An analytical local doming model

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Abstract

The trend towards slimmer Color Picture Tubes (CPTs) makes it necessary to design glass, shadow mask and beam deflection function by an integral architectural approach. An important aspect in this is the thermal expansion of the shadow mask leading to mask deformation causing luminance decrease or even discoloration. The thermal deformations are caused by ambient temperature changes and by the bombardment of electrons on the shadow mask. The heating of the mask by the high energy electrons happens both for the entire mask, overall doming, and for a small area on the mask, local doming. The main subject of this research is the local doming phenomenon.

Due to the increase of deflection angles in SuperSlim CPTs, the sensitivity for shift of the projected mask hole on the inner panel caused by mask deformation increases. In order to avoid large mask-screen distances, there is a striving for a mask that is as flat as possible, given the boundary conditions of droptest and microphony. Furthermore, for reasons of material cost reduction, the trend is to use AKOCA instead of INVAR steels. In comparison with INVAR, AKOCA has a coefficient of thermal expansion being about 10 times larger. All these developments have a negative influence on local doming performance.

Local doming is a thermo-mechanical phenomenon. Coupled Finite Element (FE) simulations require long calculation times. To make use of optimization routines a fast model is needed, which can predict mask deformations caused by local heating of the mask. The goal of this research is to get a better understanding about the local doming phenomenon and to obtain a quick tool for optimization design purposes.

To this end, an analytical local doming model is developed, based on the principle of minimum total potential energy. The analytical model deals only with the mechanics, the temperature distribution is assumed to be known.

Mask deformations predicted by the analytical model have been qualitatively compared to FE calculation results, to see whether the analytical model is suitable for the use in optimization tools. All calculations are based on the existing tube design of the 21” RealFlat SuperSlim tube, provided with an AKOCA mask.

The analytical model overestimates the mask displacement in a relatively large area near the stiff mask edge. Therefore a quick assessment of the critical positions for local doming, by comparing the analytically calculated mask displacement for different positions with respect to each other, is not directly possible. The use of a position depend weighting function may improve this critical position assessment. Trends for curvature variations are predicted quite well. This is a strong requirement for the use of the model in optimization purposes.

The analytical model describes how a homogeneously double curved thin shell, with uniformly distributed material properties, expands when it is isothermally heated. It shows that with increasing curvature the mask displacements decreases. It also shows that for a shell with anisotropic stiffness properties, the stiffness ratio for the principle curvature directions is decisive for the mask displacement. The stiffness ratio of the North-South and the East-West direction, for a slotted mask is approximately four, this makes the curvature in the North-South direction dominant.
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Chapter 1

Introduction

The shadow mask in a Color Picture Tube (CPT) is made of a thin (120 - 250 µm) metal plate with a pattern of holes. It is mounted a small distance (7 - 22 mm) behind the inside of the screen. Behind each mask hole there are three areas of phosphors. The purpose of the mask is ‘color selection’. It makes sure every beam of electrons hits its own phosphor spot (green, blue, red). The color selection is based on the different angles in which the beams hit the shadow mask. The mask is a determining factor for the image quality; this means that there are strict requirements for mechanical and thermal performance.

Thermal loads on the mask cause expansion and deformation of the mask. This will result in an electron spot shift on the screen, this effect is called doming. The spot shift will result in luminance decrease or even discoloration. The thermal loading of the shadow mask is caused by ambient temperature changes and by the bombardment of electrons on the shadow mask. The heating of the mask by the high energy electrons happens both on a large scale (overall doming) and on a small scale (local doming). The main subject of this research is the local doming phenomenon. Parameters that influence the local heating of the mask are the transmission of the mask, the reflection, the thermal conductivity and the radiation heat lost of the mask. The amount of deformation and the resulting spot shift is determined by the geometry of the mask and the material properties as there are thermal expansion and stiffness.

A drawback of CPTs is the relative large depth in comparison with the screen dimensions. Therefore, L.G.Philips displays is developing a new type, based on conventional tube techniques. In this new design, called SuperSlim, the distance between the electron gun and the shadow mask is reduced. The electrons will hit the mask with a much bigger angle than in conventional tubes. This large deflection angle makes, that small displacements of mask holes will be amplified to large spot shifts on the screen. Therefore, these tubes are much more sensitive for doming problems. Another trend in tube design is the flat screen tube. The screen from the outside is completely flat and on the mask-side it has a very large radius. The amount of glass material needed for the screen is hereby reduced in comparison with a more convex screen. This has a positive effect on the bill of material and on processing times. The decreasing curvature in screen
design also asks for more flat shadow masks. Most of the shadow masks so far were made of the material Invar. Invar is the commercial name for the FeNi alloy, which has a very low Coefficient of Thermal Expansion (CTE) of $1.2 \cdot 10^{-6} \, ^{0}\text{C}^{-1}$. The low CTE is a good property for the shadow masks, minimizing thermal expansion and thus doming. In the new strategy shadow masks will be made of Akoca. This material is much cheaper, it has good forming properties and a higher elasticity modulus. In comparison with Invar it has a CTE which is about 10 times larger. The combination of the new material with a higher CTE, the decreasing curvature of the masks, and the large deflection angles, makes local doming a growing concern.

To optimize the geometry and effective material properties of the mask, tools are necessary. Sofar, a finite element model, called Mask Performance Simulation tool (MPS), has been developed to predict the deformation and thus spot shift due to thermal loading. MPS simultaneously solves the thermal and the mechanical doming problem and is capable of calculating absolute mask deformation. Running one simulations which gives only doming performance information for one irradiated mask position, takes approximately 8 minutes. To make use of optimization routines, a fast local doming model is needed, because sequential steps are needed. An explicit model is preferable for the use in optimization. To make analytical calculations possible assumptions have to be made. The model becomes a simplification of the very complex local doming phenomenon. It only focuses on the key ingredients. This makes it possible to better understand the physics of local doming. Based on this knowledge design rules can be developed.
Chapter 2

CPTs and local doming

This chapter describes the working principle of a Color Picture Tube (CPT). One of the main components of a CPT is the shadow mask. The shadow mask plays an important role in both the manufacturing of the phosphor-screen and during service for the color selection. This chapter gives a phenomenological description of the main subject of this research, local doming. Local doming is mainly restricted to the shadow mask. To understand the local doming problem, a basic knowledge of the structural properties of the shadow mask is needed.

2.1 The Color Picture Tube

![Figure 2.1: (a) Components of a Color Picture Tube (b) Color selection by a slotted shadow mask](image)

Figure 2.1: (a) Components of a Color Picture Tube (b) Color selection by a slotted shadow mask
2.1.1 Working principle of a CPT

The CPT (Fig. 2.1a) builds on the principle of the monochrome (black & white) Cathode Ray Tube (CRT). The CPT has a three-way electron gun with three electrodes, which generate three independent electron beams. These beams are modulated by the red, green and blue video signal. The three beams are deflected collectively by the deflection coil and write three “coinciding” pictures on the screen.

The faceplate is the front plate of the picture tube. On the inside of the faceplate there is a regular structure of red, green and blue light-generating phosphors. To ensure that each electron beam can only strike its own color phosphor, a short distance from the inside of the phosphor screen there is a plate with a pattern of holes, the shadow mask. Behind each hole there are three areas of phosphors, emitting the three principle colors (color triplet). Color selection is based on the difference in angle of incidence of the three different electron beams on the mask (Fig. 2.1b). The electron beam covers an area of the mask comprising several holes. Where there is no hole, the electrons are absorbed or reflected by the mask material. This is why the mask is called shadow mask.

In order to attain a reasonable resolution (the ability to resolve details) of the displayed picture, the density of the color triplets has to be very high. Typical densities are 2,000,000 triplets/m\(^2\) in regular television tubes (TVT) and even more than 5,000,000 triplets/m\(^2\) in color monitor tubes (CMT).

Because of the high hole density, needed for resolution, the alignment of the mask holes with respect to the phosphors is very critical. That’s why the shadow mask is used as a master for the application of the phosphor triplets on the screen in the production of the CPT. This is done by a photo-chemical process in a so-called exposure table in which the electromagnetic action of the deflection coil on the electron beams is imitated by light rays passing through optical lenses. This makes the mask and the screen so-called “married part.” Any discrepancy between the imitation by the optical lenses and the real path of the electron beams in the tube in operation will lead to mislanding of the electron beam on the phosphor-screen [1].

