FE6:

6-roll Sugarcane Mill
Mathematical Model, FEA and its validation by Strain-Gauge measurement

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At: 29th ISSCT, Chiang Mai, Thailand, 8 Dec 2016
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OBJECTIVE OF THE STUDY

TO OPTIMIZE the design of Cane Mill and its components thru:

• Study of machine kinematics & development of advanced mathematical model

• Solving of the model for a selected installation and finite element analysis.

• Validation through field measurement using strain gauge technology.

Application of final model for various sizes of mills
STUDY METHODOLOGY

1. Development of new mathematical model
2. Solving of the model and FEA
3. Strain-gauge measurement
4. Application for various mill sizes
5. Analysis and validation of the model
STUDY

COLLABORATORS

• Isgec Heavy Engineering Ltd, Noida, India

• Automotive Research Association of India, a research association of automotive industry with Ministry of Heavy Industries, Govt. of India.

• Saraswati Sugar Mills Ltd, Yamunanagar, India, a 10,000 TCD sugar plant.
Previous work largely for 4-roll mill, lack field validation and ignore bearing friction.

6-roll configuration chosen for present study as its design is the most challenging.

4-roll model results can be derived from 6-roll with relative ease.
3 rolls of the mill have a common foot mounted electric drive, GPRF has a shaft mounted hydraulic drive.
DEVELOPMENT OF A NEW MATHEMATICAL MODEL
WHAT IS A MATHEMATICAL MODEL?

Mathematical description of a situation used to understand the machine kinematics and predict its behavior in future.

Typical Mathematical Model

\[
\frac{T}{\sin 120} = \frac{W}{\sin 120}
\]

\[T = W\]
Torque sharing between rollers & trash plate

Free body diagram of each Mill/GRPF roll

Bearing housing couple force diagram

Reaction forces on pressure chutes

COMPUTATION STEPS
TORQUE SHARING:
ROLLERS AND TRASH PLATE

Total torque input to mill top roll
\[ = (T_{tc} + T_{tf} + T_{tr}) + (T_{fc} + T_{ff}) + (T_{dc} + T_{df}) \]

Subscripts tc, fc & dc represent torque due to cane
Subscripts tf, ff & df represent the bearing frictional torque on top/feed/discharge rolls
Subscript tr represents cane torque on trash plate.

Total torque input to GRPF bottom roll
\[ = (T_{gtf} + T_{gtc}) + (T_{gbf} + T_{gbc}) + (T_{guf} + T_{guc}) \]

Subscripts gt, gb & gu represent GRPF top/bottom & u/feed roll
FREE BODY DIAGRAM
OF MILL TOP ROLLER
EQUATION OF MILL TOP ROLLER

\( R_{t2h} - \mu R_{t2v} \)
\[
= \frac{1}{L} \cdot \left[ \frac{L}{2} \left( -F_{fnc} \sin \frac{\alpha}{2} + F_{fc} \cos \frac{\alpha}{2} + F_{Tr} \cos \beta + F_{dnc} \sin \frac{\alpha}{2} + F_{dc} \cos \frac{\alpha}{2} - F_{trc} \cdot \sin \beta \right) \\
- (L + K) \left( -F_{fnp} \sin \frac{\alpha}{2} + F_{fp} \cos \frac{\alpha}{2} + F_{Trc} \sin \beta + F_{dn} \sin \frac{\alpha}{2} + F_{dp} \cos \frac{\alpha}{2} \right) \right] (14)
\]

\( R_{t1v} + \mu R_{t1h} \)
\[
= -R_{t2v} + (F_{fnc} + F_{fnp}) \cos \frac{\alpha}{2} + F_{trc} \cdot \cos \beta + (F_{fp} + F_{fc}) \sin \frac{\alpha}{2} \\
+ (F_{dn} + F_{dnc}) \cos \frac{\alpha}{2} - (F_{dp} + F_{dc}) \sin \frac{\alpha}{2} + F_{tr} \cdot \sin \beta - \mu R_{t2h} \quad (11)
\]

