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Dynamic Response Analysis and Control of Slot Coating*

Takeaki TSUDA**

** Dai Nippon Printing Co., Ltd., Technology Development Center
1-1-3 Midorigahara, Tsukuba, Ibaraki 300-2646 Japan
E-mail:Tsuda-T2@mail.dnp.co.jp

Abstract

A slot coating application is an attractive coating method for creating a uniform coating thickness over a substrate material. However, a variety of disturbances in operational conditions (e.g., pumping fluctuations, motor system cogging) may lead to unacceptable variations in the final coating thickness. The dynamic response characteristics of the final coating thickness resulting from such disturbances can be computed using a numerical analysis technique that employs a visco-capillary model. In addition, there are two different methods for controlling the thickness of the final coating. One passive control method changes die lip geometry, and the other active control method uses a flow feedback system coupled with a final coating thickness sensor. The passive technique can suppress final thickness variations by 20–30% in a limited number of cases, whereas the active technique substantially reduces thickness variations in every case where the disturbance frequency is less than 10 Hz.

Key words: Numerical Analysis, Film Flow, Slot Coating, Flow Control, Dynamic Response

1. Introduction

A slot coating system uses a pre-metered[1] coating method that can produce uniformly thin coatings on substrates such as plastic films, glasses, and papers. This method has recently been used to produce a variety of industrial products such as LCD display components, optical elements, and magnetic tapes. The slot coating system shown in Fig. 1 consists of two important parts: one is a cavity that serves to distribute coating liquids uniformly widthwise, and the second is a slot that produces thinner liquid film. The land areas next to the slot exit lips serve to stabilize the coating bead under the lips by providing appropriate pressure[1]. The upstream region operates under a vacuum that helps to control the coating beads by preventing their movement to a downstream region[1]. In order to investigate the static behavior of the coating beads during a slot coating process, Higgins[2] used a visco-capillary model and Silliman[3] and Sartor[4] employed a Navier–Stokes model incorporated into a finite element method analysis. Their results identified a stable region for coating system operations under ideal conditions.

In an actual coating process operation, the coating beads can vibrate as a result of periodic disturbances. Examples of these disturbances include pumping fluctuations, a backing roll run-out, variations of substrate speed and pressure fluctuations at the upstream region. The consequence of any such disturbance is a periodic variation of the resulting coating thickness. Cristodoulou[5] analyzed the dynamic behavior of coating beads for a slide coating, and he demonstrated that such periodic behavior can be described by using

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linearized unsteady Navier–Stokes equations. Cai[6] and Gates[7] used the same technique and applied it to a slot coating process. They developed a frequency response analysis to periodic disturbances and employed several numerical techniques for an efficient computation. Furthermore, Musson[8] developed an analysis technique that applies to two-layer slot coating. He showed how the thicknesses of two layers fluctuated as a result of periodic disturbances.

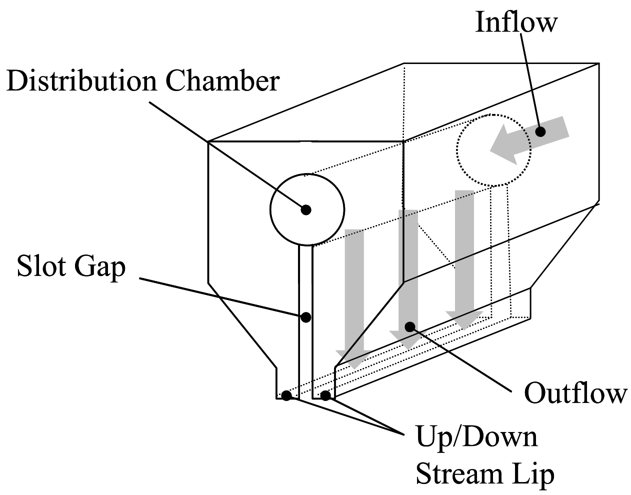


Fig 1 Configuration of slot die

These investigators did not, however, discuss their results beyond the prediction of thickness variations. In particular, they did not address methods to reduce the thickness variations caused by disturbances. In order to damp coating thickness fluctuations, it is generally necessary to update the control features of manufacturing equipment, which can entail high costs and long delivery periods. In addition, the precision requirements for producing optical materials require accuracy control that is often outside the tolerance level of current equipment. Because the Navier–Stokes[3-8] solution providing accurate computation results is computationally intensive and difficult to examine, there is a need for a simpler approach. The approach described in the present study addresses this need by employing a passive control method that adjusts die lip geometries and an active control method that uses a flow feed-back system based on sensing the final thickness of the film.