2.1.2 Image quality

As the alignment of the mask holes with respect to the light emitting phosphor triplets is obviously very important, errors in alignment lead to so-called registration errors. Registration errors leads to lack of color when an electron beam does not hit its corresponding phosphor area completely. This obviously leads to a loss of light efficiency of that particular color. When on the other hand, the electrons of a particular color beam hit the wrong color phosphor area, discoloration results. Lack of color can lead to discoloration too when the losses of light efficiency of the three main colors are not in accordance with the right proportions to produce a certain mixed color. In practice, usually loss of light efficiency and discoloration appear simultaneously.

The amount of tolerated spot shift is determined by the size and the pattern of phosphors, and is expressed in the term guard band. The theoretical guard band is defined as the sliding space of an idealized microscopic electron spot with infinitely steep flanks, situated behind each matrix window. The sliding space, is bounded by threshold points for both ‘lack of color’ and ‘wrong color’. The guard band is obviously very important for brightness efficiency as well as for color purity.
During service there are three types of effects which may result in registration errors:

- Magnetic effects
- Mechanical instabilities
- Thermal effects

The earth’s magnetic field has its influence on the trajectory of the electron beam. This can result in registration errors. Also mechanical instabilities such as microphony (“sound in picture”) or shock sensitivity play an important role in de landing performance of a tube. Mislanding due to thermal effects is called doming. Doming has two main origins. The first type of doming is caused by the absorbed electrons which produce heat within the mask. Due to the fact that as much as three color phosphor areas have to be placed behind each mask hole, the transmission of the mask is relatively low. A large proportion of the electrons, emitted by the electron guns, hit the non-productive mask material (typically more than 75%). The low transmission of the mask results in a pretty low (absolute) light efficiency and a lot of absorbed energy in the shadow mask.

The thermal load leads to mask deformations and to the consequent misalignment of the mask holes with respect to the phosphor color triplets. For standard testing four different types of loading are distinguished: local, teletext, full scan, and overall doming.

The second type of doming, the ambient doming phenomenon, refers to registration errors due to ambient temperature changes. With ambient doming both the mask and the faceplate are heated. The difference in thermal deformation behavior of the two components leads to mislanding [1].

2.2 Structural properties of the shadow mask

Shadow masks, Fig. 2.2a, are made from rolled band metal. The band thickness varies from 100 to 250 $\mu$m. The thickness is mostly a trade-off between shock resistance and costs. After the metal is cut into the required shape, a hole pattern is made in the flat metal sheet by a chemical etching process. After the metal is softened by a heat treatment, the metal is formed by deep drawing. The shape of this double curved mask technology is guaranteed by its relatively small radius of curvature. Finally, the mask is degreased and blackened. The blackening improves heat radiative power, improves rust resistance, and reduced light scattering for proper screen exposure.

The suspension of the shadow mask

The mask which results from this manufacturing process is still relatively flexible. Diaphragms parts are welded on to the mask to create a box, and make the mask more stiff. This supporting frame is attached to the suspension pins in the faceplate. The suspension plays an important role during manufacturing. Because, the mask has to be inserted into, and extracted from the faceplate several times during tube manufacturing in between the applications of the matrix layer and the three principle phosphor patterns for red, green and blue. The Philips Corner Suspension (PCS) also can compensate for differences in expansion between box and screen glass, thus for ambient or overall doming.
Hole patterns

There are two types of hole patterns for shadow masks. The first one is a pattern of dots arranged in a hexagonal structure. The other type has phosphor stripes behind slots arranged along vertical lines. The hexagonal structure theoretically has more guard bands, but is very hard to produce above certain picture formats (low intensity point source). For that reason, CRT’s with a diagonal dimension below 21” can have dots or stripes, while all CRT’s with a diagonal above 21” have stripes. In other words, slotted mask holes are applied exclusively in TV-tubes (TVT), while dotted holes are used mainly for Color Monitor-tubes (CMT).

2.2.1 Mask shape and curvature

The designed mask has two symmetry axis, the horizontal axis called the East-West \( E-W \) axis and the vertical axis called the North-South axis, Fig. 2.2b. The shape of the mask is described in a cartesian coordinate system \( \{ \mathbf{e}_x, \mathbf{e}_y, \mathbf{e}_z \} \). These are the \textit{global coordinates}. The origin lies within the center of the mask. The \( x \)- and \( y \)-axis are respectively aligned with the East and North direction of the mask, and the \( z \)-direction is pointing into the tube. The curvature of the mask is described by a polynomial, \( z = P(x, y) \). Of course, it has the properties to be symmetrical around \( x = 0 \) and \( y = 0 \):

\[
\begin{align*}
  z &= P(x, y) = (1 \ y^2 \ y^4 \ y^6) \\
  &= y^T_m \cdot m \cdot x_m
\end{align*}
\]

(2.1)

2.2.2 Micro-geometry and material properties

The hole pattern etched into the mask plate material is called the micro-geometry. This micro-geometry influences the overall mechanical and thermal behavior of the mask. The
overall response of the material is no longer that of a bulk or isotropic material. For example
the effective stiffness of the material is reduced by the micro-geometry as well as thermal
conduction and specific mass.
For calculations (both analytical and FEM) it is not possible to take the complete micro-
geometry (slots) as well as the macro-geometry (mask) into account, this is because of the
length scale difference. To make calculations possible a Micro-Macro approach is used.
This means that the effective material properties, resulting from the micro-geometry and
the isotropic material properties, are calculated first. Next they are used for the Macro-
calculations.

In general the effective material properties are anisotropic. But for simplicity reasons the
assumption is made, that the effective material properties are orthotropic. To calculate the
effective material properties for a slotted mask, MICMAC has been developed. MICMAC
(appendix A) determines the effective elasticity constants and the effective density of the
material for a certain micro-geometry. For a slotted mask the effective stiffness in North
-South directions is approximately four times bigger than the stiffness for the East-West di-
rection. From the effective stiffness and density other properties, such as thermal conduction,
can be derived. It is assumed that the holes do not influence the coefficient of thermal expan-
sion (CTE). So, the effective CTE is the same as the isotropic or bulk CTE of the shadow
mask material.

The microstructure varies along the mask, therefore the calculated effective material prop-
erties only yield for the position with the specified micro-geometry. To get a distribution of the
material properties for the complete mask, the MICMAC-calculations are performed at four
positions. The positions are: 1) center 2) north 3) east, and 4) corner.
To get the effective material properties at the other positions interpolation is used:

\[ C(c, y) = C_{cen} + dC_{eas} x^2 + dC_{nor} y^2 + dC_{cor} x^2 y^2 \] (2.2)

\( C_{cen} \) is the material property calculated in the center position and \( dC_{eas}, dC_{nor}, \) and \( dC_{cor} \)
are calculated parameters by the fitting of the equation 2.2 through the 4 MICMAC-points.

### 2.3 Local doming

Due to the low transmission, 80% of the electrons hits the shadow mask and are either re-
flected or absorbed. The energy from the absorbed electrons locally heats the shadow mask,
which wants to expand. The in-plane stiffness of the shadow mask is relatively high, therefore
the mask will bulge out of its plane on the heated area. The alignment of the mask holes and
the phosphor is disturbed, which results in mislanding. When this mislanding exceeds the
guard band image quality will be lost.

#### 2.3.1 Temperature balance

Figure 2.3 shows the thermal processes active in the thermal energy balance of the shadow
mask. The energy per unit area, \( Q \), of the electron beam which reaches the shadow mask, is
calculated from the power of the electron beam, \( P = V \Delta I \), and the irradiated area, \( A \). The
transmission, $\delta$, determines the amount of electrons that don’t hit the mask. The electron which hit the shadow mask are either absorbed or backscattered. The backscatter coefficient, $\beta$, is influenced by the surface of the shadow mask on the IMS (Inner Metal Shielding) site of the mask. It can be increases by using a coating with high backscatter coefficient, like Bismuth Oxide ($\text{Bi}_2\text{O}_3$). The total amount of energy absorbed into the mask per unit area, $q$, is given by:

$$q = Q(1 - \delta)(1 - \beta) = \frac{V \Delta I}{A}(1 - \delta)(1 - \beta) \quad (2.3)$$

The masks can also loose heat. Since the mask is inside the vacuum tube, the only mechanisms to do so, are radiation and conduction. The mask can radiated heat to the IMS, $\epsilon_{\text{IMS}}$, and the screen site, $\epsilon_{\text{screen}}$. The radiation power of the mask is improved by blackening of the mask as a final production step.

