PROPAGATION OF ACOUSTIC PULSE DUE TO PD IN POLYMERIC INSULATING MATERIAL

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1 Introduction:

In the current operational climate, continuity of electricity supply is a big challenge especially during the winter months. The power system therefore must remain operational and not affected by unplanned outages. For this to be prevented, the insulation of the electrical transmission and distribution network plays a vital role. Solid dielectrics, particularly polymeric insulating materials, are widely used as an insulation in electrical power cables. These materials are not expensive and easy to process. When the insulation is degraded, the continuous high voltage stress can initiate partial discharges (PD) which deteriorate the insulating properties of these materials. The insulation failure of the power cable network can be costly for both utilities and supplier. Therefore, in parallel to engineering novel dielectric materials with better dielectric strength, detection of the PD at initial stages is very important. Numerous PD detection techniques have been applied in recent past. The acoustic emission (AE) technique is a non-invasive PD detection and localising technique[1, 2]. This is a well-established technique to detect and locate the PD from gas and liquid insulation systems. This technique is yet not fully explored for solid insulation systems.

T. Czaszejko [3] carried out numerical simulations of creating a PD acoustic pressure pulse inside a cavity and analysed the effects of geometry of the cavity on the propagating acoustic pressure pulse. His approximated energy model in conjunction with PD event suggested that the pressure acoustic pulse initiated due to a PD event can propagate through the material. The above described model focused to analyse the effects of the shape and size of the cavity on the frequency of the acoustic pulse. Similarly, it was only able to analyse the pressure wave frequency rather than sound intensity. In fact, it is the pressure wave intensity which defines the propagation capability of the pressure wave

In this paper, Finite Element Method (FEM) based simulation model was built in COMSOL Multiphysics software to analyse the potential to use AE technique to detect and locate PD in solid insulating materials. A point source approximation was used to initiate the pressure acoustic wave and then propagation behaviour of acoustic pressure pulse was analysed by using appropriate partial differential equations (PDEs) of acoustic wave propagation. The propagation characteristics i.e, peak pressure and drop in pressure magnitude with distance of an acoustic pressure wave were analysed.

2 COMSOL Simulation Model:

The acoustic wave propagation model developed in this work is based on the Finite Element Analysis (FEA) technique. Two different model geometries i.e, spherical and cylindrical, were created and analysed for the propagation of acoustic wave in solid polymeric insulating materials. The reasons for considering these models are described in the following sections. The computer-model is divided into three parts; FEA model equations, development of the geometric-model, and development of perfectly matched layer. Several assumptions were made to simplify the computer-model.

2.1 Finite Element Analysis model

The model is implemented in three-dimensional (3D) COMSOL software. The propagation of acoustic wave in the model is solved using Partial Differential Equations (PDE). Mathematical module was chosen from the application mode to solve the problem. This gives the freedom to define our own conditions in terms of mathematical equations. In the 'Model Navigator' window of COMSOL, the '3D' space dimension is chosen and the 'coefficient form of PDE' is selected under the 'mathematical Module' to solve the acoustic wave propagation in the model.

2.2 Field model equation

The coefficient form of partial differential equation (PDE), available in mathematical mode of COMSOL Multiphysics, was selected.

$$\left\{\begin{array}{c} e_a \frac{\partial^2 P}{\partial t^2} + d_a \frac{\partial P}{\partial t} + \nabla.(-c\nabla P - \alpha P + \gamma) + \beta.\nabla P + \alpha P = f \\ \nabla = \left[\frac{\partial}{\partial x}, \frac{\partial}{\partial y}, \frac{\partial}{\partial z}\right] \end{array}\right\} \quad (1)$$

During the PD event an energy is released in a void in solid insulation resulting in fast increase in the gas pressure which generates a pressure impulse. Short duration pressure pulses generated by PD's propagate through the insulation. Assuming the source as a forcing function, the wave equation governing the propagation of acoustic wave can be represented as;

$$\frac{1}{\rho {C_s}^2} \frac{\partial^2 P}{\partial t^2} - \nabla.\left(\frac{1}{\rho}\ \nabla \mathrm{P}\right) = \mathrm{S(x, t)} \qquad (2)$$

here,ρ is the density of the material in kg/m^3, P(x,t) is the pressure in Pa, and S(x$_o$, t) is the acoustic source. The coefficient form of PDE was modified by replacing the parameters and variables to get the PDE of acoustic wave propagation.

Table 1. Coefficients of PDE for wave equation.