2. Equations of dynamic response and control

The configuration of a slot coating process is shown in Fig. 2. The liquids flowing into a slot are filled under the up and down stream lips, and they are carried to the downstream side by the substrate. The coating thickness in a steady-state flow is determined by the relationship between the inflow into the slot and the velocity of the substrate. If the upper limit of a coating thickness is approximately 100 μm in a general industrial application, the lengths of up and down stream lips are set to less than 10 mm[11]. In order to avoid recirculation in a flow field which creates aggregation of particles, Sartor[4] suggested that the coating gap should be less than three times of the coating thickness, and that the slot gap should be less than two times of the coating gap. As the basic conditions used in this study, the lengths of the up and down stream lips are set to less than 10 mm, and the slot gap conditions proposed by Sartor [4] were followed.

The configuration of the inclined up and down stream lips in the coating bead region is shown in Fig. 3.

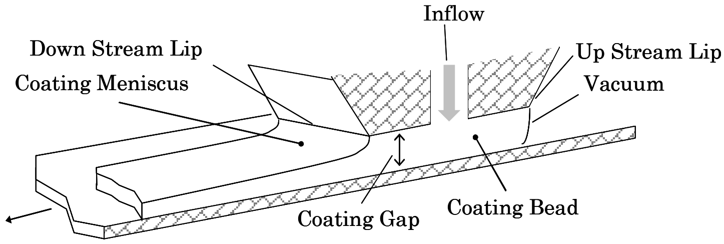


Fig. 2 Configuration of slot coating.

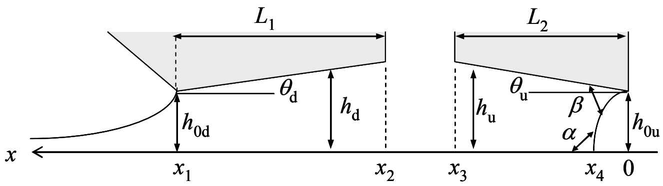


Fig. 3 Configuration of upstream and downstream lips in coating bead region.

As Higgins[2] suggested, the pressure equation for bead regions can be approximated as the visco-capillary model that assumes inertia and gravitational effects are negligible. As shown in Fig. 3, the bead regions between the lips can be divided into four parts.

First, the pressure of a coating bead at $x = x_4$ can be defined by the following equation that uses the upstream vacuum and the Young–Laplace equation:

$$p(x_4) = \frac{\sigma}{h_u(x_4)}(\cos\alpha + \cos(\beta - \theta_u)) + p_v \tag{1}$$

where σ denotes a surface tension and p_v is the ambient pressure in the vacuum region. Then, the pressure difference between x_4 and x_3 can be derived using a result from Higgins[2] with the definition of inclined lips:

$$p(x_4) - p(x_3) = -6\mu U \int_0^{L_2 - x_4} \frac{dx}{(h_{0u} + (x + x_4)\tan\theta_u)^2} \tag{2}$$

where μ is a viscosity and U is the velocity of the substrate. Assuming that $p(x_3)$ is equal to $p(x_2)$ following Higgins's approach, the equation for the pressure drop between x_1 and x_2 is given by

$$p(x_2) - p(x_1) = -\mu\left[6U\int_0^{L_1} \frac{dx}{(h_{0d} - (x - L_1)\tan\theta_d)^2} - 12Uh_\infty \int_0^{L_1} \frac{dx}{(h_{0d} - (x - L_1)\tan\theta_d)^3}\right] \tag{3}$$

Finally, at the point of $x = x_1$, by the Landau–Levich film flow approximation[12], the equation of the pressure in a coating bead is given by

$$p(x_1) = -1.34\left(\frac{\mu U}{\sigma}\right)^{2/3} \frac{\sigma}{h_\infty} \tag{4}$$

where h_∞ is the final coating film thickness. By coupling these four equations, we can derive a nonlinear pressure equation with an unknown variable x_4. We can then consider the relationship between the volumetric in and out flow rates and the deformation of the coating bead domain to derive a conservation equation in the coating bead:

$$\frac{\partial}{\partial t}\left(\int_0^{L_2-x_4}(h_{0u}+(x+x_4)\tan\theta_u)dx\right)+\frac{\partial}{\partial t}\left(\int_0^{L_1}h_{0d}-(x-x_1)\tan\theta_d)dx\right)=Q-Uh_\infty \quad (5)$$

where Q denotes a volumetric outflow rate of coating liquids from a slot gap. The conservation equation is a first-order temporal differential equation system with an unknown of x_4.

