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NUMERICAL ANALYSIS OF DEFECTS USING INFRARED THERMOGRAFY VARYING ITS DEPTH

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Abstract. *The present work is based on the analysis of the variation of the surface temperature, varying the depth of the defect in the sample. With the analysis of this sensibility, it is possible to identify the impact that this variation of depth will cause for the identification of defects in the sample. Considering that only one plan of the material will be used to make this study.*

Keywords: *MVF, Thermography, Infrared Camera, Sensitivity*

1. INTRODUCTION

For the advancement of technology and the manufacture of materials, it was necessary to perfect the materials produced. For that reason, a more effective class of methods was developed to find out if there were defects in the test piece without damaging it.

This class was called Non-Destructive Testing (NDT) in which consists of an investigation of the condition of the test piece without any interference to its physical integrity. Within this class there is a method called infrared thermography. Which is a analyses of the temporal variation of the temperature of a body through a remote sensing that interprets the electromagnetic waves emitted by a body and turns them into thermal images (Rodríguez, 2014).

These END techniques are being developed for the purpose of, production processes, the integrity of the material during its transport, inventory and manufacturing and the depreciation of the product during its useful life. This techniques can be classified into seven major categories (Hung *et al.*, 2009):

1. Visual
2. Penetrating Radiation (Raio-X)
3. Magnetic-Electricity(Foucault current)
4. Mechanical Vibrations (Ultrasound)
5. Chemistry
6. Infrared radiation and thermal tests(Infrared Thermografy)
7. Other optical methods

There are several methods to check if a material has defects. Among the NDT methods, infrared thermography has been gaining a lot of space. Since it can be divided into active or passive infrared thermography. (López Rodríguez, 2010)

The passive infrared thermography is based on analysing a body without an external temperature stimulation, observing it under normal conditions, if it is at a temperature different from the environment in which it is being studied. This method aims to look for irregularities in the temperature history via hot or cold spots. It is usually used for monitoring electrical components or for insulation problems in buildings (Kaltmann, 2008).

The active infrared thermography is based on analysing a body that undergoes an external stimulation of temperature, so that there is a thermal variation in the surface of the object. In order to analyse an object with an internal defect (holes, unknown materials, etc.) it is necessary to subject the material to a temperature variation so that it can produce different thermal patterns between the defects and the main body. The active thermography can be applied in a large scale of Non-Destructive Testing (NDT), since practically any form of energy can be used to stimulate the studied object. (Maldague, 2001).

In the identification of defects using infra-red thermography, there are several factors to be taken into consideration. In this work we will deal with the sensitivity that occurs in the variation of the surface temperature changing the depth of the defect in the material tested.

Through the study of sensitivity it will be possible to identify two important factors for the detection of defects in the material. Which would be the ideal time and the greatest amplitude according to the depth of the defect.

2. METHODOLOGY

To detect internal defects, transient thermography is used, which consists of analysing the surface temperature variation of a certain object as a function of time. With this it is possible to detect the presence of the defects being that they have a different behaviour from the defect-free part of the material. A numerical approximation was made, through the Finite Volume Method (MVF).

2.1 Computacional Procedure

In this work, the Finite Volume Method (MVF) was used to develop a FORTRAN code capable of generating and solving numerically the differential equations for any number of volumes at the specified time. This method consists of subdividing the block into several volumes of the same size by creating a set of equations and solving them to find the respective temperature values for the center of each volume. For this it is necessary to perform an energy balance by determining the local equations.

To realize the energy balance for a generic volume of size Δx, Δy and Δz it is necessary to know the heat flow coming from it. The energy balance is performed by knowing the incoming energy that comes out and the energy generated by the material in a certain time.

To obtain the numerical result for the model, you must first resolve a 3-D mesh of the general equation of transient conduction, shown in 1.

$$\frac{\partial}{\partial t}(\rho T) = \frac{\partial}{\partial x}\left(\frac{k}{c_p}\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(\frac{k}{c_p}\frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(\frac{k}{c_p}\frac{\partial T}{\partial z}\right) + S \tag{1}$$

Before integrating equation 1, it is necessary to define the time interpolation, which can be seen in figure 1 and are represented by equation 2 (Maliska, 1995).

$$T^{\theta} = \theta T + (1-\theta)T^0 \tag{2}$$

Choosing $\theta = 1$ will cause all temperatures near the study point to be evaluated at the current instant of time. A system of equations is created, which must be solved together, having to solve a linear system. The actual transient resolution of this problem is an iterative process, usually used to solve the linear system given by equation 3, the term T_p^0 should not be changed until the temperatures for that time interval have not yet converged. The time interval should be limited by precision.

