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VIBRATIONS INDUCED FLOW IN A HORIZONTAL CENTRIFUGAL CASTING

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Abstract

During the horizontal spin casting of rolls, vibrations and mould deformations seems to have a significant effect on the final quality of the product. Sources for vibrations can be found in the poor roundness and a static imbalance of the chill itself. The bending of the mould axis is also considered. Both, vibrations and axis bending, are used as an input for CFD simulations of the flow dynamics of the liquid metal inside the rotating cylinder. The aim is to study the feedback of the free surface behavior in terms of wave propagation and various wave shapes.

Introduction

The horizontal spin casting process (HSC) is a casting process that has several advantages over the traditional gravity casting processes. Centrifugally cast products have a high degree of metallurgical purity and homogeneous microstructure. A significant gain is observed for the rupture strength, the rupture strain, and the Young modulus. These properties naturally depend on the centrifugal force and thus, the best mechanical properties can be found at the largest distance from axis of rotation. However proper selection of the angular frequency has to be done in order to prevent the so-called "metal rain" i.e. metal droplets can fall down from the upper part of the cylinder due to a too weak centrifugal acceleration. In the same time excessive speeds can lead to the appearance of longitudinal cracks caused by the hoop stress in the initially solidified layer. From empirical knowledge other parameters have important influence on the casting products, it includes the pouring temperature, the pouring rate, the mould coating etc. Recently the presence of natural or forced vibrations have been identified as possible additional factors to be taken into account [1-2].

Although the mechanisms are not yet clear, the vibrations influence solidification structure and the level of porosity. A transition from the lamellar to the fibrous morphology was observed with the increase of the vibration amplitude [1-2]. An influence on the eutectic fraction was also observed. If the acceleration related to the vibration reaches a critical magnitude the grains tend to coarsen. It is generally assumed that that during the centrifugal casting the melt firstly solidifies on the mould wall, then due to the turbulent flow fragments are moved into to the melt and stand as a new nucleation points [3]. It is believed that vibrations can significantly enhance this grain refining process.

The present work presents a 2D shallow water model of a thin liquid layer in the inside surface of a rotating cylinder. From the observation (see Figure 1) of real casting process the melt was found to rotate with the mould, the fluid flow was modelled in the rotating frame of reference with the addition of the fictitious forces such as the centrifugal force and the Coriolis force. The objective is to study for specific rotation speed, the response of the liquid surface dynamic to some imposed vibrations.

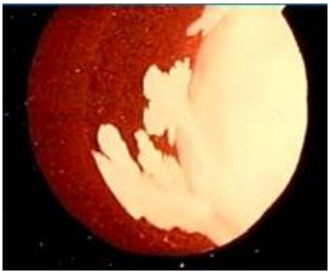

Figure 1: Liquid metal spreading inside a rotating mould

Numerical Model

Usually the flow in centrifugal configuration is solved in 3D [4-6]. Due to the limitation in the Courant number 3D approaches need extremely small time step if accurate calculations are targeted. The present model is based on so-called shallow water equations. In layman's terms, one could take it as a 2.5D model. In general, the shallow water equations are used for modelling purposes of oceanography and also belong to basic modelling tools of meteorologists. For this reason, the shallow water equations are usually defined in rotating spherical geometry. Generally, two main simplifications are introduced and are known as the traditional and the hydrostatic approximation. The first one neglects so-called metric terms coming out from the spherical geometry. The second one neglects all vertical components in momentum equations except of pressure gradient and buoyancy force. Very often due to large lengthscales involved it is common to assume inviscid flow. The velocity along the liquid height is taken as constant. A multiple layer approach is usually used to simulate vertical liquid mixing that might be for example caused by a density difference in oceanic flows.

In the present model a laminar flow is assumed and hence, a parabolic velocity profile is used. On the cylindrical wall no slip BC condition is considered. Although representing a cylindrical geometry, the shallow water model is solved in a planar coordinates (x,y) using a periodic condition in the tangential direction. The continuity equation can be integrated over the height h of the liquid film:

$$\frac{\partial h}{\partial t} + \nabla \cdot \left(h\vec{u} \right) = 0 \,, \tag{1}$$

Integrated over the liquid metal height, the momentum equation is:

$$\frac{D}{Dt}\left(h\rho\vec{u} \right) = -h\nabla p + h\mu\nabla^2\vec{u} + \rho\vec{g} - \rho h\Omega^2 \left(R - h \right)\nabla h - 2\rho\int_0^h \vec{\Omega}\times\vec{u}dh - 2\mu\frac{\vec{u}}{h} \,, \tag{2}$$

On the Right hand side of Eq.2 the terms represent successively the gradient of the static pressure, the viscous stress tensor, the gravity force, the centrifugal force, the Coriolis force, and the friction force with the wall.