Conduction, $\lambda$, is possible within the mask and between the mask and the diaphragm parts. Local doming only effects the mask in a small area. When the irradiated area lies in the center region, no thermal energy leaks to the diaphragm parts. When the loaded area is close enough to the mask edge, the mask can loose energy. The diaphragm parts only slightly increase in temperature, because they are relatively thick in comparison with the mask. Therefore the thermal expansion and accompanying deformation are mainly restricted to the shadow mask.

### 2.3.2 Spot shift

When an area of the mask is heated, this area wants to expand. Within its plane, the mask is relative stiff. Therefore when the mask moves, a material mask point will move in first order approximation perpendicular to a plane tangential to the masks surface in this point. The normal vector $\vec{n}_m$ of this tangent plane is characterized by [2]:

$$\vec{n}_m = \text{norm}^{-1}\left\{ \frac{\partial P}{\partial x} \vec{e}_x + \frac{\partial P}{\partial y} \vec{e}_y + \vec{e}_z \right\} \quad (2.4)$$
norm = \sqrt{P_{x}^2 + P_{y}^2 + 1} is used to normalize \( \vec{n}_m \) to a unit length vector. The displacement of a mask point is thus described by:

\[
\vec{u}_m = W(x, y) \vec{n}_m
\]

(2.5)

where \( W(x, y) \) is called the mask displacement function.

Figure 2.4: Spot shift due to local doming of the shadow mask

In general the mask displacement is not parallel to the direction of the electron beams. Because the mask bulges out towards the screen, the angle between the center axis and the electron beam passing through the mask \( \varphi \) decreases. This always results in a negative spot shift for local doming. In figure 2.4 the spot shift in shown for the \( xz \)-plane. Here \( s_x \) is the spot shift in \( x \)-direction resulting from the mask displacement \( W \). The spotshift is towards the vertical symmetry axis of the tube (negative).

The projection factor between mask displacement and spotshift is position dependent. This projection between mask displacement and spotshift in the \( x \)-direction is called \( \Delta s_x \), and can be calculated from the mask-screen combination:

\[
\frac{\Delta s_x}{\Delta n_m} = \frac{\sin (\varphi - \gamma)}{\cos (\varphi - \beta)}
\]

(2.6)

For a given mask-screen combination, the projection factor is expressed as a polynomial

\[
\frac{\Delta s_x}{\Delta n_m} = \begin{pmatrix} 1 & y & y^2 & y^3 \end{pmatrix} \cdot S \cdot \begin{pmatrix} 1 \\ x \\ x^2 \\ x^3 \end{pmatrix}
\]

(2.7)

\[
= y^T_s \cdot S \cdot x_s
\]

(2.8)

The resulting spotshift in \( x \)-direction can now be calculated by multiplying the mask displacement \( W \) by the projection factor for the \( x \)-direction:

\[
s_x = \frac{\Delta s_x}{\Delta n_m} W(x, y)
\]

(2.9)

The same can be done for the \( y \)-direction. In practice this is not done because of the vertical line structure of the slotted shadow mask.
Chapter 3

General mask mechanics

This chapter presents an analytical approach to calculate mask displacement due to local doming. As already mentioned in section 2.3 the local doming phenomenon is in essence a transient thermo-mechanical problem. But, the deformations due to local doming are relatively small and thus have a negligible influence on the temperature balance. Therefore, it is also possible not to solve the thermal and mechanical balance equations simultaneously, but to solve them successively. In this approach, first the thermal part of local doming is solved, based on the undeformed geometry. Then, the mechanical balance equations are solved using the temperature solution as a constant. The analytical model derived in this chapter only describes this second step. The temperature distribution is assumed to be known (e.g. from FEM).

Local doming also is a transient phenomenon. An important quantity is “time to doming”. This quantity mainly is related to the thermal part of doming, not to the mechanics. The mechanical model presented in this chapter is steady state.

3.1 Constitutive equations

The shadow mask no longer has isotropic elastic properties on a macroscopic scale, due to the micro-geometry (see section 2.2.2). The resulting anisotropic stiffness is assumed to be orthotropic. An orthotropic material has three orthogonal planes of symmetry. Taking these planes as the coordinates planes, results in a local coordinate system \( \{ \vec{e}_1, \vec{e}_2, \vec{e}_3 \} \). The plane tangent to the mask contains the local directions \( \vec{e}_1 \) and \( \vec{e}_2 \). These two directions are mutually perpendicular. The normal on the mask surface is the \( \vec{e}_3 \) direction.

The shadow mask has a small thickness (typically \( \pm 200\mu m \)) compared to its other dimensions, therefore the concept of plane stress may be used. In a state of plane stress only the in-plane stresses, \( \sigma_{11}, \sigma_{22}, \) and \( \tau_{12} \), are non-zero.

The deformations are linear elastic; the constitutive stress-strain relation used is Hooke’s law. The relevant equations for orthotropic plane stress in the local coordinate system are [3]:

\[
\begin{align*}
\sigma_{11} &= \frac{E_1}{B} \varepsilon_{11} + \frac{\nu_{12} E_1}{B} \varepsilon_{22} \\
\sigma_{22} &= \frac{E_2}{B} \varepsilon_{22} + \frac{\nu_{21} E_2}{B} \varepsilon_{11} \\
\tau_{12} &= G_{12} \gamma_{12}
\end{align*}
\]  

(3.1)
with \( B = 1 - \nu_{12} \nu_{21} \).

### 3.2 Shell kinematics

#### 3.2.1 System of reference

![Figure 3.1](image)

Figure 3.1: (a) Non-orthotropic system of reference (b) relation between skew and local coordinates

The middle surface of the shadow mask is described in the global coordinates, with a rectangular system of reference. Mask height, \( z \), is defined by equation 2.1 and is a function of \( x \) and \( y \). To define strain definitions, on the curved middle surface of a shell, coordinates cannot be simple cartesian. Here the non-orthogonal skew reference system is chosen, because this better adapts to the general shape of the middle surface of the shadow mask. The shell element, \( dA \), (see Fig. 3.1a) is not rectangle, but in first approximation a parallelogram. The \( x \) and \( y \) coordinates are sufficient to distinguish between points on the middle surface, they may be used as a pair of curvilinear coordinates on the shell. The coordinate lines \( x = \text{const.} \), and \( y = \text{const.} \) on the middle surface are obtained by intersecting this surface with planes normal to the \( x \) and \( y \) axis. These lines meet at an angle \( \omega \), for which

\[
\cos \omega = \sin \chi \sin \theta. \tag{3.2}
\]

Where \( \chi \) is the angle between line \( AB \) and the \( x \) axis and \( \theta \) is the angle between line \( AC \) and the \( y \) axis. These angles can be calculated from the mask geometry by \( \chi = \arctan(z_x) \) and \( \theta = \arctan(z_y) \) [4].

#### 3.2.2 Strains

The total strains at each point of a heated shadow mask are made up of to two parts. The first part is an expansion proportional to the temperature rise. The micro-geometry is assumed to
have no influence on the thermal expansion, thus remains isotropic. The thermal expansion
is therefore the same in all directions. Only normal strains and no shearing strains arise in
this manner. The strain due to a temperature change \( \Delta T \) equals to [5]:

\[
\varepsilon^{\Delta T} = \alpha \Delta T \mathbf{I}
\]  

(3.3)

Here the coefficient of thermal expansion (CTE) is denoted by \( \alpha \). The second part comprises
the strains required to maintain continuity of the mask. These strains, \( \varepsilon^\sigma \), are related to the
stresses by means of the stress-strain relation.

The total strain, \( \varepsilon^\nabla \mathbf{u} \), is the sum of the two components, \( \varepsilon^{\Delta T} + \varepsilon^\sigma \), and can be calculated
from the displacement distribution, \( \mathbf{u} = \mathbf{e}_x u + \mathbf{e}_y v + \mathbf{e}_z w \) (eq.