\( R_{t2v} + \mu R_{t2h} \)
\[
= \frac{1}{L} \cdot \left[ -\frac{L}{2} \left( -F_{fnc} \cos \frac{\alpha}{2} - F_{fc} \sin \frac{\alpha}{2} - F_{Tr} \sin \beta - F_{dnc} \cos \frac{\alpha}{2} - F_{trc} \cdot \cos \beta + \\
+ F_{dc} \sin \frac{\alpha}{2} \right) - (L + K) \left( -F_{fnp} \cos \frac{\alpha}{2} - F_{fp} \sin \frac{\alpha}{2} - F_{dn} \cos \frac{\alpha}{2} + F_{dp} \sin \frac{\alpha}{2} \right) \right] (13)
\]

\( R_{t1h} - \mu R_{t1v} \)
\[
= -R_{t2v} - (F_{fp} + F_{fc}) \cos \frac{\alpha}{2} - F_{tr} \cdot \cos \beta + (F_{fnc} + F_{fnp}) \sin \frac{\alpha}{2} \\
- (F_{dn} + F_{dnc}) \sin \frac{\alpha}{2} - (F_{dp} + F_{dc}) \cos \frac{\alpha}{2} + F_{trc} \cdot \sin \beta + \mu R_{t2v} \quad (12)
\]
BEARING HOUSING 
COUPLE FORCES

\[ R_{cf} = \frac{\text{(Resultant bearing reaction)} \cdot (\text{Journal radius}) \cdot \mu}{\text{square root (bearing width}^2 + \text{bearing height}^2)} \]

Regarding forces, e.g., Rcf is a couple force on the bearing housing due to friction.
Friction force = Coeff of friction x Pressure on chute x Chute plate area
SOLVING OF THE MODEL AND FINITE ELEMENT ANALYSIS OF 1980mm (78”) LONG, 6-ROLL MILL OPERATING AT 8000 TCD
### OPERATING PARAMETERS

<table>
<thead>
<tr>
<th>Description</th>
<th>Symbol</th>
<th>Unit</th>
<th>Mill</th>
<th>GRPF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roller dia.</td>
<td>D</td>
<td>mm</td>
<td>915</td>
<td>915</td>
</tr>
<tr>
<td>Crush rate</td>
<td>t/hour</td>
<td>t/h</td>
<td>330</td>
<td></td>
</tr>
<tr>
<td>Installed drive</td>
<td>–</td>
<td>kW</td>
<td>650 (DC motor)</td>
<td>315 (Hyd. motor)</td>
</tr>
<tr>
<td>Consumed power</td>
<td>P1, P2</td>
<td>kW</td>
<td>365</td>
<td>130</td>
</tr>
<tr>
<td>Operating speed</td>
<td>N1, N2</td>
<td>rpm</td>
<td>5.4</td>
<td>6.3</td>
</tr>
<tr>
<td>Roll journal dia.</td>
<td>d</td>
<td>mm</td>
<td>460</td>
<td></td>
</tr>
<tr>
<td>Roll journal crs</td>
<td>L</td>
<td>mm</td>
<td>3100</td>
<td></td>
</tr>
<tr>
<td>Top brg housing</td>
<td>wxh</td>
<td>mm</td>
<td>530 x 325</td>
<td></td>
</tr>
<tr>
<td>Hyd. load on top roll (per unit length)</td>
<td>–</td>
<td>t/m</td>
<td>206</td>
<td>–</td>
</tr>
</tbody>
</table>
**FORCE/TORQUE DISTRIBUTION**

<table>
<thead>
<tr>
<th>Description</th>
<th>Source</th>
<th>Mill</th>
<th>GRPF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Friction coeff (white metal brg)</td>
<td>Field data</td>
<td>0.06</td>
<td>0.06</td>
</tr>
<tr>
<td>% torque for mill rolls (feed / discharge / top)</td>
<td>Field data</td>
<td>24/24/52</td>
<td>--</td>
</tr>
<tr>
<td>% torque for GRPF rolls (top / bottom / UFR)</td>
<td>Assumed</td>
<td>--</td>
<td>46/46/8</td>
</tr>
<tr>
<td>Force ratio for mill: disch / feed</td>
<td>Field data</td>
<td>7:1*</td>
<td>--</td>
</tr>
<tr>
<td>Force ratio for grpf: top / bot</td>
<td>Assumed</td>
<td>--</td>
<td>1:1</td>
</tr>
<tr>
<td>Push force in pressure chute</td>
<td>Assumed</td>
<td>171 kN</td>
<td></td>
</tr>
<tr>
<td>Fraction of hydraulic force on trash plate</td>
<td>Field data</td>
<td>0.2 of hyd. load</td>
<td></td>
</tr>
</tbody>
</table>

