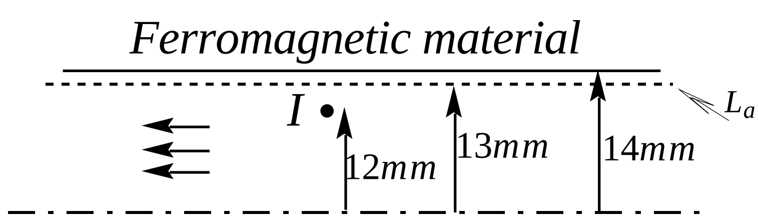

Figure 1. Geometry for velocity effects. The turn, carrying a current I moves in the direction shown by arrows inside a bore in a ferromagnetic material. Dimensions are in mm.

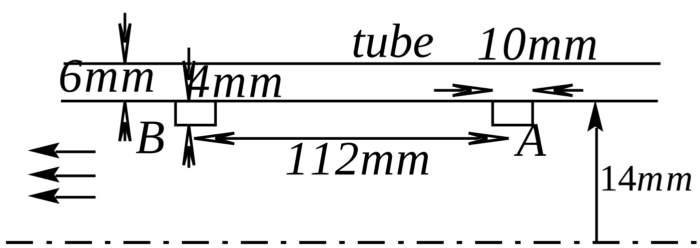

Figure 2. Geometry for the computation of flux density for the conducting (magnetic or nonmagnetic) tube. Dimensions are in mm.

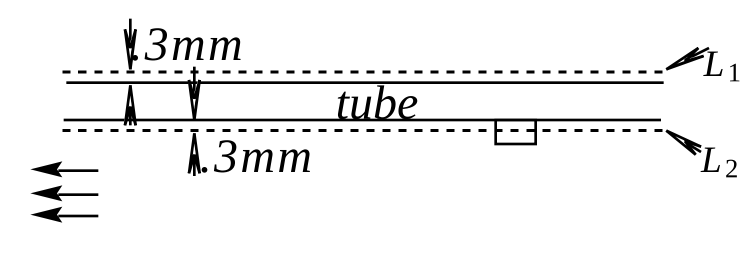

Figure 3. Geometry for computation of flux density for the conducting tube. Location at which the flux density is calculated is shown. The pickup coil is not shown.

Table 1. Flux densities at various locations and at different velocities for the loop in bore geometry on line L_a. Ferromagnetic material is assumed.

	v=0.0 m/sec		v=1.0 m/sec		v=10.0 m/sec		v=100.0 m/sec	
distance	B_r	B_z	B_r	B_z	B_r	B_z	B_r	B_z
0.1r								
0.5r								
1.0r								
1.5r								
2.0r								
2.5r								
3.0r								
3.5r								
4.0r								
4.5r								
5.0r								
5.5r								
6.0r								

Table 1. Analytic solution

	v=0.0 m/sec		v=1.0 m/sec		v=10.0 m/sec		v=100.0 m/sec	
distance	B_r	B_z	B_r	B_z	B_r	B_z	B_r	B_z
0.1r	1.31e-06	2.21e-07	1.30e-06	2.20e-07	1.27e-06	2.35e-07	9.90e-05	2.53e-05
0.5r	4.60e-07	9.93e-08	4.58e-07	1.05e-07	4.47e-07	1.15e-07	3.41e-05	1.11e-05
1.0r	1.45e-07	2.68e-08	1.45e-07	3.08e-08	1.44e-07	4.16e-08	1.15e-05	5.52e-06
1.5r	4.99e-08	8.03e-09	5.10e-08	1.07e-08	5.23e-08	1.87e-08	4.52e-06	3.17e-06
2.0r	1.70e-08	2.73e-09	1.79e-08	4.39e-09	1.94e-08	1.03e-08	1.90e-06	2.05e-06
2.5r	5.93e-09	1.44e-09	6.56e-09	2.43e-09	7.77e-09	6.86e-09	8.94e-07	1.47e-06
3.0r	2.50e-09	6.98e-10	2.92e-09	1.29e-09	3.80e-09	4.72e-09	5.04e-07	1.08e-06
3.5r	1.12e-09	6.79e-11	1.37e-09	6.57e-10	2.02e-09	3.04e-09	3.04e-07	7.97e-07
4.0r	1.69e-10	2.62e-10	3.55e-10	6.20e-10	7.99e-10	2.21e-09	1.65e-07	6.26e-07
4.5r	1.84e-10	6.87e-11	2.06e-10	3.28e-10	2.69e-10	2.08e-09	9.53e-08	5.42e-07
5.0r	4.43e-11	2.61e-10	1.32e-10	1.62e-10	3.77e-10	1.94e-09	8.66e-08	4.76e-07
5.5r	2.46e-10	2.94e-11	2.42e-10	2.07e-10	4.98e-10	1.47e-09	8.42e-08	3.93e-07
6.0r	6.26e-11	2.05e-10	6.95e-11	3.99e-10	2.60e-10	1.06e-09	5.54e-08	3.24e-07