For geometrical linear deformations, the strain \( \varepsilon^\nabla \mathbf{u} \) is defined as the increase of the length
of the line element \( AB \) in Fig. 3.1, divided by its original length, and \( \varepsilon^\sigma \mathbf{u} \) is defined in the
same way for the line element \( AC \) of the middle surface of the shell. The shear strain \( \gamma^\mathbf{xy} \mathbf{u} \)
is the decrease of the angle \( \omega \) between \( AB \) and \( AC \) [4]. The total strains in the skew systems
of reference are:

\[
\begin{align*}
\varepsilon_{xx}^\nabla \mathbf{u} &= \left( u_x \cos \chi + w_x \sin \chi \right) \cos \chi \\
\varepsilon_{yy}^\nabla \mathbf{u} &= \left( v_y \cos \theta + w_y \sin \theta \right) \cos \theta \\
\gamma^\mathbf{xy} \mathbf{u} \sin \omega &= \left( u_y \cos \theta - u_x \sin \theta \cos \chi \sin \chi \right) \cos \chi \ldots \\
&\quad + (v_x \cos \chi - v_y \sin \chi \cos \theta \sin \theta) \cos \theta \ldots \\
&\quad + w_x \cos^3 \chi \sin \theta + w_y \cos^3 \theta \sin \chi
\end{align*}
\]  

(3.4)

The strains, \( \varepsilon^\sigma \{x,y\} \), related to stresses in the constitutive model are now fully defined:

\[
\varepsilon^\sigma \{x,y\} = \varepsilon \{x,y\} = \varepsilon^\nabla \mathbf{u} \{x,y\} - \varepsilon^{\Delta T} \{x,y\}
\]  

(3.5)

But, the stress-strain relation (eq. 3.1) is defined in an orthogonal system of reference, while
the strains (eq. 3.5) make use of the non-orthogonal skew system. To convert the strains in
the skew system, \( \xi \{x,y\} \), to strains in the orthogonal system, \( \xi \{1,2\} \), the relation between these
two systems needs to be specified. The shell element \( dA \) contains the local directions, \( \mathbf{e}_1 \) and
\( \mathbf{e}_2 \). The local \( \mathbf{e}_3 \) is normal to the shell element. The relation between the two systems is
still not fully specified; one more angle is needed to relate the projected \( x \) and \( y \) directions to\( \mathbf{e}_1 \) and \( \mathbf{e}_2 \) directions. Fig. 3.1b shows how this is done. The projected \( y \) direction is
chosen to coincide with the local \( \mathbf{e}_2 \). This is done because for a slotted mask the stiffness in
the North-South direction is bigger then the stiffness in the East-West direction. The strains
related to the stresses in the same systems of reference are:

\[
\xi = \xi \{1,2\} = \begin{pmatrix}
\varepsilon_{11} \\
\varepsilon_{22} \\
\gamma_{12}
\end{pmatrix} = \begin{pmatrix}
1 & 0 & -\cot \omega \\
0 & 1 & 0 \\
\cot \omega & -\cot \omega & 1
\end{pmatrix} \cdot \begin{pmatrix}
\varepsilon_{xx} \\
\varepsilon_{yy} \\
\gamma_{xy}
\end{pmatrix}
\]  

(3.6)

\[
\begin{align*}
\xi &= Q \cdot \xi \{x,y\} \\
&= Q \cdot \varepsilon^\nabla \mathbf{u} \{x,y\} + Q \cdot \varepsilon^{\Delta T} \{x,y\}
\end{align*}
\]
3.3 Potential energy

The Theorem of Minimum Total Potential (TMTP) will be used to determine the equilibrium state of deformation. TMTP states that for a conservative (i.e., elastic) mechanical system, the state of deformation that corresponds to an equilibrium configuration has a stationary value of the Total Potential Energy, Π. Furthermore, when this stationary value is a minimum, it concerns a stable state of equilibrium.

The potential energy consists of the work done on the system by external forces, \( V \), and of the internal or strain energy, \( U \). The suspension fixes the shadow mask into the tube, since there are no displacements, the work done by this suspension is zero. There are no other forces working on the shadow mask. Therefore, the work done by external forces equals zero.

The TMTP for the shadow mask now becomes:

\[
\frac{\partial \Pi}{\partial w_i} = \frac{\partial (U - V)}{\partial w_i} = \frac{\partial U}{\partial w_i} = 0 \tag{3.7}
\]

where \( w_i \) denotes the parameters or generalized displacement of the displacement function \( W(x, y) \).

Thin shells, like the shadow mask, are capable of resisting in-plane stresses quite well, but they are very flexible for bending moments and shearing forces. Therefore the bending energy stored during elastic deformation is small compared to the membrane energy. For a rectangular cross section, the in-plane stresses are assumed to be uniformly distributed over the entire thickness [6]. The strain energy per unit area of the mask’s middle surface, \( u_0 \), for a shell with thickness, \( t \), thus becomes:

\[
u_0 = \frac{t}{2} \left\{ \sigma_{11} \varepsilon_{11} + \sigma_{22} \varepsilon_{22} + \tau_{12} \gamma_{12} \right\}. \tag{3.8}\]

The total strain energy for the complete mask with middle surface, \( A \):

\[
U = \iint_A u_0 \, da. \tag{3.9}
\]
Chapter 4

The analytical local doming model

The shell mechanics presented in the previous chapter do not build a workable model yet. A solving method for the system of PDEs needs to be chosen. In general solving such a complex system analytically is not possible. Mostly a Finite Element or a Spectral Method is used. The goal of this research is to get a better understanding about the local doming phenomenon and to obtain a quick tool for optimization design purposes. It is not necessary to calculate absolute mask deformations. Some assumptions will be made in this chapter, which simplifies the mask’s mechanics considerably, which makes analytical solving possible.

The mask displacement vector, \( \vec{u} \), is the product of the mask displacement function, \( W(x, y) \), and the normal of the shadow mask, \( \vec{n}_m = n_x \vec{e}_x + n_y \vec{e}_y + n_z \vec{e}_z \). By definition the strains contain derivatives of this displacement vector. With aid of the product rule strains can be expressed in terms containing derivatives of the displacement function and the mask’s normal.

When the displacement function is chosen to be a constant \( W \), terms containing its derivative equal zero. The remaining terms of the strains are:

\[
\begin{align*}
\varepsilon_{xx} &= W(n_{x,x} \cos \chi + n_{z,z} \sin \chi) \cos \chi - \alpha \Delta T \\
\varepsilon_{yy} &= W(n_{y,y} \cos \theta + n_{z,y} \sin \theta) \cos \theta - \alpha \Delta T \\
\gamma_{xy} &= W \sin^{-1} \omega \{ n_{x,y} \sin \omega (\cos \theta - n_{x,x} \sin \theta \cos \chi \sin \chi) \cos \chi \ldots \\
&\quad + (n_{y,x} \cos \chi - n_{y,y} \sin \chi \cos \theta \sin \theta) \cos \theta \ldots \\
&\quad + n_{x,x} \cos^3 \chi \sin \theta + n_{z,y} \cos^3 \theta \sin \chi \} \\
&= W \gamma_{xy} \sin^{-1} \omega \left( n_{x,y} \sin \omega \left( \cos \theta - n_{x,x} \sin \theta \cos \chi \sin \chi \right) \cos \chi \right) \\
&\quad + n_{x,x} \cos^3 \chi \sin \theta + n_{z,y} \cos^3 \theta \sin \chi \\
\end{align*}
\]

\[\varepsilon_{\{x,y\}} = [\varepsilon_{xx}, \varepsilon_{yy}, \gamma_{xy}]^T \] and \( \varepsilon_{\{x,y\}}^T = [\varepsilon_{xx}, \varepsilon_{yy}, \gamma_{xy}]^T \) now only depend on the mask geometry. The temperature difference \( \Delta T \) is assumed to be known, this makes the strains, \( \varepsilon_{\{x,y\}} \), with respect to the skew system of reference, only a function of the mask displacement \( W \) for a given mask.

Making use of equation 3.6 the strains \( \varepsilon_{\{x,y\}} \) can be transformed to strains with respect to
the orthogonal system of reference, \( \xi \).

\[
\xi = W \mathbf{Q} \cdot \xi_{\{x,y\}}^* - \alpha \Delta T \mathbf{Q} \cdot \xi_{\{x,y\}}^{\Delta T} \quad (4.2)
\]

The stresses can be calculated making use of the constitutive relation 3.1. Just like the strains, the stresses, \( \sigma \), are also a superposition of deformation and thermal effects:

\[
\sigma = W \mathbf{C} \cdot \xi_{\{x\}}^* - \alpha \Delta T \mathbf{C} \cdot \xi_{\{x\}}^{\Delta T} = W \mathbf{Q} \cdot \xi_{\{x\}}^* - \alpha \Delta T \mathbf{Q} \cdot \xi_{\{x\}}^{\Delta T} \quad (4.3)
\]

Now the stresses and strains are defined, it is possible to calculated the specific strain energy per unit area \( u_0 \) with equation 3.8:

\[
u_0 = \frac{t^2}{2} \sigma_{\{x\}}^T \cdot \xi_{\{x\}}^* - \frac{t^2}{2} \sigma_{\{x\}}^{\Delta T} - \alpha \Delta T \sigma_{\{x\}}^{\Delta T} \quad (4.4)
\]

To find a mechanical equilibrium the principle of minimum potential energy will be used. The only solution of the boundary value problem (BVP) with the chosen constant displacement \( W \) is zero, due to fixed displacement imposed by the suspension and the stiff mask skirt. Of course this is not the desired solutions. Physically the constant displacement \( W \) only holds for a infinitesimal small surface, \( B \). To preserve continuity, forces are working on surface \( B \) which come from the in-plane stresses. The total potential energy for this surface \( B \) is the difference between work done by external forces and the internal energy. In contrast to the entire mask surface \( A \), the work done by the external forces on surface \( B \) does not equal zero.