An active control flow diagram to compensate for input disturbances is shown in Fig. 4. In general, many external factors for a vibrating coating bead can be regarded as disturbances. Such disturbance inputs are defined by the following equations:

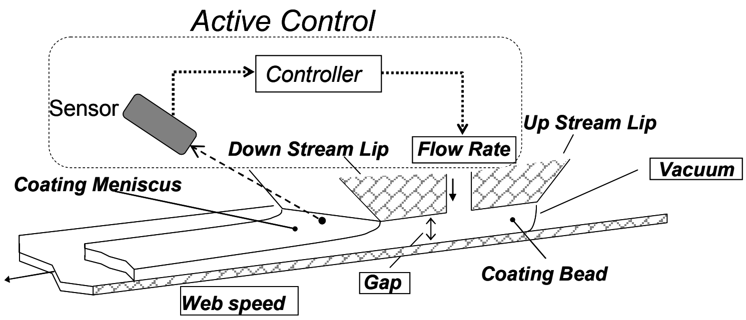


Fig. 4 Dynamic model of slot coating.

$$Q(t)=Q_{steady}(1+\varepsilon\sin\varpi t) \quad (6)$$

$$U(t)=U_{steady}(1+\varepsilon\sin\varpi t) \quad (7)$$

$$p_v(t)=p_{v\,steady}(1+\varepsilon\sin\varpi t) \quad (8)$$

$$h_{0u}(t)=h_{0u\,steady}(1+\varepsilon\sin\varpi t) \quad (9)$$

$$h_{0d}(t)=h_{0d\,steady}(1+\varepsilon\sin\varpi t) \quad (10)$$

where ε is the disturbance magnitude; the subscript "steady" relates to a value at steady-state conditions; and Q_{steady}, U_{steady}, $P_{vsteady}$, $h_{0usteady}$, and $h_{0dsteady}$ refer to volumetric flow rate, substrate velocity, ambient pressure, minimum coating gap at upstream lip, and minimum coating gap at downstream lip, respectively. Note that the same disturbance magnitude is used for both Equations (9) and (10). As shown in Fig. 4, the active control system in this study uses a sensor that measures the dynamic final coating thickness and a controller using flow rate feed-back as a compensation value defined by

$$Q(t)=Q_{steady}\left[1-\gamma\left(\frac{h_\infty(t)-h_{\infty\,steady}}{h_{\infty\,steady}}\right)\right] \quad (11)$$

where γ is the feed-back gain and $h_{\infty steady}$ is the final coating thickness at steady state. The numerical procedure for solving these equations is summarized by the following steps:

a) The conservation equation (Equation (5))

$$\frac{dx_4}{dt} = f(t, \; x_4, \; h_\infty)$$

b) The pressure equations (Combining equation (1-4))

$$0 = g(t, \; x_4, \; h_\infty)$$

The above equations a) and b) become solvable semi-explicit index-1 DAEs. The position variable x_4 in a) is computed using a Runge−Kutta−Gill fourth-order solution with a constant time step. Because the pressure equations are non-linear, the final thickness h_∞ is computed by the Newton−Raphson method. Before focusing on the specific case study, we establish realistic values for the magnitude of a disturbance and its frequency range[(13)].

3. Computation conditions and results

For computational purposes, we divide the operational frequency range into the three parts shown in Fig. 5. Furthermore, we use representative values of 0.5, 5.0, and 50.0 Hz to identify the central values of each frequency zone.