Table 1a. Flux densities at various locations and at different velocities for the loop in bore geometry on line L_a. Nonmagnetic material is assumed.

	v=0.0 m/sec		v=1.0 m/sec		v=10.0 m/sec		v=100.0 m/sec	
distance	B_r	B_z	B_r	B_z	B_r	B_z	B_r	B_z
0.1r								
0.5r								
1.0r								
1.5r								
2.0r								
2.5r								
3.0r								
3.5r								
4.0r								
4.5r								
5.0r								
5.5r								
6.0r								

Table 1a. Analytic solution

	v=0.0 m/sec		v=1.0 m/sec		v=10.0 m/sec		v=100.0 m/sec	
distance	B_r	B_z	B_r	B_z	B_r	B_z	B_r	B_z
0.1r	9.22e-05	5.33e-05	9.19e-05	5.33e-05	8.95e-05	5.35e-05	7.84e-05	6.64e-05
0.5r	2.59e-05	8.66e-06	2.58e-05	8.92e-06	2.47e-05	1.03e-05	1.83e-05	8.29e-06
1.0r	9.46e-06	6.58e-06	9.46e-06	6.84e-06	9.25e-06	8.42e-06	6.73e-06	9.36e-06
1.5r	4.21e-06	4.13e-06	4.24e-06	4.35e-06	4.32e-06	5.78e-06	3.34e-06	7.54e-06
2.0r	2.03e-06	2.64e-06	2.06e-06	2.82e-06	2.22e-06	4.05e-06	1.90e-06	6.04e-06
2.5r	1.08e-06	1.77e-06	1.11e-06	1.92e-06	1.28e-06	2.96e-06	1.23e-06	4.96e-06
3.0r	6.57e-07	1.19e-06	6.83e-07	1.31e-06	8.35e-07	2.20e-06	9.05e-07	4.11e-06
3.5r	4.11e-07	7.91e-07	4.32e-07	8.88e-07	5.61e-07	1.64e-06	6.76e-07	3.44e-06
4.0r	2.34e-07	5.47e-07	2.51e-07	6.27e-07	3.58e-07	1.28e-06	4.87e-07	2.94e-06
4.5r	1.37e-07	4.19e-07	1.51e-07	4.86e-07	2.39e-07	1.05e-06	3.67e-07	2.58e-06
5.0r	1.10e-07	3.28e-07	1.21e-07	3.84e-07	1.95e-07	8.71e-07	3.16e-07	2.29e-06
5.5r	9.56e-08	2.35e-07	1.05e-07	2.82e-07	1.66e-07	7.08e-07	2.78e-07	2.02e-06
6.0r	5.97e-08	1.64e-07	6.72e-08	2.04e-07	1.18e-07	5.77e-07	2.20e-07	1.79e-06

Table 2. Flux densities at various locations and at different velocities for the ferromagnetic material on line L_2 (13.7mm).

	v=0.0 m/sec		v=1.0 m/sec		v=10.0 m/sec		v=100.0 m/sec	
distance	B_r	B_z	B_r	B_z	B_r	B_z	B_r	B_z
0.1r								
0.5r								
1.0r								
1.5r								
2.0r								
2.5r								
3.0r								
3.5r								
4.0r								
4.5r								
5.0r								
5.5r								
6.0r								