Vibrations and axial bending of the rotating cylinder

In order to account for vibrations the model had to be significantly modified. In the first place, the term of the axial bending and vibrations must be explained and defined in the vector form. The cylinder is rotating around its horizontal axis and is supported by four rollers. On one side the two coaxial rollers are driving, while on the other side the next two are simply driven. The axial bending is assumed to have a sinusoidal shape with the two nodes positioned exactly at the rollers. The angular slope of bending is given by the following formula:

$$\tan\theta = A\frac{\pi}{\lambda}\cdot\sin\left(\frac{\pi x}{\lambda}\right), \tag{3}$$

where A is the amplitude of bending, x is the axial coordinate, and λ is the distance between two coaxial rollers (0). In the rotating frame of reference this bending is time independent.

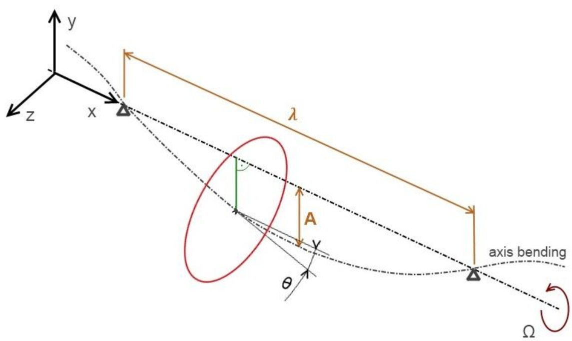

Figure 2: Sine-like axis bending

Depending on the origin, the mathematical description of the vibrations can be rather complicated. In the present investigations, vibrations are assumed to be solely arising from the poor roundness of the cylinder. The same level of roundness is assumed all along the cylinder axis. In vectorial form it can be defined as:

$$\overrightarrow{a_v}\left(0,\quad \xi\cos(\omega t+\beta),\quad \xi\sin(\omega t+\beta)\right), \tag{4}$$

where ξ is the amplitude of acceleration due to vibrations, ω is the angular frequency associated with the vibrations, and finally β is the phase. The phase β specifies where the oscillation begins. Assuming an elliptical cross section of the cylinder, the frequency of the vibrations is naturally the double of the cylinder rotating frequency $\omega = 2\Omega$. From (4) it is evident that the acceleration a_v has no component in the axial direction.

The consideration of the axis bending of axis has a considerable effect on the mathematical formulation of the gravity, the centrifugal force, the Coriolis force, and the vibrations itself. The difficulty rises from the fact that each of these forces must be expressed on coordinate system that is moving on a bended cylinder. The first one denoted as $C_1(\vec{x}, \vec{y}, \vec{z})$ is the global coordinate system, where the x-axis is strait and y- and z-axis are rotating with the angular frequency Ω. The second one denoted as $C_2(\vec{c}, \vec{d}, \vec{r})$ is a local coordinate system, where $\vec{c}$ is a unit vector parallel to the cylinder axis identical to the bending line. The unit vector $\vec{d}$ is aligned with the tangent to the cylindrical surface oriented in positive direction. The unit vector $\vec{r}$ is perpendicular to the cylindrical surface and oriented outwards. Notice that the coordinate system C_2 is consistent with the coordinate system C_3 used in the shallow water model and one can write:

$$C_2\left(\vec{c}(t), \overrightarrow{d(t)}, \overrightarrow{r(t)}\right) = C_3\left(\vec{x}', \vec{y}', 0\right), \tag{5}$$

where 0 signifies that the problem is solved only in 2 dimensions. The gravity acceleration is projected on the unit vectors of the C_2 system :

$$g_c = \vec{g} \cdot \vec{c}, \quad g_d = \vec{g} \cdot \vec{d}, \quad g_r = \vec{g} \cdot \vec{r}, \tag{6}$$

In the similar manner the centrifugal, the Coriolis and the vibrations accelerations were transformed analogically. Non-zero components in the radial $\vec{r}$ direction (vertical in the shallow layer model) are converted into hydrostatic pressure p_h by integration over the liquid height. Then 2D gradients of p_h can generate a force for the horizontal directions of momentum equations:

$$\vec{S} = -\vec{\nabla}\left(\int_0^h \vec{F} \cdot \vec{r} dr\right), \tag{7}$$

this force is added to Eq 2.

