DNS of 2D Disturbed Air Flow with Leveling Process

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Introduction

The demand for higher quality coating products, such as for an LCD's optical elements, a digital photo film or a semiconductor circuit, all of which demand high precision, has been increasing recently based on customers' requests. In order to respond to the demand from a world-wide market, an industrial research has expanded to include the analysis of a leveling process during an ante-drying period beyond a general approach.

However, thin liquid films are subject to the non-uniformity of air flow which will create surface tension gradients and the velocity magnitude of it which relates to shear stress to deform the surface.

Fig. 1 Mottling by surface tension gradients

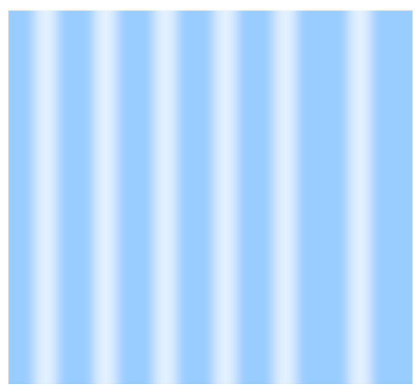


Fig. 2 Wavy instabilities by air flows

In this research, we analyzed the leveling model which contains the realistic disturbances from an air flow and a liquid film by using hybrid mesh GFEM. In the analysis of an air flow, we introduced a turbulence model (DNS: Direct Numerical Simulation) in order to depict the actual flows which influence the liquid film shape.

Theory and computation

1. Non-uniformity of air

In order to solve the problem, complex turbulent behavior must be considered. Usually, there are three types of numerical approaches.

(1) Direct Numerical Simulation: DNS

(2) Large Eddy Simulation: LES

(3) Reynolds Averaged Numerical Simulation: RANS

DNS is the method that is used to compute the Kolmogorov Scale; the minimum scale of the turbulence flow field without any estimated models. LES computes the only grid scale vortex by modeling the sub grid scale using proper filters. The typical RANS model is a *k*-*ε* model. The technique uses an ensemble averaged turbulence flow field. The DNS technique uses the induction method giving the system a random white noise as follows.

$$x(t) = \sum_{k=1}^{N} a_k \cos(\omega_k t + \theta_k) \qquad 1)$$

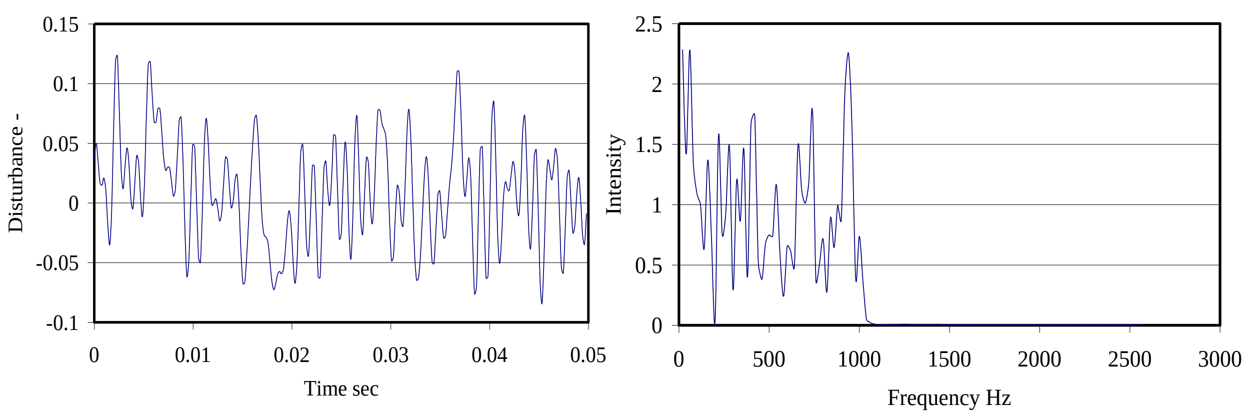
Here,

Random values for phase = θ_k

Coefficient for amplitude = $a_k = 2\sqrt{S(\varpi)\Delta\varpi}$

Frequency range = $\Delta\varpi = \varpi_{upper} - \varpi_{lower}$

Target Frequency = $\varpi_k = \varpi_{lower} + (k - 1/2)\Delta\varpi$



a) Time domain b) Frequency domain

Fig. 3 Random input for air flow fields

2. Liquid flow model

Generally, DNS is very intensive in terms of computational load. Therefore, we executed a time reduction of numerical computation by introducing the inertia-augmented visco-capillary model in the liquid film region as follows.