Name	Expression
e_a	$\frac{1}{\rho {C_s}^2}$
c	$\frac{1}{\rho}$

2.3 Modelling of acoustic source:

It was assumed that the discharge activity is like a point source emitting the acoustic waves. This point source in FEA model can be described as:

$$S(x,t) = \frac{dg(t)}{dt} \frac{\partial^2}{\partial x^2}(x - Xo) \qquad (3)$$

Here, $g(t)$ is the Gaussian pulse which can be described as:

$$g(t) = \left\{\begin{array}{ll} Ae^{-\pi^2 f_o^2 (t-\tau)^2} & for\ 0 < t < 2\tau \\ 0 & otherwise \end{array}\right\} \quad (4)$$

This above equation is obtained from the acoustic model of the Gaussian pulse point source [5]. The source emits the sound waves in time domain; just like a PD model in which a discharge site emits the electromagnetic waves. The notation A represents the rate of air flow away from the acoustic source in m^3/s. Further, τ represents the pulse width and f_0 represents the pulse bandwidth which is inversely proportional to the pulse width $f_0 = 1/\tau$.

The duration of a discharge event varies between tens and hundreds of nanoseconds. Therefore, in the simulation, the values for τ can be adjusted to reduce the computing complexity. The value of rate of air flow defines the peak value of the acoustic pressure. To simplify the model, the value of A was assumed to be unity.

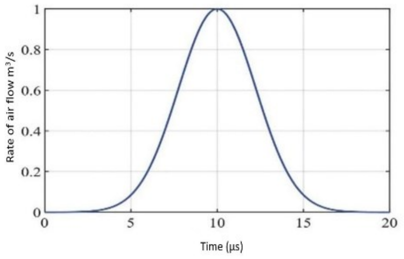


Figure 1. The gaussian point source excitation function at S(0, t).

2.4 Perfect Matched Layer (PML):

The analysis of a propagating wave can be complicated because of the reflections from the boundary of the materials geometry. To overcome this problem, a Perfect Matched Layer (PML) was added. The (PML) which can be a domain or layer (also known as sponge layer) available in COMSOL Multiphysics that can be added to an acoustic model and can serve as a non-reflecting domain (perfectly absorbing boundary or domain). The PML works with all types of waves. In time domain, the PML does not include a real stretching component. Therefore, the geometric thickness, of the layer in the geometry, needs to be set adequately.

2.5 Model geometry and parameters:

In time domain analysis, adding the PML is a challenging task especially for small geometries. As PML does not include a real stretching component, to get rid of any reflections from the boundary and acoustic scattering, choice of geometric thickness is critical. For cylindrical geometry where, radial thickness is less compared to the length of the cylinder, setting up the adequate geometric thickness becomes complex. Therefore, primarily the spherical geometric model was used to set up the layered thickness of the PML. Further, the propagation of acoustic wave and reflections from the boundary of the sphere were observed before and after the addition of the PML domain. The approach was further applied in modelling the cylindrical geometry and analysing the propagation in cylinder.

Sphere: Two 3-D layered structured spherical model geometries shown in figure 2, with different radii and having same centre were developed in COMSOL Multiphysics. The inner sphere was defined as Nylon 66.

The propagation behaviour of the acoustic wave was analysed in this region. To add a PML domain, outer layered structure sphere around the polymer was taken having the radius ten times the radius of Nylon 66 and the thickness of the layer has the dimensions three times the radius of the polymeric sphere.

Cylinder: An inner cylinder with radius 20mm and height 25m shown in figure 3, was considered to analyse the propagation of acoustic wave and the layered structured outer cylinder was considered as the PML region. The acoustic point source was placed at mid-way (12.5m) along the axial-axis. The whole process to create a geometry and PML was same as in case of sphere.

Table 2. Parameters used for the model.

Name	Expression	Description
F_{max}	100[kHz]	Pulse bandwidth
L	c_Nylon/f	Wavelength, free space
T	1/f	Period
ρ_{Nylon}	850[kg/m^3]	Density of Nylon 66
c_{Nylon}	1200[m/s]	Speed of sound in Nylon 66
N	6	No of elements per wavelength
t	1e-6	time
C_{air}	343[m/s]	Speed of sound in air
τ	1/f	Pulse width
A	1	Rate of air flow
D_{Nylon}	$1/\rho_{PU} .C_{PU}^2)$	Coefficient of e_a
C_{Nylon}	$1/\rho_{PU}$	Coefficient of PU
Z	$\rho_{PU} . C_{PU}$	Impedance
h_max	$C_{PU} /f.N$	Maximum element size

Domains and Materials; The internal sphere in figure 2 is defined as polymer. Table 3 shows the properties of the polymer. The propagating acoustic wave can be reflected from the boundary. To avoid any reflection from the boundary, a perfectly matched layer was developed around the polymeric sphere. This allowed the acoustic pulse to pass through the boundary. From the material library, air was assigned to the physical domain in the PML region.