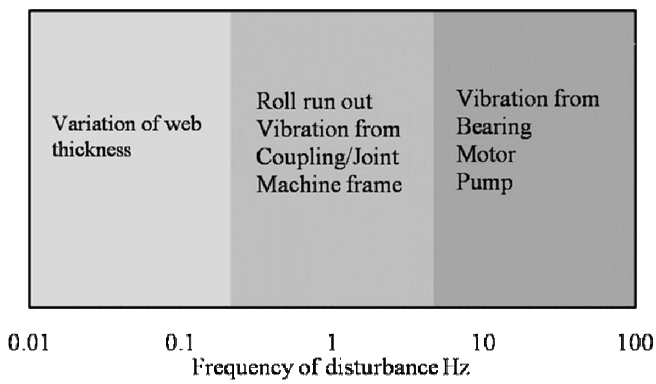


Fig. 5 Frequency band for each disturbance.

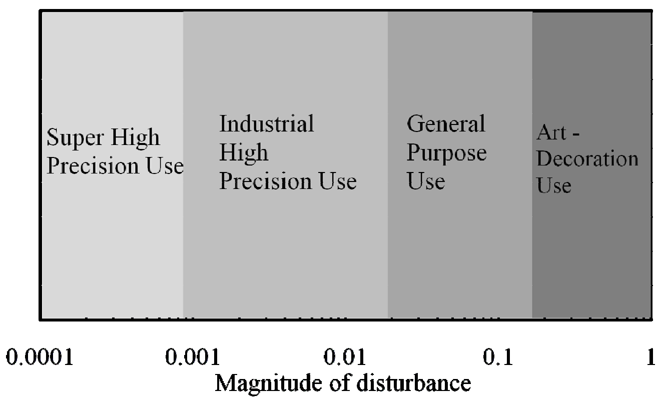
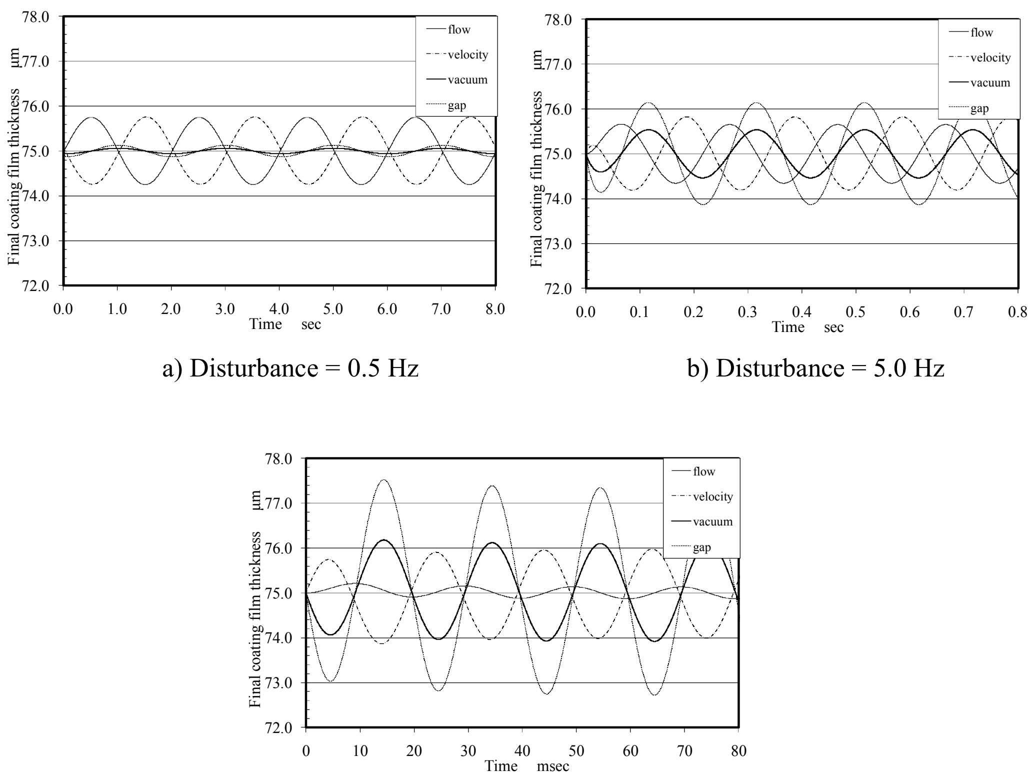


Fig. 6 Magnitude of disturbance related to applications.