Inertia Augmented Film Equation

$$-\frac{\partial p}{\partial x}=\frac{1}{h}\left[\rho[\frac{\partial q}{\partial t}+\frac{\partial}{\partial x}\int_0^h u^2dy]-\left(\mu\frac{\partial u_1}{\partial y}_{y=h}-\mu\frac{\partial u_1}{\partial y}_{y=0}\right)\right]$$

Interfacial boundary condition for Stress

$$T_{nn}=-p+2\alpha\tau_{xy}$$

1st order approximation for the stress from the air flow

Alfa=gradients of the position of free surface

3. Boundary conditions

In order to solve the two different computational domains, the ALE hybrid mesh was introduced, which can give us an accurate result avoiding concentrated mesh. On the interface, a weak coupling was used to combine the two domains together. With respect to DNS, we assumed that the input signals of random white noise were less than 1 kHz, in order to create a realistic situation. The specific boundary conditions are shown as follows.

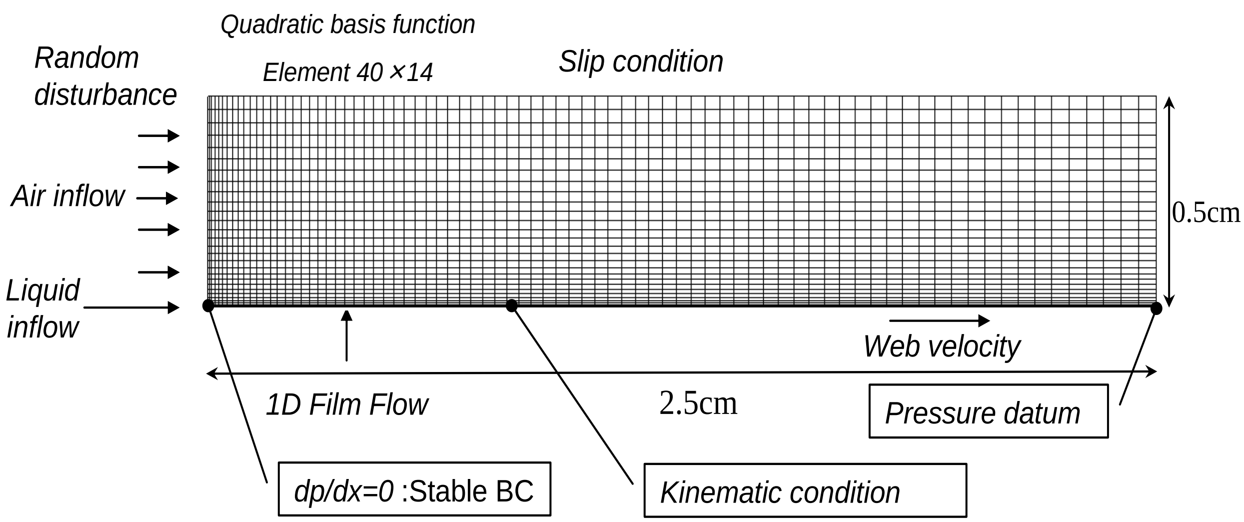


Fig. 4 Boundary Conditions

Parameters used here are as follows.

Air :0.5005-2.5m/sec, Web :0.5m/sec, Film :10μm

Viscosity 1cP, Surface tension 25dyn/cm²

4. Results

The computational result of air flows using the parameters is shown as follows.

Air velocity = 0.5005m/s

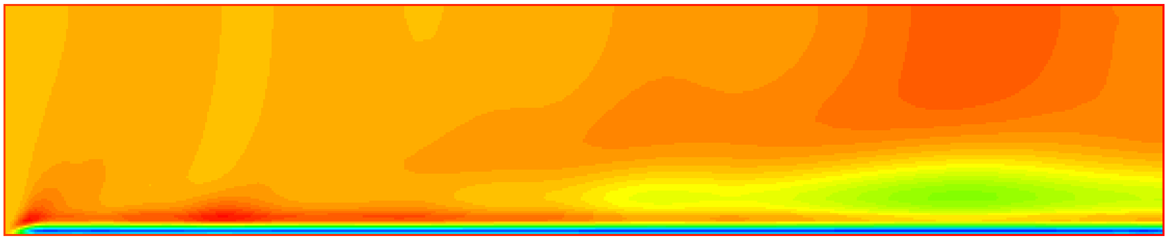


Fig. 5 Unsteady state of air flows using DNS

From those series of results, we could obtain the appropriate phenomena which are similar to the "T-S wave" in the air flow, and the criterion obtained by computational results could distinguish a stable region from an unstable region in terms of the leveling quality.

Acknowledgement

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Reference

1) Drazin PG: Hydrodynamic stability, William Hill Reid Cambridge University. Press, 2004

2) White, FM. (1991). Viscous fluid flow. McGraw‐Hill, Inc.

3) Kim J., Moin P. and Moser R. (1987) Turbulence statistics in fully developed channel flow at low Reynolds number. J. Fluid Mech.

4) Higgins BG. Capillary Hydrodynamics and Coating Beads. PhD Thesis University of Minnesota. 1980.

5) Schlichting H. Boundary Layer Theory 8th Ed. New York: Springer. 2000.

6) Tsuda T, de Santos JM and Scriven LE. (2010) Frequency Response Analysis of Slot Coating. AIChe Journal.