The balance of forces on surface \( B \) \( (\nabla c \cdot \sigma = 0) \) is neglected and only a minimum of the internal of strain energy \( U \) is determined. The stationary points of \( U \) and \( u_0 \) have the same displacement \( W \), because within the infinitesimal small area \( B \), the material properties and the derivatives of the normal are constant, which makes \( u_0 \) constant. Since \( W \) is the only parameter of the displacement function, the PDE of equation 3.7 becomes an easily solvable ODE:

\[
0 = \frac{\partial u_0}{\partial W} = \frac{\partial}{\partial W} \left( \frac{1}{2} \sigma_{\{x\}}^T \cdot \xi \right) = W \sigma_{\{x\}}^T \cdot \xi_{\{x\}}^* - \frac{\alpha \Delta T}{2} \left( \sigma_{\{x\}}^T \cdot \xi_{\{x\}}^{\Delta T} + \sigma_{\{x\}}^{\Delta T} \cdot \xi_{\{x\}}^T \cdot \sigma_{\{x\}}^T \cdot \xi_{\{x\}}^* \right) \quad (4.5)
\]

The mask displacement is expressed explicitly and is proportional with the temperature difference:

\[
W = \alpha \Delta T \frac{\sigma_{\{x\}}^T \cdot \xi_{\{x\}}^{\Delta T} + \sigma_{\{x\}}^{\Delta T} \cdot \xi_{\{x\}}^T \cdot \sigma_{\{x\}}^T \cdot \xi_{\{x\}}^*}{2 \sigma_{\{x\}}^T \cdot \xi_{\{x\}}^*} \quad (4.6)
\]
Chapter 5

Results and Discussion

The aim of this research is to get better insight in the local doming mechanics. The model derived in chapter , in spite of the drastic assumptions made, still has a fundamental base in physics. In the first section the analytical model is discussed.

The second objective was to obtain a quick tool for optimization. The see whether the analytical model is fitted for this purpose, it needs to be tested for predicting the right trends. Results from the analytical model will be compared to results from the MPS tool (Mask Performance simulation). MPS (see appendix B) can performs Finite Element simulations for several loadcases on the shadow mask, including local doming simulations.

5.1 The double curved surface

\[ W_{dc} = \alpha \Delta T \frac{E_1 n_{1,1} + E_2 n_{2,2} + \frac{1}{2}(E_1 \nu_{12} + E_2 \nu_{21})(n_{1,1} + n_{2,2})}{E_1 n_{1,1}^2 + E_2 n_{2,2}^2 + (E_1 \nu_{12} + E_2 \nu_{21}) n_{1,1} n_{2,2} + BG_{12}(n_{1,2} + n_{2,1})^2} \]  

(5.1)

Through a point \( A \) on a surface, several planes can be constructed which contain the mask normal of point \( A \). The curve of intersection between such a plane and the surface is called
the normal section. In general, each of these normal sections has a different curvature $C$. For every double curved surface it is possible to construct two orthogonal normal sections through point $A$, from which one curvature equals the maximum curvature, $C_\xi$, and the other equals the minimum curvature, $C_\eta$. These two curves are called the principle curvatures of the surface at point $A$ [6]. The corresponding direction in the $(\vec{e}_1, \vec{e}_2)$-plane are respectively called, the principle directions, $\vec{e}_\xi$ and $\vec{e}_\eta$.

The derivatives of the mask normal are related to the mask curvatures. The curvature of the principle directions equals $C_\xi = n_{\xi,\xi} = 1/R_\xi$ and $C_\eta = n_{\eta,\eta} = 1/R_\eta$. Because the principle directions represent the minimum and maximum curvature of point $A$, the terms $n_{\xi,\eta}$ and $n_{\eta,\xi}$ equal zero. When $E_\xi$ and $E_\eta$ are the stiffness components for the principle directions, and when is assumed that $\nu_{\xi,\eta} E_\xi, \nu_{\eta,\xi} \ll E_\xi, E_\eta$, the mask displacement becomes:

$$W_{dc} = \alpha \Delta T \frac{E_\xi C_\xi + E_\eta C_\eta}{E_\xi C_\xi^2 + E_\eta C_\eta^2}$$ (5.2)

Figure 5.1 shows that the curvature of the principle directions and there stiffness ratio determine how a isothermal heated unconstrained double curved shell, with uniformly distributed material and curvature properties, expands. The most simple example of such a shell, is a sphere with radius $R$. The above equation shows that a sphere which is isothermally heated expands stress-free with a displacement $W = \alpha \Delta TR$.

For a slotted shadow mask the stiffness of the north-south direction is approximately four times as high as the stiffness of the east-west direction. The curvature in the north-south direction, therefore is decisive for the mask displacement.

### 5.2 MPS local doming simulations

It is difficult to perform temperature measurements on the shadow mask within the vacuum tube. Doming test results only provide spot shift and not the accompanying temperature distributions. The analytical model assumes the temperatures to be known, therefore it is not possible to compare test data with results from the analytical model. The Mask Performance Simulation tool (MPS) performs coupled thermo-mechanical calculations and thus provides both mask displacements and temperature distributions. Therefore, the MPS results will be used to test the suitability of the analytical model for optimization purposes.

The simulations are based on an existing tube design. The 21” RealFlat SuperSlim tube is a small television tube provided with a shadow mask of Akoca. Appendix C lists the structural and material properties of the shadow mask of the 21”-rf-SuS. It also gives the ULAS (Universal Landing Analysis System) positions for the 21” tube.

The local doming loadcase is specified by the position $(x_{\text{flux}}, y_{\text{flux}})$, the size $(\Delta x_{\text{flux}} \times \Delta y_{\text{flux}})$, and irradiation power $(V \Delta I)$ of the area which is bombarded by electrons. The global coordinates $(x_{\text{flux}}, y_{\text{flux}})$ correspond to the center of the irradiated area. Three different positions are chosen to characterize the local doming behavior, ‘Center’, ‘2/3-East’, and ‘2/3-Diagonal’. These positions respectively refer to the ULAS positions $(0,0)$, $(5,0)$, and $(5,3)$.

The explicit local doming model presented in chapter 5 is put into Matlab code (see appendix D). All analytical calculations presented in this chapter make use of this script.
5.2.1 Size of the irradiation area

The general irradiation area size for local doming tests on a 21” tube is \((\Delta x_{flux} \times \Delta y_{flux}) = (76 \times 38) mm^2\).

To investigate the influence of the irradiation area size on doming performance, MPS calculations have been performed for the three positions, ‘Center’, ’2/3-East’, and ’2/3-Diagonal’. The lengths of the irradiation area \(\Delta x_{flux}\) and \(\Delta y_{flux}\) are scale proportionally. The power per unit irradiation area \(V_{\Delta A}\) which is transported to the mask by the electrons is kept constant. Therefore, the current \(\Delta I\) and the voltage \(V\) are also changed proportional with the lengths of the irradiation area.

Figure 5.2 shows the results of the MPS calculations. It shows the mask displacement per unit temperature rise for the center of the irradiation area \(\frac{W}{\Delta T}\) as a function of the length \(\Delta x_{flux}\) (blue line). The graphs also show the temperature rises for the different irradiation area sizes, calculated by MPS, \(\Delta T_{mps}\), and the mask displacement per unit temperature rise calculated by the analytical model (green line).

The MPS calculations show that the size of the irradiation area actually has a great influence on the mask displacement and that it is not simple proportional with the temperature rise. For the center position \(\frac{W}{\Delta T}\) monotonously increases with increasing \(\Delta x_{flux}\). The positions
‘2/3-East’ and ‘2/3-Diagonal’ show the same increase for small irradiation area sizes, but for larger irradiation area sizes the mask displacement per unit temperature rise start to decrease. The center position is the furthest away from the stiff mask skirt. The positions ‘2/3-East’ and ‘2/3-Diagonal’ are much more close to the mask edge and thus experience more influence, from the fixed displacement it imposes on the mask edge. For large irradiation area size, the effect of the imposed fixed displacement on the mask edge by the stiff skirt exceeds the effect of the increase of $\frac{W}{\Delta T}$ for growing irradiation area size.