Table 2. Analytic solution

	v=0.0 m/sec		v=1.0 m/sec		v=10.0 m/sec		v=100.0 m/sec	
distance	B_r	B_z	B_r	B_z	B_r	B_z	B_r	B_z
0.1r	1.32e-03	6.40e-04	1.27e-03	6.46e-04	1.06e-03	5.06e-04	5.68e-04	1.70e-04
0.5r	5.40e-03	3.35e-04	5.39e-03	3.81e-04	5.25e-03	5.22e-04	4.76e-03	6.72e-04
1.0r	1.56e-03	8.77e-05	1.57e-03	1.12e-04	1.57e-03	2.59e-04	1.49e-03	5.17e-04
1.5r	5.25e-04	3.29e-05	5.34e-04	4.28e-05	5.61e-04	1.46e-04	5.79e-04	3.43e-04
2.0r	1.85e-04	1.64e-05	1.90e-04	2.05e-05	2.17e-04	8.91e-05	2.50e-04	2.34e-04
2.5r	6.56e-05	1.04e-05	6.78e-05	1.23e-05	8.88e-05	5.74e-05	1.18e-04	1.67e-04
3.0r	2.32e-05	7.94e-06	2.43e-05	8.91e-06	3.88e-05	3.89e-05	6.12e-05	1.25e-04
3.5r	8.68e-06	6.70e-06	9.14e-06	7.33e-06	1.88e-05	2.76e-05	3.54e-05	9.72e-05
4.0r	3.74e-06	5.96e-06	3.96e-06	6.44e-06	1.03e-05	2.06e-05	2.27e-05	7.84e-05
4.5r	1.72e-06	5.43e-06	1.83e-06	5.83e-06	5.94e-06	1.61e-05	1.54e-05	6.50e-05
5.0r	6.65e-07	5.00e-06	7.30e-07	5.36e-06	3.43e-06	1.31e-05	1.08e-05	5.50e-05
5.5r	3.24e-07	4.63e-06	3.67e-07	4.95e-06	2.16e-06	1.10e-05	8.06e-06	4.74e-05
6.0r	4.38e-07	4.31e-06	4.70e-07	4.60e-06	1.69e-06	9.47e-06	6.48e-06	4.14e-05

Table 2a. Flux densities at various locations nonmagnetic material on line L_1 (20.3mm)..

	v=0.0 m/sec		v=1.0 m/sec		v=10.0 m/sec		v=100.0 m/sec	
distance	B_r	B_z	B_r	B_z	B_r	B_z	B_r	B_z
0.1r								
0.5r								
1.0r								
1.5r								
2.0r								
2.5r								
3.0r								
3.5r								
4.0r								
4.5r								
5.0r								
5.5r								
6.0r								

Table 2a. Analytic solution

	v=0.0 m/sec		v=1.0 m/sec		v=10.0 m/sec		v=100.0 m/sec	
distance	B_r	B_z	B_r	B_z	B_r	B_z	B_r	B_z
0.1r	1.66e-05	9.28e-05	9.39e-06	9.29e-05	5.85e-05	1.09e-05	1.74e-06	1.52e-06
0.5r	6.45e-05	6.05e-05	4.89e-05	7.48e-05	5.52e-05	3.21e-05	1.97e-06	1.67e-06
1.0r	6.79e-05	1.78e-05	6.82e-05	2.91e-05	2.77e-05	5.08e-05	2.32e-06	1.89e-06
1.5r	5.37e-05	1.09e-06	5.74e-05	5.78e-06	4.93e-06	4.81e-05	2.78e-06	2.13e-06
2.0r	4.19e-05	4.75e-06	4.51e-05	2.88e-06	2.28e-05	3.56e-05	3.40e-06	2.36e-06
2.5r	3.37e-05	6.23e-06	3.60e-05	5.46e-06	3.05e-05	2.31e-05	4.19e-06	2.50e-06
3.0r	2.80e-05	6.39e-06	2.97e-05	6.07e-06	3.21e-05	1.38e-05	5.09e-06	2.48e-06
3.5r	2.38e-05	6.12e-06	2.51e-05	5.98e-06	3.08e-05	7.47e-06	5.98e-06	2.25e-06
4.0r	2.07e-05	5.74e-06	2.16e-05	5.68e-06	2.84e-05	3.47e-06	6.74e-06	1.83e-06
4.5r	1.82e-05	5.35e-06	1.90e-05	5.32e-06	2.57e-05	1.32e-06	7.29e-06	1.28e-06
5.0r	1.62e-05	4.98e-06	1.68e-05	4.96e-06	2.31e-05	1.39e-06	7.59e-06	6.86e-07
5.5r	1.45e-05	4.63e-06	1.51e-05	4.63e-06	2.07e-05	2.08e-06	7.67e-06	1.57e-07
6.0r	1.31e-05	4.32e-06	1.36e-05	4.32e-06	1.87e-05	2.54e-06	7.54e-06	4.86e-07

Table 3. Flux densities at various locations nonmagnetic material on line L_2 (13.7mm)..

	v=0.0 m/sec		v=1.0 m/sec		v=10.0 m/sec		v=100.0 m/sec	
distance	B_r	B_z	B_r	B_z	B_r	B_z	B_r	B_z
0.1r								
0.5r								
1.0r								
1.5r								
2.0r								
2.5r								
3.0r								
3.5r								
4.0r								
4.5r								
5.0r								
5.5r								
6.0r								

