Finite Element Analysis of a Washing Machine Cylinder

Thesis in Applied Mechanics one year Master Degree Program

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Examiner : Prof. Ulf Stigh
Preface & Acknowledgments

This is a Master of Science thesis in the master degree program Applied Mechanics. The thesis work was carried out for Asko Appliances at the school of technology and science, University of Skövde.

I would like to thank all of the involved persons at the university and especially my supervisor’s Tobias Andersson and Kent Salomonsson. I would also like to thank Alexander Eklind who has been helpful with ideas and suggestions in the course of this thesis work. Also many thanks are dedicated to the examiner Prof. Ulf Stigh.

I would also like to thank Peder Bengtsson, Stefan Tholin and Markus Persson at Asko Appliances for their help and support during this thesis work.

Saidulu Gundeboina
Skövde, April 2011.
Abstract

In this thesis a finite element model of a household washing machine cylinder is built and analysed in ABAQUS 6.9-2. The aim is to help Asko appliances in conducting similar analysis for future manufacturing of high capacity cylinders by reducing experimentation. The analysis is mainly concerned with an evenly distributed load at a constant angular velocity. The load is applied with the help of lead plates instead of clothes. The cylinder is loaded with three thin (2 mm) lead plates weighing 2 kg each. The plates with dimensional 370x240x2 mm are mounted with one strip of double sided foam tape inside the cylinder. To estimate the behavior of the cylinder the strains are measured when the cylinder is rotating at 1620 and 2200 revolution per minute (rpm). To validate the model the numerical analyses are compared with experimental results. The results clearly show that the numerical strain values fit with experimental strain values.

Keywords: Washing machine, Angular velocity, Cylinder.
# Table of Contents

Preface & Acknowledgments ........................................................................................................ iv
Abstract ......................................................................................................................................... iv

1 Introduction ................................................................................................................................ 1
2 Today’s Washing Technology ........................................................................................................ 1
3 Front loading washing machine ................................................................................................. 1
4 Purpose ...................................................................................................................................... 2
5 The washing machine cylinder assembly ...................................................................................... 3
5.1 The Cylinder ............................................................................................................................. 3
5.2 Front side and rear side .............................................................................................................. 3
5.3 The paddles............................................................................................................................... 4
5.4 Material properties .................................................................................................................. 5
6 Finite element model .................................................................................................................... 6
7 Pressure loads ............................................................................................................................. 9
8 Boundary condition ................................................................................................................... 11
9 Numerical results ....................................................................................................................... 12
10 Experiment results ................................................................................................................... 14
11 Loading of the drum ................................................................................................................... 15
12 Results & validation ................................................................................................................... 15
13 Conclusions ............................................................................................................................. 17
14 References ............................................................................................................................... 18
1. Introduction

Asko Appliances was founded in 1950 as one of many washing machine manufacturer but is today one of two Swedish washing machine manufacturer on the market. Even in 1950 most of the washing machines were equipped with spin ability and is still one area in which improvements can be made. Currently, washing machine manufacturers are aiming to minimize vibrations in order to increase the spin speed.

2. Today’s washing technology

Washing is a regular activity which involves hard work in scrubbing and rinsing clothes by hands. Today we are lucky to have a machine which is quite cheap and makes our work simple with little time consumption. Vatican newspaper funnily stated that women are enjoying freedom with the invention of washing machines as it relieved them from very high stress caused during manual washing. This is considered the high end development which brought smiles in the faces of women than any other development in 20th century [1].

The washing machines are classified into two broad categories:

(a) Top-loading machines.

(b) Front-loading machines.

In thesis only a front-loading washing machine is considered.

3. Front loading washing machine

Front loading washing machines have a horizontally mounted cylinder as shown in Figure 1. The door is made transparent to enable the user watch the action inside the washer. There are paddles inside the cylinder which lifts and drops the clothes during rotation. Today’s loading machines use less water which means less detergent. The maintenance and repair costs of front loading machine are higher than the top washers.
It is the consumer who is the final decision maker depending on his/her needs to choose the best type of machine which suits the requirements.