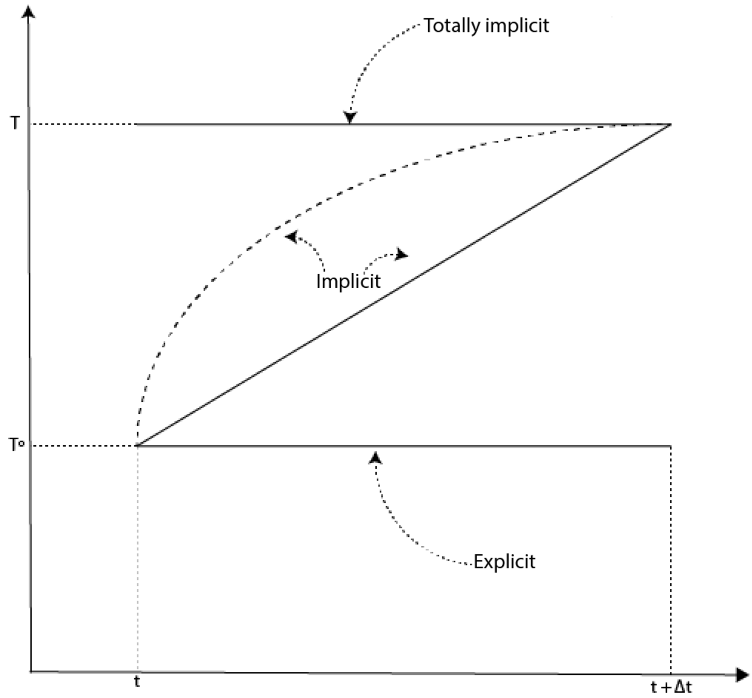
By integrating this equation into space and time, making an approximation of the derivatives in the interfaces of the elemental volume by central differences and using a fully explicit formulation, we have the equation 3

$$A_pT_p = A_eT_e + A_wT_w + A_nT_n + A_sT_s + A_{zf}T_{zf} + A_{zb}T_{zb} + B \tag{3}$$

The equation 3 is the approximate equation for a generic elementary volume, being deduced taking into account an internal volume, all internal volumes have the same approximate equation. To obtain the complete algebraic equation system, it is also necessary to know the equations for the boundary volumes. The coefficients presented in the equation ref eq: General-Approximate-Conduction are respectively:

$$A_e = \left.\frac{k}{c_p\Delta x}\right|_e \Delta y\Delta z \tag{4}$$

Figure 1. Time interpolation



$$A_w = \frac{k}{c_p \Delta x}\bigg|_w \Delta y \Delta z \tag{5}$$

$$A_n = \frac{k}{c_p \Delta y}\bigg|_n \Delta x \Delta z \tag{6}$$

$$A_s = \frac{k}{c_p \Delta y}\bigg|_s \Delta x \Delta z \tag{7}$$

$$A_{zf} = \frac{k}{c_p \Delta z}\bigg|_{zf} \Delta y \Delta x \tag{8}$$

$$A_{zb} = \frac{k}{c_p \Delta z}\bigg|_{zb} \Delta y \Delta x \tag{9}$$

$$M_p = \rho \Delta x \Delta y \Delta z \tag{10}$$

$$M_p^0 = \rho^0 \Delta x \Delta y \Delta z \tag{11}$$

$$B = \frac{M_p^0}{\Delta t} T_p^0 \Delta x \Delta y \Delta z + S_c \Delta x \Delta y \Delta z \tag{12}$$

$$A_p = A_e + A_w + A_n + A_s + A_{zf} + A_{zb} + \frac{M_p}{\Delta t} - S_p \Delta x \Delta y \Delta z \tag{13}$$

