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Excitation source optimisation for active thermography.

Simon Verspeek [1]*, Jeroen Peeters[1], Bart Ribbens[1,3] and Gunther Steenackers [1,2]

[1] Op3Mech research group, Faculty of Applied Engineering, University of Antwerp, 2020 Antwerp, Belgium
[2] Acoustics & Vibration Research Group, Department of Mechanical Engineering, Vrije Universiteit Brussel, 1050 Brussels, Belgium
[3] Multimedia and Communication Technology, Karel de Grote University College, Salesianenlaan 90, B-2660 Antwerp, Belgium
* Correspondence: Simon.Verspeek@uantwerpen.be

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Abstract: In active thermography the use of an optimised excitation source can simplify the interpretation of measurement results. Our custom designed source, especially designed for dynamic line scanning thermography, minimises the needed excitation power and the biasing side effects generated by a wide-range heat source. The source is redesigned, starting from a regular heat source, to focus the available energy such that the needed heating power is provided in a small band. Ray tracing software is used to design absorbers and reflectors in order to focus the electromagnetic radiation as well as the heat in a thin line. The most optimal design is manufactured and validated on a laminated test sample. The acquired thermographic data are then compared to the data captured in the old-fashioned way with widely available excitation sources. The redesign is also tested on durability and practical use to make sure that it is easy to handle and that it can be used as a long-term solution. Experienced inspectors evaluated the ease of use of it in comparison to the existing sources. A redesigned excitation source minimises the generated biasing side-effects resulting in more energy efficient and safer measurements.

Keywords: infrared thermography; optimisation; reflector)

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1. Introduction

Non-destructive testing (NDT) is worldwide advancing in the market of material inspections. Almost every object can be examined due to inspections without damaging the product itself. There is no longer the need to produce extra items in order to submit them to destructive tests. Those non-destructive tests offer a reliable, fast and cost-efficient way to inspect structures without affecting their functionality [1,2]. Within the use of infrared thermography, a variety of techniques can be distinguished according to the origin of the measured temperature differences. Passive thermography takes advantage of the emissivity of each object at a temperature above absolute zero (0K), active thermography on the other hand uses an external excitation source to excitate an object in order to measure the temperature difference between the heating and cooling down. Different excitation sources can be used such as laser heating, halogen lamps, flash lamps, ultrasonic excitation, eddy currents excitation, microwaves, etc. Each of these sources has its advantages and disadvantages, laser heating for example creates the possibility to heat highly focussed. On the other hand are halogen lamps a much cheaper and safer way to heat the object.
Until now the use of halogen lamps led to heating up a wide area of the specimen to be inspected. Several efforts have been done to minimise the heated region. Most of them make use of a slit in order to achieve the desired heating range. Each ray not reaching the specimen is a loss of energy, so the

(a) **(b)**

Figure 1. Two experimental set-ups are shown as they were used until now.
a) Experimental test-setup for dynamic line scanning on a conveyor belt.
b) Cylindrical reflector designed to focus the electromagnetic radiation in a thin line.

amount of those rays should be minimal. Figure 1 shows two experimental set-ups that are used until now in order to minimise the heated region.

An optimised reflector shape could offer a safer and low-budget alternative for the use of laser excitation and could also be a huge step in the further development of Dynamic Line Scan Thermography. Concentrating the heating power in a small region offers a bigger temperature difference between the excitation and cooling down of the specimen to be inspected. This way, more excitation power can be delivered in a short period of time resulting in a more effective heating. The excitation source resembles flash excitation instead of the long step heating.
Multiple applications exist where electromagnetic radiation is focussed in order to produce heat, those are mostly powered by sunlight and therefore focussed using parabolas [3–5]. Incident parallel rays are focussed in the focal point of the parabola, consequently rays leaving the focal point of the parabola will be reflected parallel to each other. Lee et al. [6,7] studied the use of parabolic and elliptical mirrors for near infrared radiation to induce local heating of high-strength steels. Unvala and Maries [8] inspected the heating characteristics of an tungsten halogen lamp in combination with an elliptical reflector. Temperatures of 1200°C were measured using a 1kW heating source. The heated region was minimised to two cm.
In this paper we try to combine the advantage of local heating of laser heating with the low cost and safety of halogen lamps. In order to focus the power of a halogen lamp a reflector is designed using ray tracing software.

2. Methodology

2.1. Requirements

In order to optimise an excitation source for active thermography, several requirements are predefined for the heat source. First of all the focus length of the heat source is defined at 25cm, this value is based on previous test where a non-focused heating source was placed 25cm above the specimen. A second requirement is the use of an tungsten halogen lamp, known as an halogen lamp, these lamps are widely available and are safe to use in almost every circumstance. The focussed beam should be minimised and we aim to focus minimum 80 percent of the heat radiation. Active thermography requires heating of the specimen to be inspected, therefore the heating power should be focussed. Radiation focussing can be performed in multiple ways: using mirrors/ reflectors or using lenses for example. Heat rays on the other hand can't be focused using glass lenses because of the energy losses in the lenses resulting in heating the lenses. A germanium lens on the other hand is suitable for focussing heat radiation, but these are very expensive.