![Figure 1. Front loading washing machine.](image)

### 4. Purpose

The main purpose of developing a finite element model is to perform simulation instead of experiments thus reducing the cost in manufacturing a future cylinder. In the model the weight is applied by means of three lead plates weighing 2 kg each. A plate is shown in figure 2 (a). The numerical model is validated by comparing it to experimental results.

![Figure 2. (a) One lead plate on the inner surface of the cylinder. (b) 2 mm lead plate.](image)
5. The washing machine cylinder assembly

The final assembly of the cylinder is shown in figure 3. The main parts included in this washing machine are the cylinder, rear side, paddles and front side.

![Assembly of a washing machine cylinder](image)

Figure 3. Assembly of a washing machine cylinder.

5.1 The cylinder

Asko Appliance uses a component in their washing machine called the cylinder. The cylinder is made of a 0.6 mm thick cold rolled stainless steel sheet and is assembled by three parts by folding its edges together. It is also punched and bent to create the perforated surface of the cylinder.

5.2 Front side and rear side

The front and rear components are also made out of 0.6 mm thick stainless steel sheets. These parts are fixed to the front and rear sides of the cylinder. The front side edge is joined by folding as shown in figure 4 (a). The rear side is connected to the cylinder with three bolts as shown in figure 4 (b).
5.3 The paddles

Front loading washing machine has three paddles assembled on the inner surfaces of the cylinder. The paddles help the clothes to follow the rotation of the cylinder. The bottom surface of the paddle connected to the inner surface of the cylinder by means of six heels connection as shown in figure 5 (b). The paddles are made of a Polyethylene HDPE plastic material and has a complex solid geometry.

Figure 4. (a) Front side  (b) Rear side.

Figure 5. (a) The paddle top surface and bottom surface. (b) Connection of heels.
5.4 Material properties

The cylinder is made of stainless steel. Material data are obtained from tensile tests [2]. Depending upon these properties we can define whether the material is in the elastic region, 0-300 MPa, or in the plastic region, 300-580 MPa. The stress-strain relationship is shown in figure 6.

![Figure 6. Stress strain curve.](image-url)

Material properties for cylinder, front side and rear side values are shown in table 1.

<table>
<thead>
<tr>
<th>S.No.</th>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Modulus of elasticity</td>
<td>210 GPa</td>
</tr>
<tr>
<td>2</td>
<td>Mass density</td>
<td>7800 kg/m³</td>
</tr>
<tr>
<td>3</td>
<td>Poisson’s ratio</td>
<td>0.33</td>
</tr>
<tr>
<td>4</td>
<td>Yield tensile strength</td>
<td>300 MPa</td>
</tr>
</tbody>
</table>

Table 1. Material properties of stainless steel.

Material properties for polyethylene HDPE are given in table 2.

<table>
<thead>
<tr>
<th>S.No.</th>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Modulus of elasticity</td>
<td>800 MPa</td>
</tr>
<tr>
<td>2</td>
<td>Mass density</td>
<td>1400 kg/m³</td>
</tr>
<tr>
<td>3</td>
<td>Poisson’s ratio</td>
<td>0.28</td>
</tr>
</tbody>
</table>

Table 2. Material properties of the HDPE.
Material properties of the lead plates are given in table 3.

<table>
<thead>
<tr>
<th>S.No.</th>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Modulus of elasticity</td>
<td>14 GPa</td>
</tr>
<tr>
<td>2</td>
<td>Mass density</td>
<td>11340 kg/m³</td>
</tr>
<tr>
<td>3</td>
<td>Poisson's ratio</td>
<td>0.431</td>
</tr>
</tbody>
</table>

Table 3. Material properties of lead.

6. Finite element model

The development of the FE-model starts by importing the CAD model of the washing machine cylinder assembly into Pro/Engineer 4.0 software (Pro-E). The assembly only consider the cylinder, front, rear sides and peddles as shown in figure 7. The assembled Pro-E model is then exported to Abaqus 6.9-2 using the .igs format.