In establishing the magnitude of each potential disturbance, we assume that the tolerance for precise industrial production is less than a few percent. Thus the magnitude of the disturbance for high-precision production is assumed to be 1% ($\varepsilon = 0.01$), as shown in Fig. 6. In addition, the dimensions used in the present study are $h_{0dsteady} = h_{0usteady} = 2.5 \times 10^{-4}$ m, $L_1 = L_2 = 1.0 \times 10^{-3}$ m, and $\theta_d = \theta_u = 0.0$º. The fluid viscosity, surface tension, and dynamic /static contact angles used here are $\mu = 20.0$ mPa·s, $\sigma = 60$ mN/m, $\alpha = 120.0$º, and $\beta = 60.0$º, respectively. The fluid, substrate and die metal used here are corresponding to 72wt% glycerin/water solution, PET and stainless steel. The coating operation conditions for substrate speed, vacuum, and final thickness are assumed to be $U_{steady} = 0.2$ m/s, $p_{ysteady} = -600$ Pa, and $h_{\infty steady} = 7.5 \times 10^{-5}$ m, respectively. Computational results showing the temporal response of the final coating thickness at standard conditions are given in Fig. 7.



a) Disturbance = 0.5 Hz

b) Disturbance = 5.0 Hz

c) Disturbance = 50.0 Hz

Fig. 7 Dynamic response of coating thickness.

The results shown in Fig. 7 suggest that the final coating thickness responds sensitively to fluctuations in flow and substrate speed in the low frequency region (e.g., 0.5 Hz), while it is less sensitive to other disturbances. In contrast, as the disturbance frequency increases to approximately 5 Hz, the final thickness responds in the same way to every disturbance source. Furthermore, when the frequency reaches 50 Hz, the sensitivity of the coating thickness with respect to the type of disturbance becomes more visible. In particular, the coating thickness response is more sensitive to gap oscillations and less sensitive to a disturbance in the pump flow rate. Those trends indicate a strong frequency dependency.

The response sensitivity of the variation of thickness to the disturbances is defined as GAIN = $|\,(h_\infty(t)/h_{\infty steady} - 1)/\varepsilon\,|$. The frequency responses associated with each disturbance are given in Fig. 8.

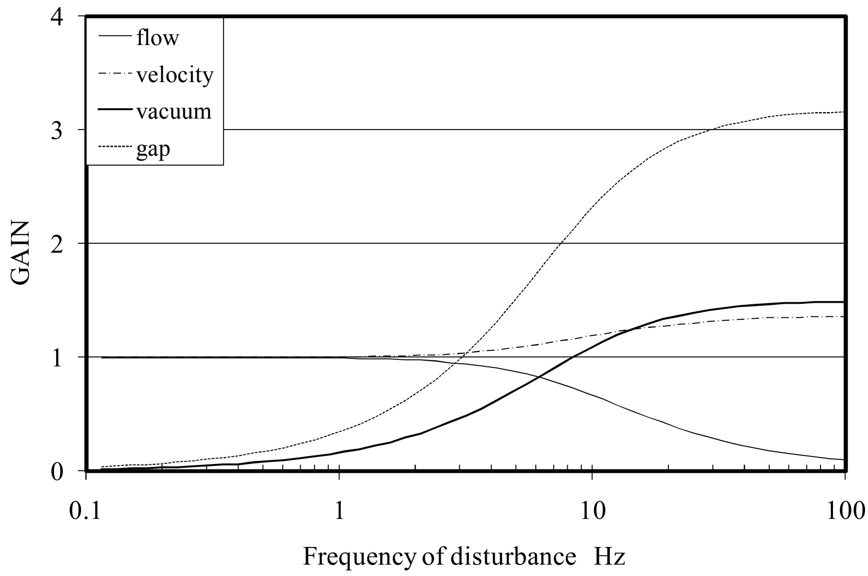
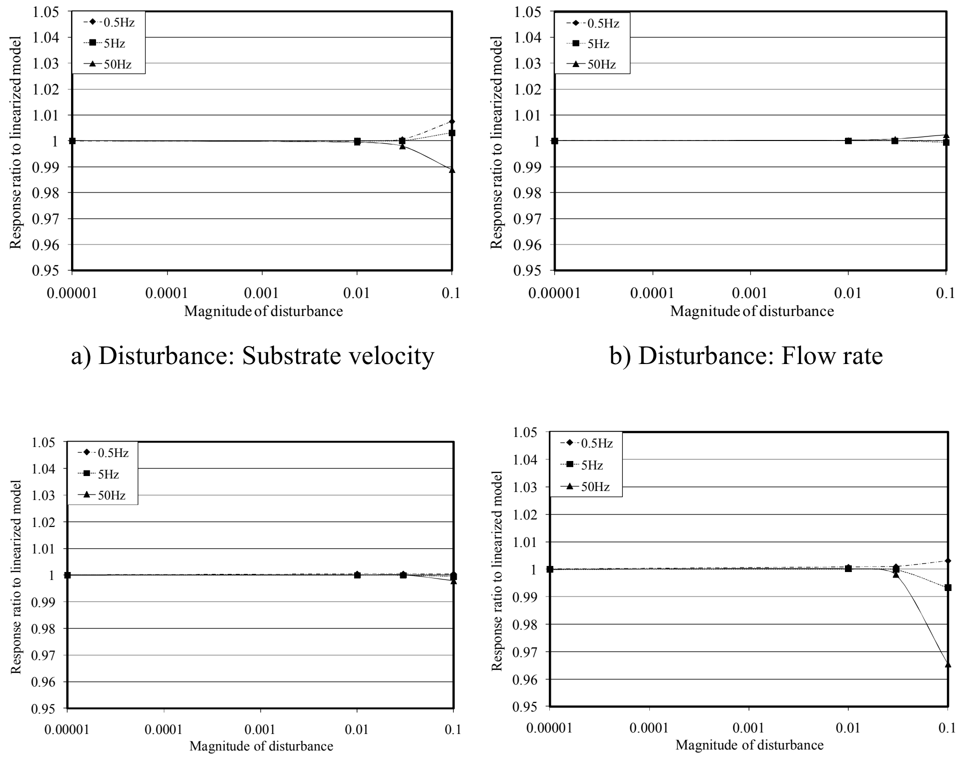