2.2. Geometry

A parabola has the characteristic to reflect incident parallel rays to the focus point of the parabola. This characteristic is better known as the reflective property of a parabola and is proven by several [11–14]. Consequently rays leaving the focal point of a parabola are always reflected along a line parallel to the symmetry axis of the parabola. Using a parabola is therefore not suitable for our application. We aim to focus the rays in a narrow point in order to minimise the heated region.

An ellipse on the other hand can be used because of the specific geometry of an ellipse. The ellipse has the property that any ray leaving one of the foci will be reflected to the other focus point of the ellipse, known as the focal property of an ellipse [15]. The foci of the ellipse are generally named F1 and F2, as visualised in Figure 2. We place the halogen tube lamp in F1 of the ellipse and the predefined heated region in F2. This way every ray leaving the halogen lamp will be reflected to F2 (the heated are on the specimen to be inspected). Figure 2 shows the different characteristics of a parabola and an ellipse.

By using an ellipse it would be theoretically possible to focus the electromagnetic radiation in one single point. In practice this is not possible, because the ellipse should remain a closed curve to ensure all rays are reflected to the other focal point. This is impossible for our application because the rays need to leave the reflector in order to heat up the specimen to be inspected. Opening the elliptical reflector results in a part of the rays not being reflected to the focus point what leads to a wider radiation pattern. The amount of direct radiation towards the specimen can be found using simple mathematics. Figure 2 represents a simplified visualisation of the halogen lamp and the heated region as result of direct illumination. $\overline{OF}$ equals the focus distance between the lamp and the specimen to be inspected, $\overline{E_2E}$ represents the width of the gap in the elliptical reflector and $\overline{H_2H}$ stands for the desired heating region. Consider the triangle △OFE, the angle between $\overline{OF}$ and $\overline{FE}$ equals 90°. This implies that the length of $\overline{OE}$ can be found using Pythagoras Theorem:

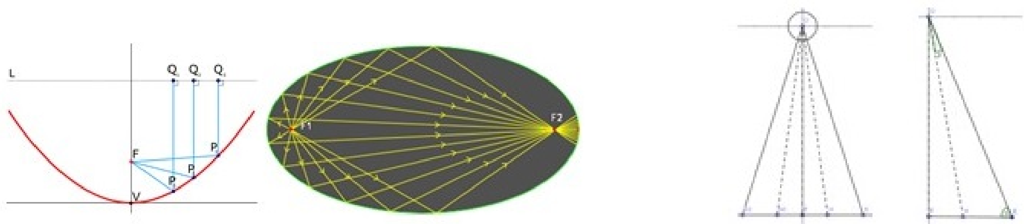
$$\overline{OE}^2 = \overline{OF}^2 + \overline{FE}^2 \tag{1}$$

The value for α is consequently found using:

$$\alpha = sin^{-1}(\frac{\overline{OF}}{\overline{OE}}) \tag{2}$$

The length of a $\overline{HE}$ can easily be found by the subtraction of the total illuminated region $\overline{FE}$ and the desired heating region $\overline{FH}$. Now consider the triangle △OHE, the length of $\overline{OH}$ can be calculated using the law of cosines.

$$\overline{OH}^2 = \overline{HE}^2 + \overline{OE}^2 - 2 * \overline{HE} * \overline{OE} * cos(\alpha) \tag{3}$$



(a) **(b)**

Figure 2. a) The reflecting characteristics of a parabola and an ellipse are visualised [9,10].
b) Geometrical representation in order to calculate the amount of rays not being reflected by the ellipse.

Consequently the angle between $\overline{OH}$ and $\overline{OE}$ can be found using the law of cosines a second time.

$$\overline{HE}^2 = \overline{OE}^2 + \overline{OH}^2 - 2 * \overline{OE} * \overline{OH} * cos(\beta) \tag{4}$$

The area of the lamp illuminating the specimen directly outside the desired region is represented by:

$$A_{\text{outside}} = \beta * r^2 \tag{5}$$

This area equals the summation of the circular sectors in triangle $\triangle$OHE and $\triangle OH_2E_2$. Notice that β is in radian to calculate the area of the circular sector. The percentage of the lamp directly illuminating the specimen can finally be calculated:

$$\%_{\text{outside}} = \frac{A_{\text{outside}}}{\Pi * r^2} * 100\% = \frac{\beta}{\Pi} * 100\% \tag{6}$$

Opening the elliptical reflector for our application at 24cm from the top, results in an heated region of 4.76cm and the desired maximum width of the heated region is 2cm. According to previous calculations the difference of 2.76cm equals an area of 1.83% of our excitation source. A circular sector of the light emitting halogen tube lamp will directly illuminate the specimen to be inspected because of the opening in the elliptical reflector. To ensure that the wish of a 2cm wide focussed light beam is reached additional reflectors are inserted in the ellipse. Figure 3 visualises the designed geometry of the reflector according to the simulations. According to the focal property of an ellipse, a ray leaving in a focal point is reflected to the other focus point of the ellipse. The halogen lamp has a diameter larger then the focal point of the ellipse consequently the rays are not leaving exactly in the focal point of the ellipse. Assuming that the rays leave the halogen lamp normal to the length of it, the extended rays intersect the focus of the ellipse, approving the use of an elliptical reflector.