![Figure 7. The geometric model is shown in the various views.](image)

The washing machine cylinder is meshed based on a 3D geometry model. The cylinder, front side, rear side and lead plates are meshed with 3-noded shell elements (S3) with an average size of 1.5 mm. Each shell element have 6 degree of freedom per node and 5 integration points through the thickness are used. The paddles have a complicated geometry are meshed using 3D solid 4-node elements (C3D4). To calculate the strains at positions 1, 2, 3 and 4 shown in figure 8, 4-noded shell elements (S4) are used.
The element type and various material properties and thickness assigned for the components are given in Table 4, 5 and 6.

<table>
<thead>
<tr>
<th>Element type</th>
<th>3-node shell elements (S3) and 4-node shell elements (S4).</th>
</tr>
</thead>
<tbody>
<tr>
<td>Young's modulus</td>
<td>210 GPa</td>
</tr>
<tr>
<td>Mass density</td>
<td>7800 kg/m³</td>
</tr>
<tr>
<td>Poisson's ratio</td>
<td>0.33 -</td>
</tr>
<tr>
<td>Plastic region</td>
<td>300-580 MPa, see [2]</td>
</tr>
<tr>
<td>Shell thickness</td>
<td>0.6 mm</td>
</tr>
</tbody>
</table>

Table 4. Material properties of stainless steel.

<table>
<thead>
<tr>
<th>Element type</th>
<th>3-node shell elements (S3).</th>
</tr>
</thead>
<tbody>
<tr>
<td>Young's modulus</td>
<td>14 GPa</td>
</tr>
<tr>
<td>Mass density</td>
<td>11340 kg/m³</td>
</tr>
<tr>
<td>Poisson's ratio</td>
<td>0.431 -</td>
</tr>
<tr>
<td>Shell thickness</td>
<td>2 mm</td>
</tr>
</tbody>
</table>

Table 5. Material properties of lead

Figure 8. Finite element model of assembly.
Element type : 4-node solid elements (C3D4).

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Young's modulus</td>
<td>800 MPa</td>
</tr>
<tr>
<td>Mass density</td>
<td>1400 kg/m³</td>
</tr>
<tr>
<td>Poisson's ratio</td>
<td>0.28</td>
</tr>
</tbody>
</table>

Table 6. Material properties of HDPE.

Contact conditions are applied between the cylinder - paddle and between cylinder - lead plates. The friction between the paddles (plastic), cylinder (stainless steel) and lead plates are assumed to be low and as a result the friction is set to zero. Also, tie constraints are applied between the paddle heels and the outer surface of the cylinder as shown in figure 9 (b).

![Figure 9](image)

Figure 9. (a) The box shown represents the contact zone between the paddle and the cylinder. (b) Position of ties constraints.

The lead plates are mounted on the inner surface of the cylinder by means of a double sided foam tape as shown in figure 10 (a). In the numerical model tie constraints are applied in the middle of the lead plate as shown in figure 10 (b).
Figure 10. (a) Position of the double sided foam tape. (b) Position of tie constraints.

To define the stresses in the cylinder we consider a cylindrical pressure vessel with radius $r$ and wall thickness $t$ subjected to an internal gage pressure $p$. There are two kind of stresses when a pressure is subjected a cylinder. One is the longitudinal stress (or axial stress) $(\sigma_l)$ which acts along the length of the cylinder as shown in figure (a). The other is called the hoop stress $(\sigma_h)$ which acts along the circumference of the cylinder as shown in figure 13(b).

Figure 13. (a) longitudinal stress $(\sigma_l)$. (b) circumference stress $(\sigma_h)$. 
7. Pressure loads

The analysis consider two loading cases where case 1 deals with 2200 rpm and case 2 deals with 1620 rpm. The first step in case 1 is to apply a pressure load, on the inner surface of the cylinder as shown in figure 11 (a), due to the constant rotation of the cylinder. The second step is to apply a pressure load due to the rotation of the lead plates shown in figure 11 (b). These steps are also done in case 2 to see the effects of these loads in both cases.