Fig. 8 Frequency response of gain.

In Fig. 8, the frequency responses to each disturbance change continuously and smoothly with respect to frequency. Note also that a gap oscillation generates the largest gain among the responses. The reason for this result is related to the energy supplied to the coating beads. That is, a gap oscillation vibrates the whole bead (similar to a pumping action), which induces a large coating thickness variation. In contrast, a flow rate variation affects solely liquids in the inflow region, while a variation of substrate speed affects only the Couette flow component of coating beads, and a variation of pressure only affects the upstream meniscus, which cannot induce a large magnitude variation of coating thickness. One reason for the frequency dependency of the responses can be understood by examining the conservation equation (Eq. 5). When Q is constant and there is a pressure disturbance or a gap oscillation, the cross-sectional-area of the bead changes, which leads, in turn, to variations in the final coating thickness. Because the equation is a first-order temporal differential equation, the variation of final thickness increases with an increase in the disturbance frequency. When Q is not fluctuating, the fluctuation energy is damped by the accumulation effect of the coating beads acting similar to a flow integrator and variations in final thickness decrease.

The dynamic analysis described above employed a linearized model that was implemented by a perturbation method that assumes a small fluctuation value, ε, (e.g., ε = 0.00001), around steady state conditions. In order to include non-linear characteristics in the computed dynamic behavior, we can compare the response amplitudes $h_{\infty steady}$ obtained using the linearized model with the amplitude $h_{\infty}(t)$ obtained from a non-linear model by defining a normalized response ratio $|h_{\infty}(t) - h_{\infty steady}| / h_{\infty}(t)$. The results of such a comparison are shown in Fig. 9.



a) Disturbance: Substrate velocity b) Disturbance: Flow rate

c) Disturbance: Pressure d) Disturbance: Gap Oscillation

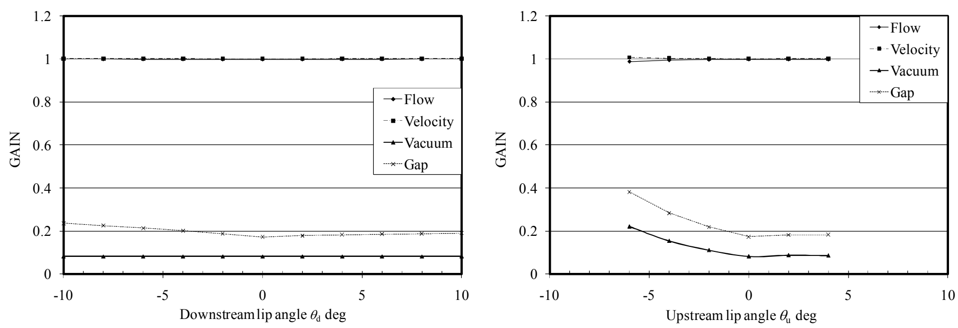
Fig. 9 Response ratio to linearized model.