Results

All simulations were run with constant physical properties of the liquid metal (ρ =6800 kg/m^3, μ =0.006 kg/m-s). The cylinder is 0.372 m radius and 3.2 m long. Two different angular frequencies Ω are considered 30 rad/s and 71.2 rad/s. Several liquid layer heights h were considered (5, 10, 20, 30, 40 mm). Note that the filling of the liquid was not included in the model, an initial distribution of the liquid height was imposed. Two distinct initial liquid height distributions were considered. It was assumed either a flat surface with constant liquid height h_0 or perturbed surface using the following function:

$$h_0 = h_{avg}\left[\sin\left(a \cdot (x' - b)^2\right) + \sin\left(c \cdot (y' - d)^2\right)\right], \tag{8}$$

where constants *a*, *b*, *c*, and *d* were 10, 0.4, 12, and 0.3, respectively. This function (8) was chosen in order to perturb the free surface with different wavelengths in both directions (x' and y').

Several cases labeled from N1 to N10 were calculated with the model settings listed in Table 1. The time step was held constant (Δt =0.001 s) so that the local Courant number was always smaller than 0.1. Second orders schemes were used for the space and time discretization. Results were compared in terms of amplitude, which was defined as a difference between the minimum and the maximum liquid height found in the entire computational domain divided by two. The evolution of the mean amplitudes is shown in figure 3 for the angular frequency of 71.2 rad/s and in figure 4 for Ω=30 rad/s. In Figure 5, examples of shape of the free surface are shown in the plane [x'y']. Note that y' coordinate stands for the circumferential position on the cylinder. At 4 s a single wave travels along the cylinder circumference, whereas at 100 s fully-developed chaotic waves travel mainly in the axial direction.

Several general features can be observed in the results:

1) Mean amplitudes never drop to zero within the calculated time range (≈180 s). Certain waves survive even for small liquid height.
2) A single longitudinal wave is formed in early stages due to the gravity and the inertia interaction no matter whether the free surface was initially perturbed or not. As the velocity field develops, the longitudinal wave diminishes within an apparent relaxation time ranging from 20 s to 40 s.
3) The higher the liquid height, the higher is the amplitude of the oscillations.
4) In all final states, waves are traveling moves in the axial direction. This transfer of momentum from the circumferential and radial directions (gravity and vibrations) to the axial direction is due to the rotational nature of the Coriolis force.

<table>
<tr><th></th><th>Ω [rad/s]</th><th>h [mm]</th><th>vibrations [-]</th><th>initial perturbation [-]</th></tr>
<tr><td>N1</td><td rowspan="7">71.2</td><td>5</td><td rowspan="9">YES</td><td rowspan="5">YES</td></tr>
<tr><td>N2</td><td>10</td></tr>
<tr><td>N3</td><td>20</td></tr>
<tr><td>N4</td><td>30</td></tr>
<tr><td>N5</td><td>40</td></tr>
<tr><td>N6</td><td>5</td><td rowspan="3">NO</td></tr>
<tr><td>N7</td><td>10</td></tr>
<tr><td>N8</td><td rowspan="3">30</td><td rowspan="3">20</td></tr>
<tr><td>N9</td><td>YES</td></tr>
<tr><td>N10</td><td>NO</td><td>NO</td></tr>
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Table 1: List of model settings for cases N1–N10

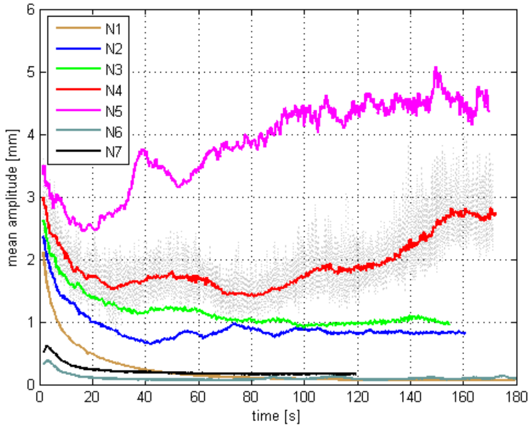

Figure 3: Evolution of the amplitude of metal/air interface for Ω=71.2 rad/s

Almost no influence of the initial perturbation on the final state can be observed between the cases N1 and N6. Without perturbation case N7 converges towards a relatively quite state, with perturbation the same case converges towards a state where the oscillations are four times larger.