Because the analytical model neglects the balance of forces due the continuity, mask displacement per degree temperature rise only depends on the curvature and material properties of one point. Therefore the mask displacements predicted by the analytical model are independent of the irradiation area size.

### 5.2.2 Critical locations

![Image](image.png)

Figure 5.3: (a,b,c) calculated mask displacement per unit temperature rise for position on the upper-right quarter of the mask (d) projection factor for mask displacements to spot shift in the $x$-direction for the 21”-RF-SuS

The analytical model is not capable of predicting absolute mask displacement. To investigate whether the analytical model can give a quick assessment of what mask positions are most
sensitive for local doming, the results at different positions are compared relative to each other.

Figure 5.3a and b shows respectively the MPS results for the irradiation areas (76×38) mm$^2$ and (25.3×12.7) mm$^2$. The positions of the MPS calculations correspond to the ULAS-positions. Through the mask displacement per unit temperature rise calculated at the ULAS-position the surface was fitted, shown in figure 5.3a and b. The overall pictures from these two sets of calculations show strong resemblances. The mask displacements near the stiff mask edge are approach zero. The maximum can be found near the center of the mask (the maximum marked by * in (b) is overestimated, because of by MPS wrongfully assumed symmetry boundaries, see appendix B). The difference between the two sets is that for the large irradiation area the effect of the stiff mask edge is present in a larger area near the mask edge. This is especially clear for the East-West direction. This is in agreement with the results presented in paragraph 5.2.1.

Figure 5.3c shows that mask displacement per unit temperature rise calculated by the analytical model for all positions on the North-East quarter of the mask. The analytical results don’t approach zero near the mask edge, due to the reasons already discussed. The maximum mask displacement are found near the center position.

The main reason why the mask displacement predicted by MPS and the analytical model are so different is that the analytical model does not ‘feel’ the presence of the stiff mask skirt. The analytical model could be correct with aid of a well chosen position depend weighting function, which approaches zero near the mask edge. To determine such a weighting function for a given irradiation area size, solutions of actual BVPs of several irradiation positions are required.

5.2.3 Curvature variations

For mask geometry optimization, it is a strong requirement that analytical model predicts the right trend for mask curvature variations. To investigate whether this is true, the mask geometry is varied, and the corresponding mask displacement where calculated by both MPS and the analytical model.

The mask geometry is described by the mask height, $z$, see polynomial 2.1. The total curvature of the mask was varied by multiplying the mask height by a scaling factor. For the designed mask geometry of the 21"-rf-SuS this scaling factor equals one. Figure 5.4 shows the MPS and analytical model (red line) results. The relative mask displacement per unit temperature rise, $(\frac{W}{\Delta T})_{rel}$ is given a function of the scale factor. The relative mask displacement per unit temperature rise is defined as $\frac{W}{\Delta T}$ divided by the mask displacement per unit temperature rise for the case the scale factor is one, $(\frac{W}{\Delta T})_{sf=1}$.

Again the calculations were performed for the three positions ‘Center’, ‘2/3-East’, and ‘2/3-North’. For the center position 2 different irradiation area sizes where used, (76×38) mm$^2$ (green line) and (25.3×12.7) mm$^2$ (blue line). For the other two positions the only size used was (25.3×12.7) mm$^2$.

In all these cases the effect of curvature variations is slightly overestimated by the analytical model. But the general trend is predicted well. Because the curvature variations for all directions are proportional with the scale factor, it can not be concluded that for other variations trends are also predicted will.
Figure 5.4: The influence of variation of the mask geometry on the mask displacement, calculated by both MPS and the analytical model
Chapter 6

Conclusions

An analytical local doming model has been developed. With the assumption that the potential energy of a mask element only dependents on the strain energy, the balance of forces thereby was neglected. This made it possible to explicitly express the mask displacement as a function of the mask geometry, stiffness and thermal expansion properties and a known temperature. The assumption came to the price, that the predicted mask displacement no longer are solutions of the actual boundary value problem (BVP).

Results of the analytical model have been compared to results of the Finite Element base tool MPS. The analytical model overestimates the mask displacement in a relatively large area near the stiff mask edge, due to the neglected balance of forces. Therefore a quick assessment of the critical positions for local doming, by comparing the analytically calculated mask displacement for different positions with respect to each other, is not directly possible. The use of a position depend weighting function may improve this critical position assessment.

The analytical model seems to predict the mask displacement changes due to curvature variations quit well. This is a strong requirement for the use of the model in optimization purposes. But from the calculations presented here it is not indisputable shown, that the analytical model also performs well, when the orthotropic stiffness properties of the curvature in the different directions independently are varied.

The analytical model is a description of how a homogeneously double curved thin shell, with uniformly distributed material properties, expands when it is isothermally heated. It shows that with increasing curvature the mask displacements decreases. It also shows that for a shell with anisotropic stiffness properties, the stiffness ratio for the principle curvature directions is decisive for the mask displacement. The stiffness ratio for a slotted mask in the North-South and the East-West direction is approximately four, this makes the curvature in the North-South direction dominant.
Appendix A

The MicMac tool

The MicMac tool [7] is a finite element program able to compute the effective material properties of slotted masks. It uses the finite element package MSC.marc and its pre- and post-processing interface MENTAT.

The geometry a slot (with and without)“dogbones” for a certain position in CPT masks is parameterized. From these defined dimensions the MicMac program is capable of building a 3D mesh from a piece of the micro-geometry, see Fig. A. With aid of harmonic boundary conditions the repetitive character of geometry is simulated.

Isotropic material properties of the mask material are assigned to the elements. Through the analysis of the results of different loadcases, the effective material properties are calculated. The program is capable of computing the effective values for:

- Youngs moduli: $E_{xx}$, $E_{yy}$, and $G_{xy}$
- Poisson ratio: $\nu_{xy}$
- Youngs moduli for bending: $E_{xx}^{\text{bend}}$, and $E_{yy}^{\text{bend}}$
- Density $\rho$
The Poisson ratio $\nu_{yx}$ is given by the Maxwell relation $E_x \nu_{xy} = E_y \nu_{yx}$. Other material properties such as the heat capacity and the thermal conduction are derivatives of the effective quantities mentioned above.

For example, the effective heat capacity is calculated by multiplying the isotropic heat capacity by the ratio of the effective and isotropic density: $c_{\text{eff}} = c_{\text{iso}} \frac{\rho_{\text{eff}}}{\rho_{\text{iso}}}$. The heat conduction in $x$-direction is assumed to be equal to the product of the isotropic heat conduction multiplied by the ratio of the effective elasticity modulus in the $x$-direction and the isotropic elasticity modulus: $\lambda_{\text{eff}}^x = \lambda_{\text{iso}} \frac{E_{\text{eff}}^x}{E_{\text{iso}}}$. 
Appendix B

The MPS tool

The MPS (Mask Performance Simulation) tool is a custom interface to perform Finite Element simulations for a number of different mask loadcases such as:
- Linear and non linear buckling limits
- Modal frequency analysis
- Dynamic droptest under prescribed g-load
- Vibration and resulting spot shift
- Local and teletext doming and resulting spot shift

The underlying code is MARC/MENTAT and all functionality is embedded in this code and its related FORTRAN user subroutines.

Local doming loadcase in MPS

For this research the local doming analysis was used. The physical doming test is very much alike with the MPS doming loadcase. For the physical test, the mask is mounted in the tube and is bombarded locally with electrons with a given voltage and current. This causes the mask to heat up with accompanying deformations. The electron beam will shift from its original position and its displacement is measured. The actual cause of the spotshift, the temperature rise, and the mask displacement can not be measured.

For the MPS local doming loadcase the mask is bombarded in a prescribed rectangle area \((dx\,flux \times dy\,flux)\) situated around a prescribed center-position \((x\,flux \times y\,flux)\). The temperature change and the deformations are calculated and the resulting spot shift is determined. The loaded area is described in the ‘_mps_loc.in’-file. This file also contains the ambient temperature \(T_{amb}\), the applied current \(\Delta I\) and, the voltage \(V\).