These results indicate that gap oscillation produces a strong non-linear relationship between the magnitude of the disturbance and the response gain when compared to other disturbance sources. In addition, the results also reveal that non-linear characteristics are more noticeable above $\varepsilon = 0.01$.

Note that the linearization technique for the dynamic coating flow analysis that was used previously [(6-8)] can be assumed valid since we are considering a precision coating process.

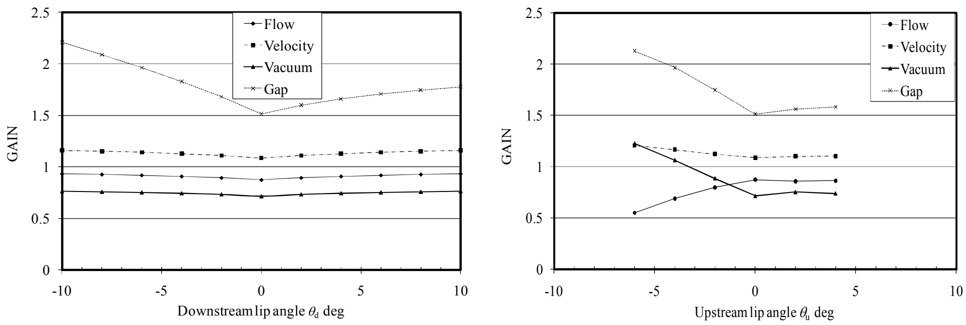
4. Passive control method

A modification of the lip angle can be considered as a passive control method since variations in this parameter correlate well with the dynamic response variation of coating thickness. Lip angles θ_d and θ_u were adjusted between −10º and 10º in an effort to improve the coating quality at steady state [(4) (7)]. The results obtained from these variations are shown in Figs. 10–12.



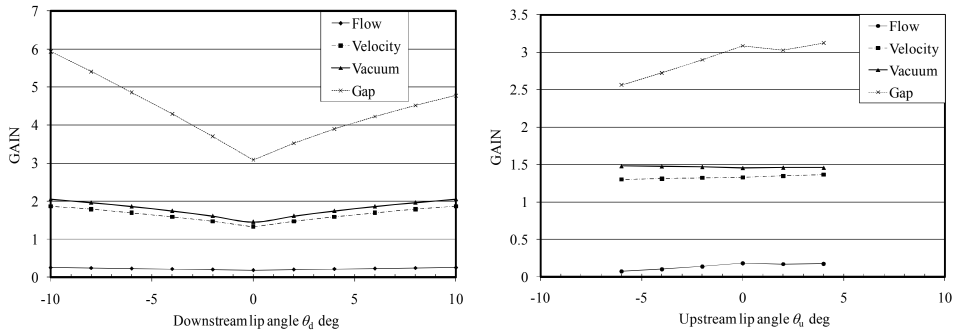
a) $\theta_u = 0.0^{\circ}$ b) $\theta_d = 0.0^{\circ}$

Fig. 10 Effects from the change of one lip angle at 0.5 Hz.



a) $\theta_u = 0.0°$ b) $\theta_d = 0.0°$

Fig. 11 Effects from the change of one lip angle at 5.0 Hz.



a) $\theta_u = 0.0°$ b) $\theta_d = 0.0°$

Fig. 12 Effects from the change of one lip angle at 50.0 Hz.

Conditions where it is impossible to form a coating film because of slipping out of the dynamic contact line beyond the up and down stream lip surface(2) were neglected in this analysis. In order to consider only effects of lip angle, in the case of a negative lip angle, we set the minimum gap to the values of $h_{0usteady}$, $h_{0dsteady}$ at $x = x_2$, x_3, respectively.

Note that a gap oscillation generates the largest gain among the responses. The reason for this result is related to the energy supplied to the coating beads. That is, a gap oscillation vibrates the whole bead (similar to a pumping action), which induces a large coating thickness variation.