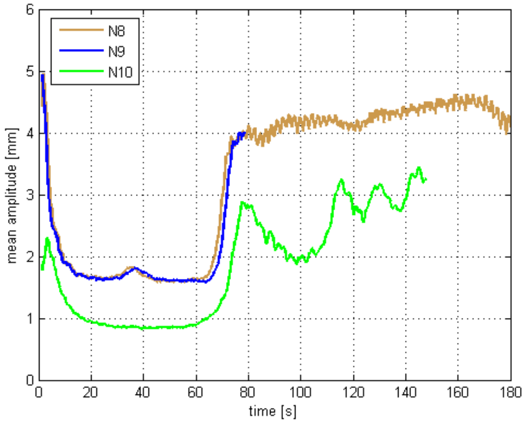

Figure 4: Evolution of the amplitude of metal/air interface for Ω=30 rad/s

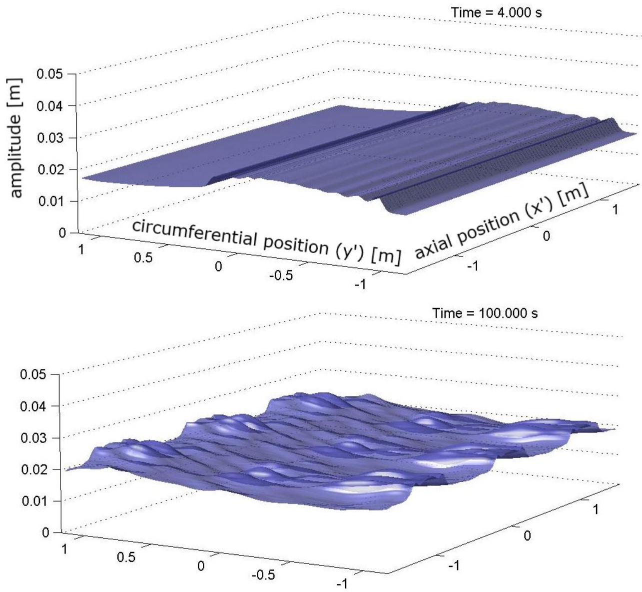

Figure 5: Actual shape of free surface for N8 at times 4 s and 100 s

At lower rotation speed a transition between a calm and dynamic sate occurs after 60 second real time. Notice the relatively low amplitude region from 20 s to 60 s with a sudden transition to instability at 60 s. N10 with no vibrations involved is significantly different compared to N8. By comparing case N10 with cases N8 and N9, it can be stated that vibrations amplify and stabilize the amplitude of oscillations of the interface. The origin of the stabilizing effects of the perturbations is not yet clear.

Conclusions and future prospects

A shallow water model for the flow of liquid metal layer on the inside surface of a rotating cylinder was developed. The objective was to study wave patterns of the free surface, wave birth, propagation, and death. Besides, the aim was also to study a response of the system on different initial conditions i.e. the initial liquid height was either constant or perturbed using a sine-like function. The main assumptions of the model are: The angular frequency Ω of the cylinder is so high that the fluid is mainly rotating with the cylinder. For this reason, the model was defined in the rotating frame of reference. A parabolic velocity profile along the liquid height was taken into account with no slip boundary condition on the cylindrical wall. The model was further extended in order to account for vibrations and an axis bending. It was shown that despite extremely high centrifugal forces (~100 G) acting on a liquid layer the interaction between the inertia, the gravity, and the vibrations can lead to the formation of waves on the free surface. The higher the liquid height is, the more it is prone to instabilities. In the future a solidification model will be included using two layers approach, one for the liquid and one for the solidified layer by taking into account the heat conduction inside the mould and also heat losses into ambient. The magnitude of accelerations and flow velocities predicted by the present model leads to the idea that strong fragmentation of the solidified elements occur. In order to take into account this phenomenon, a 3 layers model will be under consideration.

Acknowledgement

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