The thermal and mechanical problems are solved simultaneously in the same increment, so that only one coupled thermo-mechanical run is required. This simplifies the analysis procedure and is time considerably. Note also that it is a transient time domain analysis and that, when the equilibrium situation is required, the maximum time must be set sufficiently high \([8]\).
the model

Geometry

The mesh is made from 3D-shell elements for thin constructions for coupled thermo-mechanical analysis. The element types available are 139 (quad4) and 138 (tri, degenerated). These elements represent three strain components, so they only use $3 \times 3$ of the compliancy matrix. The shadow mask inclusive skirt is modeled, see Fig. B. In principle the mask is still flat. MPS adds the mask curvature which is defined by the mask polynomial. The mask curvature polynomial is imported from the MsCombi.list file. This file contains all geometrical data that is needed for MPS simulations. The used parts of the listing are the mask shape polynomial $P$ and the spot shift polynomial $\Delta m$.

The position of the mask with respect to the global coordinate system is very important. This, because the material properties of the mask are position dependent. It is assumed that the center of the mask is at the $x = y = 0$ position and the East and North axis are aligned with respectively the $x$- and $y$-axis.

Boundary and initial conditions

Only one quarter of the mesh is model, because the mesh is symmetrical about the North axis and the East axis. Therefore symmetry boundary conditions are applied along these two edges. The positions where the mask is welded to the diaphragm parts have fixed displacements for the $z$-direction.

Beside these mechanical boundary conditions, there are also boundary conditions for the thermal boundaries. The boundary condition ‘heatflux’ is a ‘face flux’ which is added to all horizontal elements. Via this ‘heatflux’, MPS prescribes the absorbed energy by the electron bombardment. The boundary conditions ‘radiationmask’ and ‘radiationframe’ are ‘face films’ which are applied to all elements. They represent the energy exchange between the mask and its environment by radiation.

Initially the mask is stress free at the temperature ‘Tempini’ of 25 $^\circ$C.

Material properties

Because of the varying hole dimensions, the mask has position dependent material properties and these cannot be defined directly in MENTAT. This is done in the user subroutines. The mesh does not discriminate between the isotropic and orthotropic part of the mask. This is
also accounted for in the user subroutines. The position dependent properties are calculated by MICMAC (appendix A), written to the global fort.1088, and imported in MARC via the user subroutines.

**The local doming loadcase and output**

The local doming loadcase is a coupled analysis. The analysis options ‘Large displacements’ and ‘Update Lagrange’ are put on. It uses Multi-criteria stepping procedure with automatic cut back. Beside the default .t16 MARC output file also a fort.1200 file is generated. This contains for each time increment the nodes information. For each node the original position, the displacements and the nodal temperature is printed to the fort.1200 ASCII file.

**Drawbacks of MPS**

MPS has a restriction to which shell elements are possible to use, this is causes by the subroutines. E.g. the thin shell element 72 (quad8) has only 3 degrees of freedom (no rotation) and is inadequate for the use in MPS. Adjustment to existing meshes are very difficult. Because of the subroutines, the ‘ortho’-elements have to be continuously numbered. For example mesh refinements on existing meshes are nearly impossible.

The largest drawback of MPS with regard to the local doming loadcase, is the assumption of symmetry for the North and East axis. This assumptions is correct for the mask geometry and material properties, yet the bombarded area is asymmetrical with respect to these axis. Basically, only the loadcase where the center of the bombarded area is in the center of the mask, is fundamentally correct. For loadcases where the bombarded area is near one of the symmetry axis, local doming is overestimated. When two bombarded areas on both side of a symmetry axis approach, they intensify each other. This effect can be compared to enlarging the bombarded area. Temperatures within the bombarded area increase and therefore mask displacements also increase.
Appendix C

The 21” RealFlat SuperSlim tube

The 21” RealFlat SuperSlim is a small television tube. It belongs to the SuperSlim family because of its limit depth, which is less than 35 cm. The 21”-rf-SuS is one of the first tubes with a shadow mask made of AKOCA. In this appendix the structural and material properties of the shadow mask of the 21”-rf-SuS are listed.

Structural mask properties

The shadow mask has a thickness of 200 μm and has a slotted hole pattern. The main dimensions of the mask are:
- Center to East: $X_{\text{norm}} = 197 \text{ mm}$
- Center to North: $Y_{\text{norm}} = 154 \text{ mm}$

The mask shape can be calculated by equation 2.1. When a so called relative mask polynomial is used, the coulombs $x$ and $y$ need to be based on the relative $x$ and $y$ coordinates. The relative coordinates are: $x_r = x/X_{\text{norm}}$ and $y_r = y/Y_{\text{norm}}$. The relative mask polynomial coefficients $m$ for the 21”-rf-SuS are:

$$m = \begin{pmatrix} 0 & 4.0387 & 11.1015 & 0.604329 \\ 10.5434 & 7.78634 & -13.527 & 0 \\ -0.632936 & -9.25677 & 12.8938 & 0 \\ 1.37978 & 0 & 0 & 0 \end{pmatrix} \cdot 10^{-3} \quad (C.1)$$

In this report the ULAS-positions (Universal Landing Analysis System) are used to specify the center of irradiation areas. The positions on the East direction are numbered 0 to 9 and on North from 0 to 7. The ‘Center’-position corresponds to ULAS-position (0,0), ‘1/2-East’ to ULAS(3,0), ‘2/3-East’ to ULAS(5,0) and ‘2/3-Diagonal’ to ULAS(5,3).
These are the absolute \( x \)-coordinates for the ULAS position in [mm]:

\[
\begin{array}{cccccccccc}
7 & 0.00 & 32.42 & 63.30 & 91.27 & 115.46 & 135.57 & 151.76 & 164.46 & 174.23 & 185.87 \\
6 & 0.00 & 32.43 & 63.29 & 91.24 & 115.40 & 135.51 & 151.73 & 164.51 & 174.40 & 186.02 \\
5 & 0.00 & 32.44 & 63.30 & 91.25 & 115.41 & 135.52 & 151.77 & 164.59 & 174.54 & 186.12 \\
4 & 0.00 & 32.44 & 63.33 & 91.30 & 115.48 & 135.60 & 151.86 & 164.72 & 174.71 & 186.22 \\
3 & 0.00 & 32.45 & 63.36 & 91.36 & 115.58 & 135.73 & 152.01 & 164.86 & 174.85 & 186.22 \\
2 & 0.00 & 32.45 & 63.37 & 91.42 & 115.69 & 135.88 & 152.15 & 164.97 & 174.90 & 186.08 \\
1 & 0.00 & 32.45 & 63.37 & 91.45 & 115.77 & 135.98 & 152.24 & 165.01 & 174.88 & 185.85 \\
0 & 0.00 & 32.44 & 63.37 & 91.46 & 115.79 & 136.01 & 152.26 & 165.01 & 174.85 & 185.74 \\
\end{array}
\]

The absolute \( y \)-coordinates [mm] are:

\[
\begin{array}{cccccccccc}
7 & 145.66 & 145.64 & 145.51 & 145.12 & 144.42 & 143.49 & 142.49 & 141.54 & 140.71 & 139.65 \\
6 & 133.58 & 133.49 & 133.20 & 132.65 & 131.85 & 130.90 & 129.92 & 129.03 & 128.27 & 127.30 \\
5 & 122.12 & 122.03 & 121.73 & 121.20 & 120.46 & 119.61 & 118.76 & 117.98 & 117.31 & 116.48 \\
4 & 106.54 & 106.45 & 106.19 & 105.72 & 105.08 & 104.35 & 103.62 & 102.97 & 102.41 & 101.72 \\
3 & 86.19 & 86.12 & 85.92 & 85.55 & 85.05 & 84.47 & 83.89 & 83.36 & 82.91 & 82.36 \\
2 & 60.96 & 60.93 & 60.81 & 60.57 & 60.23 & 59.83 & 59.41 & 59.03 & 58.70 & 58.29 \\
1 & 31.66 & 31.64 & 31.59 & 31.48 & 31.32 & 31.11 & 30.89 & 30.68 & 30.50 & 30.28 \\
0 & 0.00 & 0.00 & 0.00 & 0.00 & 0.00 & 0.00 & 0.00 & 0.00 & 0.00 & 0.00 \\
\end{array}
\]

The projection factor \( \Delta x_{\,\text{nm}} \) for the mask displacement comes from the polynomial description in equation 2.9. The polynomial coefficient \( s_{\Delta x} \) for the spot shift in \( x \)-direction are:

\[
\begin{bmatrix}
0 & 851.7850 & 268.9294 & -400.9387 \\
0 & 40.09447 & -184.2704 & 123.5219 \\
0 & -362.7008 & 1009.323 & -421.6148 \\
0 & 349.9853 & -851.5866 & 371.7331 \\
\end{bmatrix} \cdot 10^{-3} \quad (C.2)
\]