Table 3. Analytic solution

	v=0.0 m/sec		v=1.0 m/sec		v=10.0 m/sec		v=100.0 m/sec	
distance	B_r	B_z	B_r	B_z	B_r	B_z	B_r	B_z
0.1r	8.31e-04	2.20e-03	8.08e-04	2.20e-03	5.93e-04	2.18e-03	5.30e-04	3.71e-03
0.5r	3.44e-03	1.09e-04	3.43e-03	1.34e-04	3.34e-03	3.39e-04	2.30e-03	3.29e-04
1.0r	1.20e-03	6.81e-04	1.20e-03	7.02e-04	1.22e-03	8.87e-04	8.14e-04	1.39e-03
1.5r	5.36e-04	4.80e-04	5.40e-04	4.94e-04	5.77e-04	6.28e-04	4.42e-04	1.25e-03
2.0r	2.66e-04	3.18e-04	2.70e-04	3.27e-04	3.04e-04	4.21e-04	2.93e-04	1.04e-03
2.5r	1.43e-04	2.12e-04	1.46e-04	2.19e-04	1.72e-04	2.84e-04	2.15e-04	8.57e-04
3.0r	8.13e-05	1.45e-04	8.34e-05	1.50e-04	1.03e-04	1.96e-04	1.65e-04	7.06e-04
3.5r	4.94e-05	1.02e-04	5.08e-05	1.06e-04	6.44e-05	1.38e-04	1.32e-04	5.84e-04
4.0r	3.17e-05	7.42e-05	3.27e-05	7.64e-05	4.22e-05	9.99e-05	1.06e-04	4.84e-04
4.5r	2.10e-05	5.51e-05	2.16e-05	5.67e-05	2.83e-05	7.37e-05	8.67e-05	4.03e-04
5.0r	1.41e-05	4.18e-05	1.46e-05	4.30e-05	1.93e-05	5.56e-05	7.08e-05	3.37e-04
5.5r	9.87e-06	3.25e-05	1.02e-05	3.33e-05	1.35e-05	4.27e-05	5.82e-05	2.82e-04
6.0r	7.32e-06	2.56e-05	7.54e-06	2.63e-05	9.95e-06	3.34e-05	4.83e-05	2.37e-04

Table 3a. Flux densities at various locations and at different ferromagnetic material on line L_1 (20.3mm)..

	v=0.0 m/sec		v=1.0 m/sec		v=10.0 m/sec		v=100.0 m/sec	
distance	B_r	B_z	B_r	B_z	B_r	B_z	B_r	B_z
0.1r								
0.5r								
1.0r								
1.5r								
2.0r								
2.5r								
3.0r								
3.5r								
4.0r								
4.5r								
5.0r								
5.5r								
6.0r								

Table 3a. Analytic solution

	v=0.0 m/sec		v=1.0 m/sec		v=10.0 m/sec		v=100.0 m/sec	
distance	B_r	B_z	B_r	B_z	B_r	B_z	B_r	B_z
0.1r	1.86e-04	8.76e-04	1.69e-04	8.79e-04	1.77e-05	8.86e-04	6.01e-04	2.64e-04
0.5r	6.93e-04	4.81e-04	6.84e-04	4.91e-04	5.92e-04	5.72e-04	2.58e-04	4.94e-04
1.0r	6.31e-04	3.65e-06	6.31e-04	4.94e-06	6.27e-04	7.71e-05	1.23e-04	3.66e-04
1.5r	3.98e-04	1.44e-04	4.01e-04	1.40e-04	4.26e-04	1.02e-04	2.23e-04	1.84e-04
2.0r	2.38e-04	1.50e-04	2.42e-04	1.49e-04	2.70e-04	1.33e-04	2.17e-04	7.87e-05
2.5r	1.44e-04	1.25e-04	1.47e-04	1.25e-04	1.71e-04	1.20e-04	1.87e-04	2.44e-05
3.0r	8.99e-05	9.79e-05	9.19e-05	9.82e-05	1.10e-04	9.87e-05	1.57e-04	3.40e-06
3.5r	5.79e-05	7.54e-05	5.93e-05	7.58e-05	7.25e-05	7.84e-05	1.30e-04	1.71e-05
4.0r	3.84e-05	5.81e-05	3.94e-05	5.85e-05	4.90e-05	6.18e-05	1.07e-04	2.37e-05
4.5r	2.63e-05	4.51e-05	2.70e-05	4.55e-05	3.39e-05	4.88e-05	8.88e-05	2.63e-05
5.0r	1.85e-05	3.55e-05	1.90e-05	3.58e-05	2.40e-05	3.87e-05	7.37e-05	2.67e-05
5.5r	1.33e-05	2.82e-05	1.37e-05	2.85e-05	1.73e-05	3.10e-05	6.13e-05	2.59e-05
6.0r	9.79e-06	2.27e-05	1.00e-05	2.30e-05	1.27e-05	2.51e-05	5.11e-05	2.44e-05

Table 4. Induced voltages at different velocities for the pickup coil shown in Fig 2. Ferromagnetic material is assumed for the tube.