In the boundary conditions will be considered the heat exchanges by convection and radiation. We must match the heat that comes from convection and radiation with the heat by conduction into the boundary volume, thus we have the equation for the boundary volumes, shown in equation 14. (López Rodríguez, 2010)

$$k_f \frac{T_f - T_p}{\Delta x_f} = h(T_{\text{inf}} - T_f) + \sigma\epsilon(T_{amb}^4 - T_f^4) \tag{14}$$

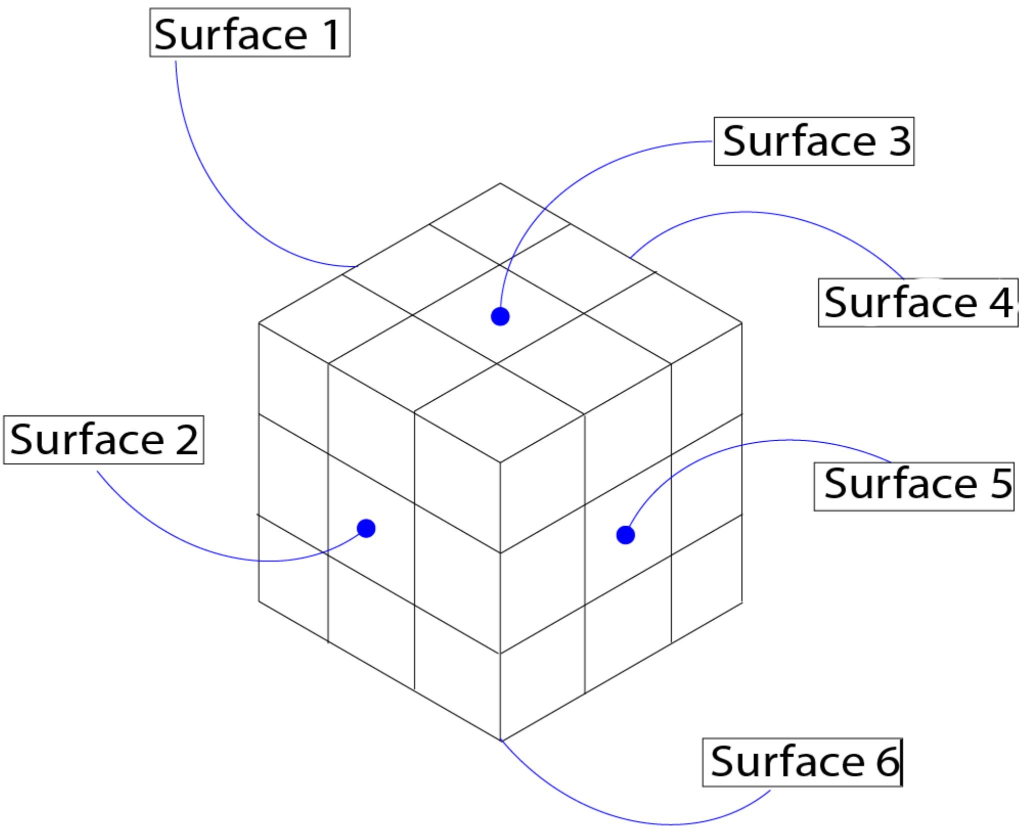
In equations 4 to 14, the variable T represents the temperature of the object for any point with x, y, and z coordinates. T_amb represents the ambient temperature, considering that the air and the neighborhood are at the same temperature. Some of the important variables cited in the equations above are described below:

1. σ**:** Stefan Boltzmann constant.
2. k**:** Thermal conductivity of the material.
3. h_{conv}**:** Coefficient of heat transfer by convection.
4. c_p**:** Specific heat of the material
5. ρ**:** Density of thmaterial
6. t**:** Time control variable.

Knowing that each face of the studied material will represent a different contour condition, since the material has six faces, we will have six different conditions. Using them together with the initial condition it is possible to numerically express the surface temperature which is equivalent to the thermograms obtained with the infrared camera during an active test.

The boundary volumes, which represent all the volumes contained in the surface area shown in the figure 2, should use a different equation than the internal volumes because the surface temperatures are unknown. Since they depend directly on the convective heat exchanges and radiation they suffer from the environment, it is necessary to perform a energy balance on the surface in question to obtain the desired equations.