Just as for the mask shape polynomial the \( x \) and \( y \) coordinates need to be scaled. This time the corresponding scaling lengths for the relative coordinates are:

- \( x_{\text{sens}} = 185.776 \) mm
- \( y_{\text{sens}} = 145.661 \) mm

**Mask material properties**

**Isotropic**

The shadow mask of the 21”-rf-SuS is made of Akoca. Table C.1 contains the isotropic material properties. The thermal expansion \( \alpha \) and the thermal conduction \( \lambda \) are based on the reference temperature \( T_{\text{ref}} \) of \( 20 \, ^{0}\text{C} \).
Table C.1: Isotropic material properties of Akoca

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modulus of elasticity</td>
<td>$E_{iso}$ = 180 GPa</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>$\nu_{12}$ = 0.3</td>
</tr>
<tr>
<td>Density</td>
<td>$\rho_{iso}$ = 7800 kg/m³</td>
</tr>
<tr>
<td>Specific heat capacity</td>
<td>$Q_{iso}$ = 460.0 J/(kg·K)</td>
</tr>
<tr>
<td>Coeff. of thermal expansion</td>
<td>$\alpha_0$ = 12.0 · 10⁻⁶ K⁻¹</td>
</tr>
<tr>
<td></td>
<td>$\alpha_1$ = 0.0 K⁻³</td>
</tr>
<tr>
<td>Coeff. of thermal conduction</td>
<td>$\lambda_0$ = 81.00 W/(m·K)</td>
</tr>
<tr>
<td></td>
<td>$\lambda_1$ = 0.00 W/(m·K³)</td>
</tr>
</tbody>
</table>

Table C.2: Orthotropic material properties, 21”-rf-SuS mask

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_{orth}^{11}$</td>
<td>27.031 GPa</td>
</tr>
<tr>
<td>$E_{orth}^{22}$</td>
<td>110.1010 GPa</td>
</tr>
<tr>
<td>$E_{orth}^{b,11}$</td>
<td>27.40400 GPa</td>
</tr>
<tr>
<td>$E_{orth}^{b,22}$</td>
<td>120.0020 GPa</td>
</tr>
<tr>
<td>$G_{orth}^{12}$</td>
<td>6.476000 GPa</td>
</tr>
<tr>
<td>$\nu_{orth}^{12}$</td>
<td>0.07079430</td>
</tr>
<tr>
<td>$\rho_{orth}$</td>
<td>5039.000 kg/m³</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$dC_{cen}$</td>
<td>-123.6806 GPa/m²</td>
</tr>
<tr>
<td>$dC_{nor}$</td>
<td>-343.8889 GPa/m²</td>
</tr>
<tr>
<td>$dC_{eas}$</td>
<td>3.777778 GPa/m²</td>
</tr>
<tr>
<td>$dC_{cor}$</td>
<td>-708.1778 GPa/m²</td>
</tr>
<tr>
<td>$\epsilon_{mask2scr}$</td>
<td>0.68</td>
</tr>
<tr>
<td>$\epsilon_{scr2mask}$</td>
<td>0.87</td>
</tr>
<tr>
<td>$\epsilon_{screen}$</td>
<td>0.15</td>
</tr>
<tr>
<td>$\epsilon_{IMS}$</td>
<td>0.31</td>
</tr>
</tbody>
</table>

Orthotropic

The macro-orthotropic material properties of the Akoca mask material depend on the micro-geometry and are thus position depend. In table C.2 the coefficient are listed to calculate the orthotropic material properties for the 21”-rf-SuS with equation 2.2. The orthotropic Poisson’s ratio $\nu_{21}$ is calculated by the Maxwell equation $\frac{\nu_{12}}{E_2} = \frac{\nu_{21}}{E_1}$.

Other properties

In table C.3 properties for the interaction between the shadow mask and the environment are listed.
Appendix D

Matlab code

function [WperT, PF]=locdom(x_in,y_in, ra)
% e11_ort, de11_on, de11_oe, de11_oc, e22_ort, de22_on, de22_oe, de22_oc,
% g12_ort, dg12_on, dg12_oe, dg12_oc, rnu12_ort, dnu12_on, dnu12_oe, dnu12_oc,
% alp
load material_prop
% Rp(=relative polynomial), xmax, ymax, dsxdnm, xsens, ysens
load geomdata

% ra = 1 absolute, ra = 0 relative coordinates
if ra==0, x = x_in; y = y_in; xa = x_in*xmax; ya = y_in*ymax;
elseif ra==1, x = x_in/xmax; y = y_in/ymax; xa = x_in; ya = y_in;
end
% spot shift factor
xs=xa/xsens; ys=ya/ysens;
PF=[1 ys ys^2 ys^3]*dsxdnm*[1 xs xs^2 xs^3]';

% x and y koloms
x_k = [1 x^2 x^4 x^6]';

y_k = [1 y^2 y^4 y^6]';

dx_k = [0 2*x 4*x^3 6*x^5]./xmax;
dy_k = [0 2*y 4*y^3 6*y^5]./ymax;
d2x_k = [0 2 12*x^2 30*x^4]./xmax^2;
d2y_k = [0 2 12*y^2 30*y^4]./ymax^2;

% derivatives of mask polynomal
z = y_k'*Rp*x_k;

zx = y_k'*Rp*dx_k;

zy = dy_k'*Rp*x_k;

zxy = dy_k'*Rp*dx_k;

% mask normal components
norm = sqrt(1+zx^2+zy^2);

nx = zx/norm;
ny = zy/norm;
nz = 1/norm;

% derivatives of mask normal
nxx = (zxx*norm^2-zx*(zx*zxx+zy*zxy))/(norm^3);

nyy = (zyy*norm^2-zy*(zy*zyy+zx*zxy))/(norm^3);

nxy = (zxy*norm^2-zx*(zx*zxy+zy*zyy))/(norm^3);

nyx = (zyx*norm^2-zy*(zy*zyx+zx*zxx))/(norm^3);
nzx = -(zxx+zyx)/2/norm^3;
nzy = -(zyy+zxy)/2/norm^3;
% angles for skew system
chi = atan(zx); theta = atan(zy); omega = acos(sin(chi)*sin(theta));
% strain in skew reference system
eps_xx_nablaU = (nxx*cos(chi)+nzx*sin(chi))*cos(chi);
eps_yy_nablaU = (nyy*cos(theta)+nzy*sin(theta))*cos(theta);
gam_xy_nablaU = inv(sin(omega)) ...
*(nxy*cos(theta)-nxx*sin(theta)*cos(chi)*sin(chi))*cos(chi) ...
+(nyx*cos(chi)-nyy*sin(chi)*cos(theta)*sin(theta))*cos(theta) ...
+nzx*cos(chi)^3*sin(theta)+nzy*cos(theta)^3*sin(chi));
eps_nablaU_xy = [eps_xx_nablaU; eps_yy_nablaU; gam_xy_nablaU];
eps_xx_deltaT = 1; eps_yy_deltaT = 1; gam_xy_deltaT = 0;
eps_deltaT_xy = [eps_xx_deltaT; eps_yy_deltaT; gam_xy_deltaT];
% trans tensor {x,y}->{1,2}
Q = [1 0 -cot(omega); 0 1 0; cot(omega) -cot(omega) 1];
% strain in local orthonormal reference system
eps_nablaU_12 = Q * eps_nablaU_xy;
eps_deltaT_12 = Q * eps_deltaT_xy;
% material properties for given point
E1 = e11_ort + de11_on*ya^2 + de11_oe*xa^2 + de11_oc*xa^2*ya^2;
E2 = e22_ort + de22_on*ya^2 + de22_oe*xa^2 + de22_oc*xa^2*ya^2;
G12 = g12_ort + dg12_on*ya^2 + dg12_oe*xa^2 + dg12_oc*xa^2*ya^2;
nu12 = rnu12_ort + dnu12_on*ya^2 + dnu12_oe*xa^2 + dnu12_oc*xa^2*ya^2;
nu21 = nu12 * E1 / E2;
B=1-nu12*nu21;
% orthogonal stiffness matrix
E = [E1/B nu12*B E2/B; nu12*B E1/B B; 0 0 G12];
% stresses
gam_nablaU_12 = E * eps_nablaU_12;
gam_deltaT_12 = E * eps_deltaT_12;
% mask displacement per unit temperature [m/K]
WperT_num = (gam_nablaU_12'*eps_deltaT_12+gam_deltaT_12'*eps_nablaU_12);
WperT_den = 2*gam_nablaU_12'*eps_nablaU_12;
WperT = alp * WperT_num / WperT_den;
Bibliography