Velocity [m/s]	Re(V)	Im(V)	|V|	Phase
0				
5				
10				
15				
20				
25				
30				
35				
40				
45				
50				
60				
70				
80				
90				
100				

Units: Velocity: m/sec, V: Volts, Phase: Degrees

Table 4. Analytic solution

Velocity [m/s]	Re(V)	Im(V)	|V|	Phase
0	-9.4403e-06	-2.3648e-05	2.5463e-05	-1.1176e+02
5	-1.2770e-05	-3.2328e-05	3.4759e-05	-1.1155e+02
10	-1.6913e-05	-4.4368e-05	4.7483e-05	-1.1087e+02
15	-2.1389e-05	-6.1892e-05	6.5483e-05	-1.0906e+02
20	-2.4451e-05	-8.2529e-05	8.6075e-05	-1.0650e+02
25	-2.5453e-05	-1.0175e-04	1.0488e-04	-1.0404e+02
30	-2.4925e-05	-1.1739e-04	1.2001e-04	-1.0199e+02
35	-2.3581e-05	-1.2937e-04	1.3150e-04	-1.0033e+02
40	-2.1928e-05	-1.3843e-04	1.4015e-04	-9.9001e+01
45	-2.0257e-05	-1.4545e-04	1.4685e-04	-9.7929e+01
50	-1.8707e-05	-1.5118e-04	1.5233e-04	-9.7054e+01
60	-1.6144e-05	-1.6073e-04	1.6154e-04	-9.5736e+01
70	-1.4262e-05	-1.6943e-04	1.7003e-04	-9.4812e+01
80	-1.2886e-05	-1.7807e-04	1.7854e-04	-9.4139e+01
90	-1.1858e-05	-1.8678e-04	1.8716e-04	-9.3633e+01
100	-1.1063e-05	-1.9549e-04	1.9581e-04	-9.3239e+01

Units: Velocity: m/sec, V: Volts, Phase: Degrees

Table 4a. Induced voltages at different velocities for the pickup coil shown in Fig. 2. Nonmagnetic material is assumed for the tube.

Velocity [m/s]	Re(V)	Im(V)	|V|	Phase
0				
5				
10				
15				
20				
25				
30				
35				
40				
45				
50				
60				
70				
80				
90				
100				

Units: Velocity: m/sec, V: Volts, Phase: Degrees

Table 4a. Analytic solution

Velocity [m/s]	Re(V)	Im(V)	|V|	Phase
0	-2.4010e-06	-6.9217e-05	6.9259e-05	-9.1987e+01
5	-2.7326e-06	-7.6089e-05	7.6138e-05	-9.2057e+01
10	-3.1347e-06	-8.4191e-05	8.4249e-05	-9.2132e+01
15	-3.6233e-06	-9.3796e-05	9.3866e-05	-9.2212e+01
20	-4.2165e-06	-1.0522e-04	1.0531e-04	-9.2295e+01
25	-4.9300e-06	-1.1880e-04	1.1890e-04	-9.2376e+01
30	-5.7849e-06	-1.3491e-04	1.3503e-04	-9.2455e+01
35	-6.7686e-06	-1.5392e-04	1.5407e-04	-9.2518e+01
40	-7.9451e-06	-1.7616e-04	1.7634e-04	-9.2582e+01
45	-9.2766e-06	-2.0196e-04	2.0217e-04	-9.2630e+01
50	-1.0760e-05	-2.3154e-04	2.3179e-04	-9.2661e+01
60	-1.4188e-05	-3.0263e-04	3.0296e-04	-9.2684e+01
70	-1.8091e-05	-3.8957e-04	3.8999e-04	-9.2659e+01
80	-2.2198e-05	-4.9040e-04	4.9090e-04	-9.2592e+01
90	-2.6367e-05	-6.0256e-04	6.0314e-04	-9.2506e+01
100	-3.0390e-05	-7.2320e-04	7.2384e-04	-9.2406e+01

Units: Velocity: m/sec, V: Volts, Phase: Degrees