![Figure 11](image)

Figure 11. (a) Pressure load on inner surface the cylinder. (b) Pressure load due to lead plates.

The cylinder utilize a cylindrical coordinate system with $r$, $\theta$ and $z$ as coordinates. The coordinate $r$ gives the radial distance of the point normal to the longitudinal axis (in figure 15 normal to this paper). The coordinate $z$ gives the longitudinal axis direction. The coordinate $\theta$ is subsequently normal to $r$ and $z$.

Case 1: 2200 rpm

Pressure is an effect which occurs when force is applied on a surface and mathematically calculated as force per unit area.

$$ p = \frac{F}{A} \quad (1) $$

To calculate the force is consider Newton's second law. Mathematically, the force is mass times the acceleration.

$$ F = ma \quad (2) $$
The angular velocity is known and it has to be converted to acceleration to find out the force and finally the pressure load. The acceleration is radius times the square of angular velocity.

\[ a = r \omega^2 \]  \hspace{1cm} (3)

Since the pressure load due to the rotation only acts on the cylinder walls, only the circumference of the cylinder is considered.

\[ A = 2\pi rh \]  \hspace{1cm} (4)

where \( r \) is the cylinder radius and \( h \) is the cylinder height. Here the total cylinder mass is 3 kg, \( r = 0.225 \) m and \( h = 0.325 \) m. Using equation (1) to (4) the pressure is calculated to \( p_{\text{cylinder}} = 64 \) kPa.

We also calculate the pressure load due to the lead plates. The mathematical calculations are similar to the steps above where pressure on the lead plates is considered. The area of the plate is considered as

\[ A = lb \]  \hspace{1cm} (5)

where \( l \) is the length of the lead plate and \( b \) is the width. Here the total plate mass is 2 kg, \( l = 0.240 \) m and \( b = 0.370 \) m. Using equation (1) to (3) and (5) the pressure is calculated to \( p_{\text{plate}} = 118 \) kPa.
Case 2: 1620 rpm

The pressure in case 2 is calculated similar to the pressure calculated in case 1. The major difference is the constant rotational velocity which is 1620 rpm in this case. By using equation (1) to (4) the pressure is calculated to $p_{\text{cylinder}} = 42 \text{ kPa}$ on the inner surface of the cylinder. The pressure loads on the lead plates are calculated using equation (1) to (3) and (5) to be $p_{\text{plate}} = 77 \text{ kPa}$. Finally, calculated pressures are shown in table 5.

<table>
<thead>
<tr>
<th>Case 1: 2200 rpm</th>
<th>Case 2: 1620 rpm</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_{\text{cylinder}} = 64 \text{ kPa}$</td>
<td>$p_{\text{cylinder}} = 118 \text{ kPa}$</td>
</tr>
<tr>
<td>$p_{\text{plate}} = 42 \text{ kPa}$</td>
<td>$p_{\text{plate}} = 77 \text{ kPa}$</td>
</tr>
</tbody>
</table>

Table 5. Applied pressure loads.

8. Boundary conditions

The rear side is connected to a very stiff external component at 3 places shown in figure 12. These places are assumed to be fully constrained.

Figure 12. The position of the boundary conditions.

Two simulations are carried out using Abaqus at two different velocities where the von Mises stresses are plotted in figure 14 and 15.

For case 1 resulting the maximum von Misses stress is determined to 549 MPa which is in the plastic region.

For case 2 stress according to von Misses becomes 300 MPa.

The numerical model is compared to the experiments to validate the numerical model. The numerical and experimental results are explained in detail.

The cylinder undergo strains when a pressure load is applied. High strains are located at position 2 and 3 which are located in the middle of the cylinder as shown in figure 16. Lower strains are located at position 1 and 4 which are located near to the
front and the rear side of the cylinder as shown in figure 16. These strains give a clear idea of the deformation of the cylinder at high rotational speeds.

Figure 16. Numerical model of the cylinder where position 1-4 indicates the position of the strain gauges.