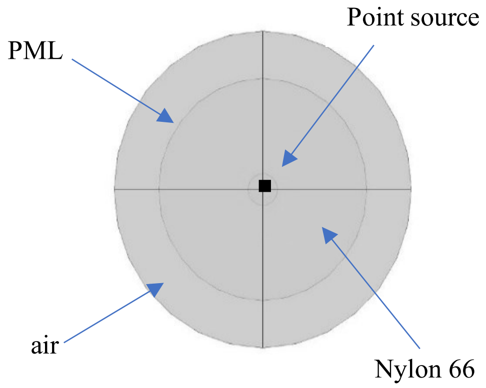
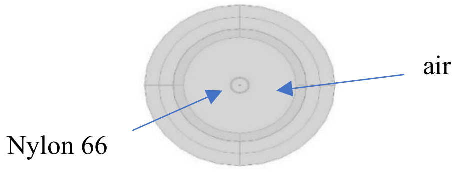


Figure 2. Spherical model geometry

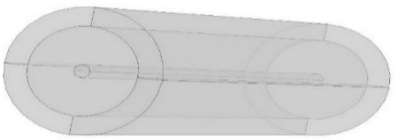
Table 3. Parameters associated with Polyurethane

Material	Speed of sound	Density
Nylon 66	1200[m/s]	1050[kg/m^3]
Air	343 [m/s]	1.204

Similarly, for cylindrical model the acoustic point source was placed at 12.5m along the z-axis as shown in figure 3. The whole process to create a geometry and PML was same as in case of sphere.



(a) xy



(b) xyz

Figure 3. cylindrical model geometry

Meshing: The meshing is divided into three sets. The tetrahedral shape elements of quadratic Langrage order were used for meshing the polymer domain and physical domain. In order to resolve the propagation of acoustic wave, a minimum of 5 to 6 mesh elements per wavelength is required. When using quadratic Langrage elements. The maximum mesh size was calculated by [4]:

$$h_{max} = \frac{\lambda_{min}}{N} = \frac{c_{min}}{f_{max}.N} \qquad (5)$$

Where h_{max} is the maximum mesh element size, λ_{min} is the minimum wavelength calculated at maximum frequency and minimum speed of sound c_{min} in the region, and N is the number of elements per wavelength. All these parameters are defined in table 2. The maximum element size h_{max}= 0.0017m is taken for the meshing of the polymer domain and physical domain. The swept distribution mesh was created in PML domain having number of elements 6. Free triangular mesh was created on rest of the geometry.

Study and Solver: The model is computed for a time-dependent study of 600μs using the MUMPS (Multifrontal massively parallel sparse) direct solver. To adequately resolve the propagation of acoustic wave in the time, a minimum value of time step △t is calculated by:

$$\triangle t = \frac{h_{max}\,CFL}{c_{min}} \quad (6)$$

Where CFL is the non-dimensional number; it can be interpreted as the fraction of an element the wave travels in a single time step. To minimize the error, the value of CFL number should be less than 0.2 for quadratic mesh elements. For the model, $f_{max} = 100kHz$, N=6, CFL=0.1, a time step of $\triangle t = 0.1667\,\mu s$ is taken to solve the model.

3. Results and Discussion:

The cylindrical and spherical models were simulated and run in COMSOL Multiphysics. Apart from the different geometries, the whole simulation process was same for both of the models. The propagation of acoustic wave in a sphere at different time is shown in figure 4.

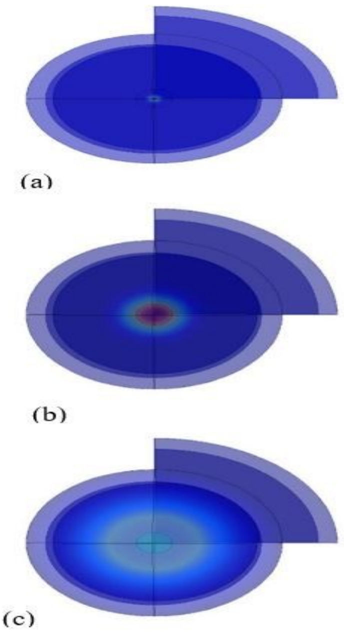


Figure 4. Acoustic pulse propagation in spherical model geometry. a) t = 1μs, b) t = 100 μs, c) 500 μs.