*Initial assumption 2:1 corrected to 7:1 after field validation
### Model OUTPUT

#### Reaction Forces on Bearing Housing (kN)

<table>
<thead>
<tr>
<th>Description</th>
<th>Mill roller bearing housing</th>
<th>GRPF bearing housing</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Top roll</td>
<td>Feed roll</td>
</tr>
<tr>
<td>Drive side</td>
<td>Rh2</td>
<td>1468</td>
</tr>
<tr>
<td></td>
<td>Rv2</td>
<td>2255</td>
</tr>
<tr>
<td>Pintle side</td>
<td>Rh1</td>
<td>847</td>
</tr>
<tr>
<td></td>
<td>Rv1</td>
<td>2060</td>
</tr>
</tbody>
</table>

#### Forces on trash plate, pressure plate and bearing couple (kN)

<table>
<thead>
<tr>
<th>Description</th>
<th>Trash plate</th>
<th>Pr. chute</th>
<th>Mill hsg</th>
<th>GRPF housings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drive side</td>
<td>25</td>
<td>401</td>
<td>171</td>
<td>446</td>
</tr>
<tr>
<td>Pintl side</td>
<td>25</td>
<td>401</td>
<td>171</td>
<td>216</td>
</tr>
</tbody>
</table>
MODEL OUTPUT USED AS INPUT FOR FEA
FEA OUTPUT:

STRESS PATTERN

A: Pintle End side with Pressure chute
Equivalent Stress
Type: Equivalent (von-Mises) Stress
Unit: MPa
Time: 1
Custom
Max: 313.56
Min: 0.00043989
14-03-2016 11:40

ANSYS
R15.0

PINTLE SIDE

DRIVE SIDE
FEA OUTPUT:
DEFLECTION PATTERN

Total Deformation
Type: Total Deformation
Unit: mm
Time: 1
Custom
Max: 1.2744
Min: 0
01-09-2016 18:08

ANSYS R15.0
STRAIN-GAUGE MEASUREMENT ON 1980mm (78”) LONG, 6-ROLL MILL OPERATING AT 8000 TCD
STRAIN GAUGE: THE SMALL WONDER

Strain Gauge measures expansion / contraction of surface

- Stress of component having complex geometry can be derived using FE analysis.
- FEA is validated thru strain measurement at various locations of the component under actual operating conditions.

Stress = Measured strain x Young’s Modulus
STRAIN GAUGE: THE SMALL WONDER

32 locations on 6-roll mill used for strain measurement.
TYPE OF STRAIN
GAUGES USED

Full Wheatstone Bridge

Rossette

Uni-axial
STRAIN GAUGE
FIXING & PROTECTION
IDENTIFICATION

METHODOLOGY
IMPORTANT LOCATIONS

GRPF pressure Chute

Foundation Bolt Reactions
IMPORTANT LOCATIONS

GRPF Top Cap

[Images of GRPF Top Cap]
DATA LOGGING AND ANALYSIS

80-channel eDAQ portable system of Somat (USA) used at 100Hz for data acquisition and continued for 3 consecutive days: 10 hrs on 19 Dec, 10 hrs on 20 Dec, 8 hrs on 21 Dec 2015.