Figure 2. Surface areas in a cubic material



To obtain the equations of the surface volumes it is fundamental to carry out the energy balance at the boundaries. We can see that the energy received through radiation and convection media is transported into the volume by conduction, since the distance from the node to the wall is $\Delta X/2$ the equations of the boundary conditions for the volumes in the center of each surfaces shown in the figure 2, are:

- **Surface 1:**

$$\frac{k}{\Delta z/2}(T_{(i,j,k+1)} - T_{(i,j,k)})\Delta x \Delta y = h_{lat}(T_{amb} - T_{(i,j,k)})\Delta x \Delta y + \sigma\epsilon(T^4_{amb} - T^4_{(i,j,k)})\Delta x \Delta y \quad (15)$$

- **Surface 2:**

$$\frac{k}{\Delta x/2}\left(T_{(i-1,j,k)} - T_{(i,j,k)}\right)\Delta z \Delta y = h_{lat}(T_{amb} - T_{(i,j,k)})\Delta z \Delta y + \sigma\epsilon(T^4_{amb} - T^4_{(i,j,k)})\Delta z \Delta y \quad (16)$$

- **Surface 3:**

$$\frac{k}{\Delta y/2}\left(T_{(i,j-1,k)} - T_{(i,j,k)}\right)\Delta z \Delta x = h_{lat}(T_{amb} - T_{(i,j,k)})\Delta z \Delta x + \sigma\epsilon(T^4_{amb} - T^4_{(i,j,k)})\Delta z \Delta x \quad (17)$$

- **Surface 4:**

$$\frac{k}{\Delta x/2}\left(T_{(i+1,j,k)} - T_{(i,j,k)}\right)\Delta z \Delta y = h_{lat}(T_{amb} - T_{(i,j,k)})\Delta z \Delta y + \sigma\epsilon(T^4_{amb} - T^4_{(i,j,k)})\Delta z \Delta y \quad (18)$$

- **Surface 5:**

$$\frac{k}{\Delta z/2}\left(T_{(i,j,k-1)} - T_{(i,j,k)}\right)\Delta x \Delta y = h_{lat}(T_{amb} - T_{(i,j,k)})\Delta x \Delta y + \sigma\epsilon(T^4_{amb} - T^4_{(i,j,k)})\Delta x \Delta y \quad (19)$$

- **Surface 6:**

$$\frac{k}{\Delta y/2}\left(T_{(i,j+1,k)} - T_{(i,j,k)}\right)\Delta z \Delta x = h_{lat}(T_{amb} - T_{(i,j,k)})\Delta z \Delta x + \sigma\epsilon(T^4_{amb} - T^4_{(i,j,k)})\Delta z \Delta x \quad (20)$$

In order to solve the system of linear equations, the TDMA (TriDiagonal Matrix Algorithm) method was used knowing that the presented problem is three-dimensional, this method must be executed iteratively, making sweeps through rows and columns and checking for each instant of convergence time.

2.2 Sensitivity

To determine the effect that the depth of the defect causes on the surface of the material. It is important to perform a sensitivity analysis of the mathematical model in question. To carry out this identification, the proposed model will be divided into 30 x 30 x 30 equal volumes, in this analysis the depth of the defect will vary in the Z axis of the volume 2 to volume 29, volumes 1 and 30 will be discarded because if location in the regions of frontier, assuming that each volume has dimensions of 1mm X 1mm X 1mm. The tests performed in the model simulated a 30,000 second test, in the table below we can see more results.The information about the tests are in Tab. 1.

Table 1. Tests changing the depth of the defect

Test	Depth(mm)	Time(s)	X(mm)	Y(mm)	Z(mm)
1	2	30000	15	15	2
2	5	30000	15	15	5
3	8	30000	15	15	8
4	11	30000	15	15	11
5	14	30000	15	15	14
6	17	30000	15	15	17
7	20	30000	15	15	20
8	23	30000	15	15	23
9	26	30000	15	15	26
10	29	30000	15	15	29

For these analyses all the thermophysical properties of the material were kept constant, only the depth at which the defect will be generated will be altered. The method chosen was Ordinary Least Squares Estimators (OLS), which consists of an approach to adjust a mathematical or statistical model to data,in cases in which the ideal value given by the model is linearly expressed in terms of unknown variables. The result of this adjusted model can be used for several purposes, such as predicting not observed values and to understand the mechanisms that may be hidden in the system. A test was performed without the defect, to be based on its surface temperature. With this standard model the other 10 tests were performed, through the equation 21 a sensitivity value was calculated for each time point for each test.