Strain results from the numerical model are shown in table 6 and 7.

<table>
<thead>
<tr>
<th>RPM</th>
<th>Strain 1 [ppm]</th>
<th>Strain 2 [ppm]</th>
<th>Strain 3 [ppm]</th>
<th>Strain 4 [ppm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2200</td>
<td>- 299</td>
<td>248</td>
<td>278</td>
<td>- 58</td>
</tr>
</tbody>
</table>

Table 6. Average strain in one element from case 1.

<table>
<thead>
<tr>
<th>RPM</th>
<th>Strain 1 [ppm]</th>
<th>Strain 2 [ppm]</th>
<th>Strain 3 [ppm]</th>
<th>Strain 4 [ppm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1620</td>
<td>- 683</td>
<td>65</td>
<td>171</td>
<td>- 350</td>
</tr>
</tbody>
</table>

Note: the unit ppm is the same as micro strain, micro meter/meter

Table 7. Average strain in one element from case 2.
10. Experiment results

Measurements with strain gauges on the outside of the drum are performed by ASKO. The strain gauges are positioned as shown in figure 17 with the measuring direction shown by the arrow.

Figure 17. Strain gauges positioned at four places.

11. Loading of the drum

The drum is loaded with three thin (2mm) lead plates weighing 2.0 kg each. The plates measure 370x240x2 mm and are placed on the cylinder inner surface with double sided foam tap. The tape strip is just strong enough to keep the lead plate from falling down before the spinning of the drum begins. When the drum spins the centrifugal force keeps it in place. Strain results from the experimental model are shown in table 8.

<table>
<thead>
<tr>
<th>RPM</th>
<th>Strain 1 [ppm]</th>
<th>Strain 2 [ppm]</th>
<th>Strain 3 [ppm]</th>
<th>Strain 4 [ppm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1620</td>
<td>-635</td>
<td>58</td>
<td>145</td>
<td>-318</td>
</tr>
<tr>
<td>2200</td>
<td>-330</td>
<td>219</td>
<td>286</td>
<td>-66</td>
</tr>
</tbody>
</table>

note: the unit ppm is the same as micro strain, micro meter/meter

Table 8. Summary of the strain experiment results.
12. Results & validation

The graphs plotted between the two cases results clearly show that the numerical strain values in both cases fit with experimental strains.

Case 1: 2200 rpm

<table>
<thead>
<tr>
<th>Strain Gage</th>
<th>Analysis</th>
<th>Experiment</th>
<th>% Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-299</td>
<td>-330</td>
<td>9</td>
</tr>
<tr>
<td>2</td>
<td>248</td>
<td>219</td>
<td>13</td>
</tr>
<tr>
<td>3</td>
<td>278</td>
<td>286</td>
<td>2</td>
</tr>
<tr>
<td>4</td>
<td>-58</td>
<td>-66</td>
<td>12</td>
</tr>
</tbody>
</table>

Graph 1

![Graph 1: Strain measurements at 2200 rpm](image)
Case 2: 1620 rpm

<table>
<thead>
<tr>
<th>Strain Gage</th>
<th>Analysis</th>
<th>Experiment</th>
<th>% Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-683</td>
<td>-635</td>
<td>7</td>
</tr>
<tr>
<td>2</td>
<td>65</td>
<td>58</td>
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<tr>
<td>3</td>
<td>171</td>
<td>145</td>
<td>17</td>
</tr>
<tr>
<td>4</td>
<td>-350</td>
<td>-318</td>
<td>10</td>
</tr>
</tbody>
</table>

Graph 2

13. Conclusions

From the above results it can be concluded that:

1. The numerical analysis results and the experimental real time results obtained at Asko Appliance have been carefully observed at two different speeds of 2200 and 1620 rpm. The graphs plotted between the two cases results clearly show that the numerical strain values in both cases fit with experimental strains. The maximum error is calculated is 17%.

2. The analysis methodology can be applied to enhanced capacities of washing machines, reducing the experiments for each model.
14. References