Although Sator(4) concluded that the downstream lip angle could improve coating conditions at steady state, we find that in a dynamic situation a zero lip angle is the best condition with respect to sensitivity to external fluctuations. In contrast, for the upstream lip angle, as the frequency of oscillation increases, a negative lip angle becomes effective in reducing the sensitivity of final coating thickness to external fluctuations. These observations suggest that a lip angle adjustment can be used to reduce the non-uniformity of the final coating thickness by 20–30% in specific cases.

5. Active control method

Results for the frequency response of the final coating thickness when active control is applied during inputting parameter variations are presented in Fig. 13.

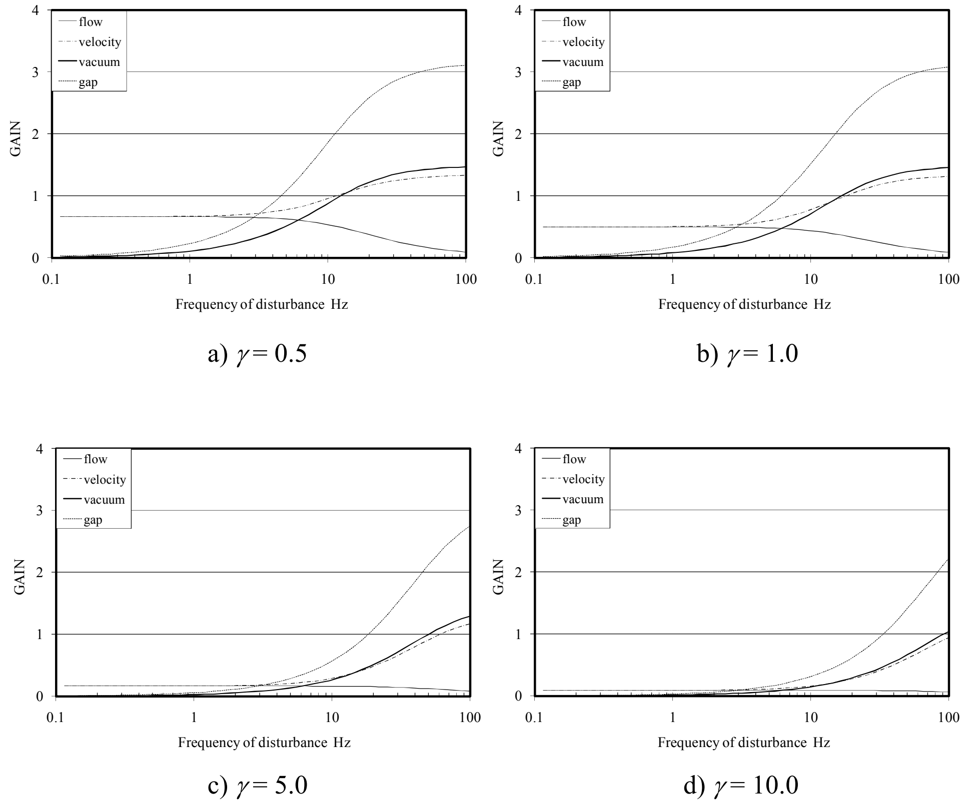


Fig. 13 Frequency response of gain.

The curves in this figure indicate that active control completely suppresses final coating thickness variations due to flow rate disturbances. In contrast, active control only suppresses fluctuations at less than a 10 Hz disturbance frequency for other disturbance sources. However, significant damping effect is evident compared to the results obtained for passive control.

6. Conclusions

In this study, we investigated the dynamic response of coating thickness variations to various disturbances for a slot coating process. Both a passive control method that relies on adjusting the processing lip angles and an active control using a feedback system are proposed. The conclusions of the study are summarized as follows.

(1) The responses to each disturbance change continuously and smoothly with the disturbance frequency. In particular, the variations in the gap dimension have the largest gain among all of the parameter variations that were considered.

(2) Gap oscillations result in a strong non-linear relationship between the magnitude of a disturbance and the response gain compared to other disturbance sources. Non-linear effects are most pronounced for perturbations exceeding $\varepsilon = 0.01$.

(3) An adjustment of the processing lip angle can be used to reduce the non-uniformity of the final coating thickness by 20–30% in specific cases.

(4) Using an active control system can significantly reduce variations of final coating thickness that result from disturbances when the disturbance frequency is less than 10 Hz.

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