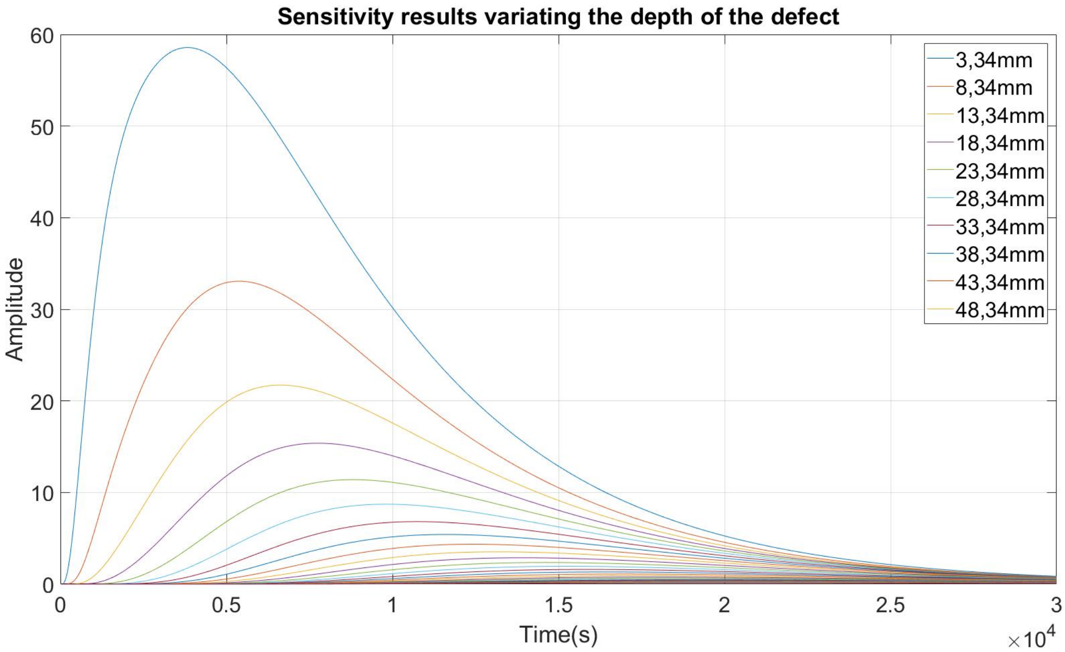
$$Sensibilidade(t) = (T_{(S/Def)}(x,y,t) - T_{(C/DEF)}(x,y,t))^2 \tag{21}$$

3. RESULTS

With this analysis it is possible to locate for each depth that the defect is located, an ideal time where its sensitivity will have reached the maximum value, in this point we can affirm that for this locality and at this instant of time the surface temperature will already present all the fundamental information to the location of the defect. The ten tests described on the table 1 was made for two types of materials, the first was a aluminium block with an air bubble defect and the second a concrete block with the same type of defect.

In figure 3 are the sensitivity curves representing the variation of depth of the defect, in the concrete block. It is possible to verify that the closer to the surface the defect is, the greater its amplitude and the less time is necessary to reach it's maximum value. With the information in the table 2 it is possible to have this maximum time and amplitude information for each respective test.

Figure 3. Sensitivity results variating the depth of the defect in the concrete block.



In the figure 4 it is possible to verify that the variation of maximum amplitude according to the depth is proportionally smaller, seeing that the difference between the shallower defect and the deeper defect is of 20 percent smaller. Compared with that of concrete that has a reduction of 99 percent, it is possible to affirm that for the detection of deeper defects, the material more indicated would be the aluminum.

In the table 3 it is seen that the ideal time for the aluminum test has a low initial value compared to that of the concrete and its variation according to the depth is also smaller than that of the concrete. It can then be stated that for the search of defects, aluminum would be the most suitable material, because its maximum sensitivity is much greater, for all the points of depth, than the one of the concrete facilitating its detection. And the time required to perform these tests will also be shorter with the aluminum block.