Following Data Acquired

• Strain at 32 locations
• Mill/GRPF roller speed
• Load at mill/GRPF drives
• Top roller lift
• GRPF hydraulic pressure
• Cane crush rate

Data Acquisition System
STRAIN GAUGE
OUTPUT DATA
CORRECTION (TYPICAL)

Original Data with drift

Filtered Data with drift removed
Strain at start of mill (Side cap at feed side)

Bi-Axiality ratio

Resultant principal angle
STRAIN GAUGE OUTPUT
DATA OBSERVATIONS

Out of phase data: Mill load Vs strain

Same phase data: Mill load Vs strain

Top Pin of Discharge
Side Cap

Turn beam
ANALYSIS AND VALIDATION OF THE MODEL
## VALIDATION:
### RESULT COMPARISON

<table>
<thead>
<tr>
<th>Gauge mark no./type</th>
<th>Stress value (MPa)</th>
<th>From field measurement</th>
<th>Calculated from FEA model</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Gauge fixed at headstock side face</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>01 R(+)</td>
<td>34.4</td>
<td>33.6 / 35.7</td>
<td></td>
</tr>
<tr>
<td>02 R(+-)</td>
<td>14.3</td>
<td>16.8 / 18.9</td>
<td></td>
</tr>
<tr>
<td>03 R(+)</td>
<td>8.4</td>
<td>8.4 / 9.45</td>
<td></td>
</tr>
<tr>
<td>04 R(+-)</td>
<td>5.4</td>
<td>9.8 / 10.5</td>
<td></td>
</tr>
<tr>
<td><strong>Gauge fixed at side caps</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>07 R(+)</td>
<td>0.6</td>
<td>1.1 / 1.3</td>
<td></td>
</tr>
<tr>
<td>08 R(+)</td>
<td>23.7</td>
<td>27.3 / 29.4</td>
<td></td>
</tr>
<tr>
<td><strong>Gauge fixed at mill hydraulic top cap</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>09 R(+-)</td>
<td>8.1</td>
<td>12.6 / 13.6</td>
<td></td>
</tr>
<tr>
<td><strong>Gauge fixed at mill bottom roller bearing housing</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10 R(-)</td>
<td>1.8</td>
<td>1.2 / 1.4</td>
<td></td>
</tr>
<tr>
<td>11 R(-)</td>
<td>15.9</td>
<td>17.2 / 18.4</td>
<td></td>
</tr>
</tbody>
</table>
## VALIDATION: RESULT COMPARISON

<table>
<thead>
<tr>
<th>Gauge mark no./type</th>
<th>Stress value (MPa)</th>
<th>From field measurement</th>
<th>Calculated from FEA model</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Gauges fixed at GRPF side face</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12 R(+/-)</td>
<td>7.9</td>
<td></td>
<td>7.3 / 7.8</td>
</tr>
<tr>
<td>13 U(+)</td>
<td>2.9</td>
<td></td>
<td>4.6 / 5.5</td>
</tr>
<tr>
<td><strong>Gauges fixed at turn beam</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>16B U(+)</td>
<td>11.1</td>
<td></td>
<td>12.6</td>
</tr>
<tr>
<td><strong>Gauges fixed at GRPF Stools</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>24A U(-)</td>
<td>3.4</td>
<td></td>
<td>1.9 / 2.1</td>
</tr>
<tr>
<td>24B U(-)</td>
<td>1.2</td>
<td></td>
<td>2.5 / 2.7</td>
</tr>
<tr>
<td><strong>Gauge fixed at headstock base</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Mill drive side (discharge)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>25 R(+/-)</td>
<td>2.1</td>
<td></td>
<td>10.5 / 12.6</td>
</tr>
<tr>
<td><strong>Mill drive side (feed)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>27 R(+/-)</td>
<td>2.31</td>
<td></td>
<td>1.9 / 3.1</td>
</tr>
</tbody>
</table>
OBSERVATION ON FIELD VALIDATION

• Initially assumed feed to discharge ratio of 2 corrected to the field result of 7.

• Initially assumed value of 80 t/m load on GRPF roller corrected to field result of 26 t/m.

• Frictional power loss at the mill and GRPF bearings is 20% and 10% of consumed power.

• Field measured data differs widely from FEA in some cases, particularly at top cap and fdn bolts.
CONCLUSION

• A new mathematical model of a 6-roll mill has been developed which also takes into account friction loss at mill roller bearings.

• The model was prepared and solved for a 1980 mm size mill based on field measured data for force and torque distribution.

• The model was fine tuned on the basis of comparison of FEA and strain gauge data.
APPLICATION OF STUDY

Models developed for different configurations to engineer sturdy design of 2030 mm to 2790 mm (80” to 110”) long mills
Thank You

Presented By

Isgec Heavy Engineering Ltd, Noida, India