Figure 4 shows that the acoustic wave propagate with a spherical wave front. The amplitude of the spherical wave is inverse square of the radius of the wave front. This was confirmed in spherical model of the geometry. As there were no reflections from the boundary, therefore, the resulting wave propagation was perfectly observed in cylindrical geometry as well. Point probes were used to detect the propagating pulse at different locations in the model geometry and two examples are shown in figure 5. Further, it was observed that the propagating acoustic pulse entered the PML region instead of reflecting from the boundary of the Nylon 66.

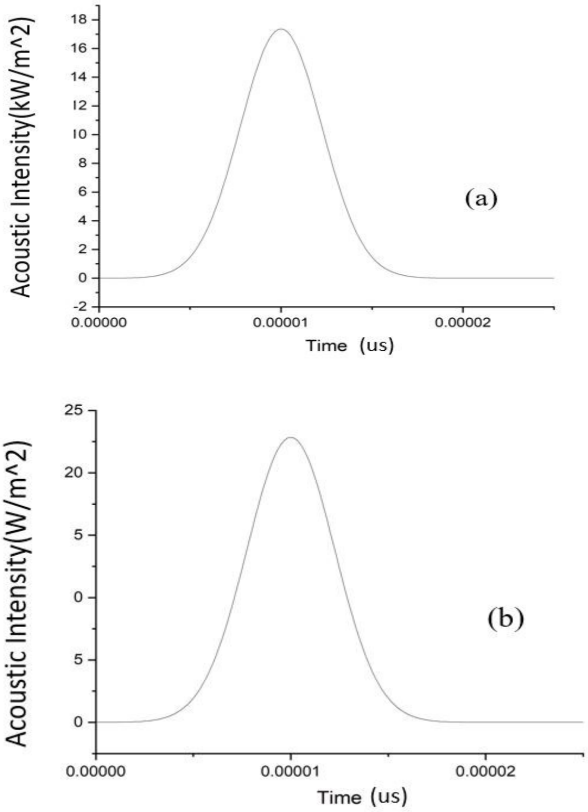


Figure 5. Acoustic wave in cylinder at different locations (a) source, (b) 20cm away from source.

The drop in the magnitude of pressure pulse can be depicted from figure 5(a) and 5(b). The magnitude of the pressure acoustic pulse decay sharply with distance. The decay is $1/r^2$ where r is the distance away from the source. This high drop in magnitude is the key factor to limit the use of the acoustic emission technique in solid insulating materials. The reasons behind the high decay are still unknown and needs more study.

The magnitude of the propagating acoustic pulse was observed at different points along the axial direction of the cylinder by using point probe. Figure 6 shows the magnitude at different points away from the source. A curve joining the points was used to analyse the drop-in magnitude along the distance.

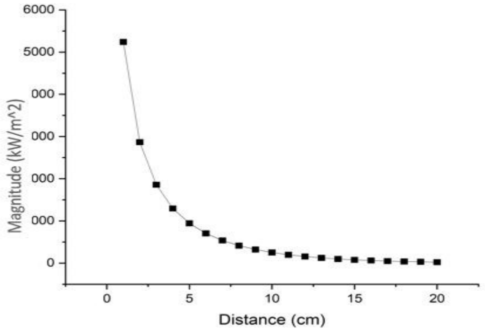


Figure 6. Drop in magnitude of the propagating acoustic pulse with distance.

4. Conclusion:

This article describes the development of the acoustic emission model in COMSOL and then time domain analysis of the propagation of acoustic pulse in Nylon 66 using COMSOL Multiphysics. The results suggest that the decay rate of the acoustic pulse may limit the use of this technique in detecting the PD in solid insulating materials over a distance that is typical of cable lengths in an electricity network. The developed model was based on the assumptions about the pressure. There is need to calculate the amount of energy emitted from the discharge source in actual PD event and use that to define the peak value of the pulse in the simulation which then can be used to see the propagation capability of the acoustic pulse in Nylon 66. Further, the effects of material`s physical and chemical characteristics on the propagating acoustic wave need to be investigated.

6. References:

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