4. Conclusion

It is possible to verify that the depth of the defect considerably affects the surface temperature and the ideal time for its detection. It is seen that for greater detectability it will be necessary for the defect to be closer to the surface.

Table 2. Test specifications by changing the depth of the defect

Teste	Depth(mm)	Time(s)	Maximum Sensitivity	Ideal Time(s)
1	2	30000	58,5694	3830
2	5	30000	15,3794	7750
3	8	30000	06,8193	10730
4	11	30000	03,5251	13190
5	14	30000	01,9378	15250
6	17	30000	01,1028	17010
7	20	30000	0,6466	18460
8	23	30000	0,3900	19460
9	26	30000	0,2402	19830
10	29	30000	0,1482	19410

Figure 4. Sensitivity results variating the depth of the defect in the aluminium block.

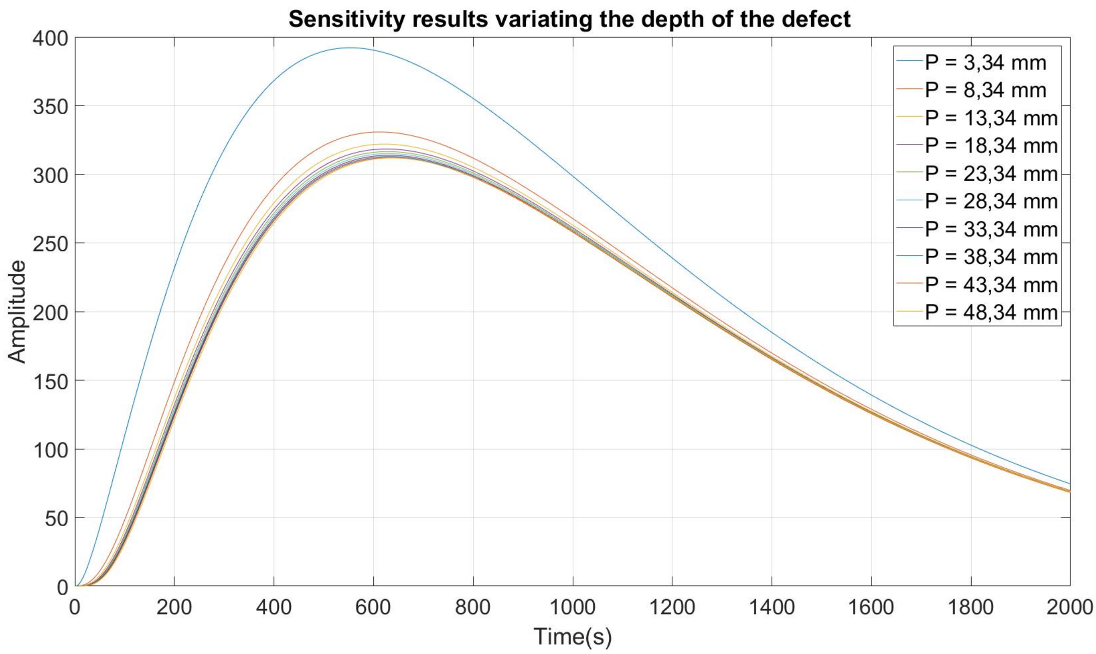


Table 3. Test specifications by changing the depth of the defect

Teste	Depth(mm)	Time(s)	Maximum Sensitivity	Ideal Time(s)
1	3,34	30000	392,0981	554
2	8,34	30000	330,7576	613
3	13,34	30000	321,9179	622
4	18,34	30000	318,3528	625
5	23,34	30000	316,4243	627
6	28,34	30000	314,9958	630
7	33,34	30000	313,7551	631
8	38,34	30000	312,8261	632
9	43,34	30000	312,1470	634
10	48,34	30000	311,8298	637

In the graphs 3 and 4 it is possible to verify that the material in which the defect is located also affects the sensitivity of the surface temperature and the ideal time for its detection. Seeing that in the aluminum block the location of a defect with a significant depth would be faster and easier than in the concrete block. So for deeper detections it is better to choose a aluminium block over a concrete one.

5. References

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