(a) Optimised geometry according to simulations. **(b)** Ray trajectories according to ray-tracing simulation.

Figure 3. Visualisation of the optimised geometry and the related ray trajectories.

2.3. Simulation

The shape of the reflector is optimised during different stages in order to split the search in smaller steps. In the first place a relatively simple simulation model has been built in COMSOL® 5.2 to ensure the principal working of the model before optimising the shape of the reflector. Afterwards the model is linked with a batch-script to diversify the parameters used in the parametric geometries. This way the shape with the highest intensity in a predefined region can be found using parametric sweep over the different parameters.

For the optimisation of the geometry, following assumptions were made:

- The geometry is made of aluminium.
- The surfaces are highly polished, resulting in a reflection coefficient of almost one.
- The EM-radiation is uniform along the length of the halogen lamp.
- The excitation source and reflector are considered to be indefinitely so the sides can be neglected.

2.3.1. Ray-tracing model

A 2D ray-tracing model is build in COMSOL® 5.2 in order to find the optimal shape for a section of the reflector. A 2D simulation can be used due to the simple geometry of a halogen tube lamp. After parametric designing the optimised section of the reflector it can easily been extruded over the length of the halogen tube. The geometry in the simulation consists of the halogen lamp, the reflector and a specimen on which the incident radiation will be measured. Figure **??** shows the result of a ray-tracing simulation in ideal circumstances.

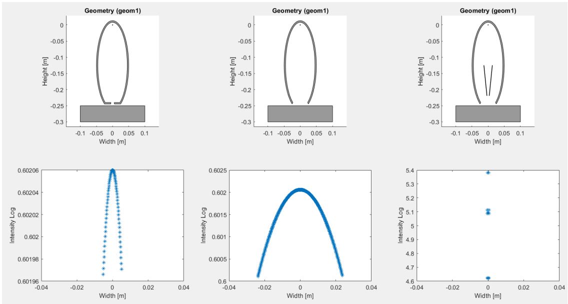


Figure 4. Several geometries are compared to each other. The placing height of the halogen tube lamp varies to identify the difference in heating as result of placing the lamp not exactly in the focus point of the ellipse.

2.3.2. Automated batch-script

Different shapes were examined in order to find the optimal reflector shape. In order to automate the search for the best shape the curvature is completely built up from parametric sections. This way a parametric sweep could be performed using a batch-script. Two parameters are used during this parametric sweep, the first one to change defines the width of the reflector and the second one the height of it. The height of the ellipse is defined by the semi-major axis and the width by the semi-minor axis. The length of the semi-major axis varied between 0 and 0.3 using steps of 0.001. The semi-minor axis on the other hand diversified in a range between 0.1 and 0.2 with steps of 0.001. For each iteration the intensity in a determined region is calculated and compared to the best simulation solution at that moment. As a result of the script a plot is generated visualizing the optimised geometry, the ray trajectories and the computed intensities.

An additional Matlab®-script is used to calculate the impact of inaccurate assembling of the reflector and excitation source. Multiple placement heights of the lamp are simulated to visualise the influence of the error. This error is calculated for three different geometries in order to select the most adequate one out of the simulated geometries. Those geometries are in addition compared to three experimental set-ups. Two of them are shown in Figure 1. Figure 4 shows the visual output of the Matlab®-script used to visualise the impact of the misplacing of the halogen lamp.

3. Results & Discussion

Multiple ray-tracing simulations indicate that the use of an ellipse in combination with additional reflectors is the most suitable solution for the focussing of the electromagnetic radiation coming from an halogen lamp. The width and height of the ellipse are variating according to the predefined requirements for the measurement set-up. The optimised geometry is resistant to flaws as misplacing of the excitation source. The electromagnetic radiation is focussed in a narrow region due to the elliptical reflector and the additional straight reflectors. Those straight reflectors deliver additional energy to the heated specimen in comparison to a reflector with a slit at the bottom to narrow down the heated area.

4. Conclusions

In this paper we have designed a reflector for a tungsten halogen lamp in order to combine the ease of use and the safety of a halogen lamp with a minimal heating region. Using this reflector could resolve in faster and more accurate measurements using dynamic line scan thermography whereby a specimen is inspected using a linear movement. The reflector geometry is designed using ray-tracing software and optimisation software to fulfil the predefined requirements of the measurement set-up. The obtained shape consists of an ellipse with foci at the position of the halogen lamp and at the surface of the specimen. Additional straight reflectors provide an extra energy gain in comparison to using a slit in order to obtain a small heated region.

Further investigation is necessary to define the possible increase of movement speed and accuracy of dynamic line scan thermographic inspections. Simulations regarding heat distribution through the reflector as well as the heat through the specimen as result of the focused beam need to be performed.

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