Multishoe Caliper Controlled Roll with Static Bearing Technology

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Mitsubishi Heavy Industries, Ltd. (MHI) has developed a high-performance controlled multishoe crown roll to control the caliper cross profile. It has the following advantages: (1) Fine profile correction and stable oil film using small multiple shoes, (2) Reduced drive due to small multishoe footprint, (3) PC-based user-friendly control. Theoretical and experimental studies with a test stand proved the applicability of the Multishoe CC Roll for calendars.

1. Introduction

Paper industry has striven in recent years to respond to demand for improved paper quality in terms of the cross directional profile of basis weight, moisture content, and caliper. In particular, correction of the cross-directional profile of paper caliper is significantly controlled at the calender part of paper machine. Control of paper caliper in the conventional process is done by installing an external heating device, which is divided into several segments in the cross direction, on a hot roll to create cross-directional temperature differences, thus in order to vary the diameter of the hot roll along the axis. The conventional method, however, has disadvantages that the uneven temperature profile on the hot roll aimed at changing the diameter of the roll along the axis adversely affects the paper quality. A further disadvantage is that the temperature change on the surface of the roll takes a time to occur.

To address this point, the Mitsubishi Multishoe Caliper Controlled Roll assures a uniform temperature profile on the surface of the roll and quick response by locating hydraulically controlled shoes inside the roll facing the hot roll to vary the surface profile of the roll shell.

2. Characteristics of the multishoe caliper controlled roll

2.1 Structure of the multishoe caliper controlled roll

Fig. 1 shows the structure of the multishoe caliper controlled roll. A center shaft is fixed with shoes that are separately controlled by individual hydraulic systems. One of the upper and lower shoes shown in Fig. 1 comes in contact with the hot roll to form a nip to treat the web, while the other is called the "counter shoe." The hydraulic pressure of shoe on the nip side becomes relatively high when pressure is applied against the counter shoe. Accordingly, the counter shoe functions to create a sharp deformation of the shell having a slight recess from average shell face.

Fig. 2 presents an external view of a shoe. The shoe has four static pressure pockets. An oil film is formed between the shoe and the inner face of the shell, in accordance with hydrostatic bearing theory. Thus, the static pressure of the pockets balances the hydraulic pressure at the bottom of the piston. Consequently, if the shoe position tilts, the pocket pressure increases at the side where the clearance narrows between the shoe and the inner face of the shell, while the pocket pressure decreases at the side where the clearance widens. As a result, the shoe is subjected to a recovery moment. Through a sequential series of actions,
every pocket has a function to maintain the correct shoe position, or has the self-stand recovery control function.

The caliper control performance is evaluated by two parameters. One is the pitch of pressure peak positions, while the other is the response width for caliper control against pressure. The response width is about 400 mm. The peak position of nip pressure is arbitrarily moved in the cross direction of paper with respect to the pitch by adjusting the hydraulic pressure of plurality of shoes in the cross direction.

The multiple shoe caliper controlled roll system has advantages compared with the use of an external heating device. These include quick response and of freedom from an uneven temperature profile in the cross direction of the shell owing to the direct control of shell deformation through its ability to adjust the pressure of individual shoes using hydraulic pressure.

2.2 Control system

Fig. 3 illustrates the control system. The multishoe caliper controlled roll consists an on-line sensor, a PC for computation, a PLC cabinet, and a hydraulic unit as the major devices. The on-line sensor monitors the paper on on-line basis to determine basis weight (weight of paper per unit area), caliper (paper thickness), and other characteristics of the paper. The PC for computation processes caliper data acquired by the on-line sensor in order to determine the necessary hydraulic pressure for each shoe. The PLC transmits signals of the data coming from various machine controllers and from the PC for computation to servo-valve controllers. The hydraulic unit controls servo-valves via the servo-valve controller to establish an optimum level of the hydraulic pressure at each shoe.

3. Analysis of lubrication characteristics using the hydrostatic bearing theory

3.1 Outline of the analytical method

Fig. 4 shows an analytical model of a static shoe. In analysis of lubrication characteristics, the hydrostatic shoe under hybrid lubrication condition is assumed to be a tilting pad bearing that is similar to a hydrodynamic shoe. The analysis is conducted by assuming the position of seal-ring at lower part of the piston as being the virtual pivot point.

The flow of the oil film is assumed to consist a steady laminar flow, and the lubricant oil is assumed not to undergo any change in viscosity and further is assumed to be an incompressible fluid. Under these assumptions, the basic equation governing oil film pressure is given by a Reynolds equation:

\[
\nabla \left( \frac{h^3}{12\mu} \nabla p \right) = \frac{1}{2} \nabla (hU) + \frac{\partial h}{\partial t}
\]

(1)

Where, \( \partial \) is a differential operator. Discretization of eq.(1) by the Galerkin method finally provides a set of linear simultaneous equations that are expressed by respective pair of: known boundary pressure and unknown boundary flow rate; known supply pressure and unknown pot flow rate; unknown area pressure and known area flow rate. The linear simultaneous equations determine the oil film pressure inside the area.

3.2 Flowchart

Fig. 5 shows the flowchart of calculation performed
as part of the analysis. Based on the condition of force equilibrium and of moment equilibrium relating to the position of static pressure shoe, the eccentricity and the shoe tilting angle are derived by repeated calculation. The vertical load is determined by domain integration of the pressure on oil film in the loading direction. The value of vertical load is equal to the value derived by subtracting the self weight of the piston head from the hydraulic force applied to the bottom face of the piston. The tilt angle of the static shoe is determined from the balance between the moment induced by the oil film pressure around the seal ring position at lower part of the shoe piston, the moment induced by viscous frictional force, and the moment resisting to rotation of the seal ring. The resistance to rotation is simulated by a linear spring. The convergence in repeated calculation is assumed to be established at a point where the load error and the residual moment enter respective allowable ranges.

4. Control software

4.1 Outline of the control software

The multishoe caliper controlled roll provides an desired caliper profile through optimum values of individual control parameters. A major feature of the control system is the optimization of not only the shoe hydraulics pressure profile but also the external (strike-through: pressure) force of the multishoe CC roll for controlling the caliper profile that is measured by on-line sensor located at downstream. That is, the conventional system cannot correct the tilt angle of the caliper profile in the cross direction of paper solely by the shoe hydraulics profile. However, the optimization of the external (strike-through: pressure) force at both ends of the multishoe CC roll using the observed caliper profile signals allows providing significantly high level of controllability.

4.2 Optimum nip profile calculation

The optimum nip profile is determined by the successive quadratic programming method \(^{(2)}\). This is most effective and stable for solving nonlinear programming problems.

Each of the influence coefficients of the roll deformation is calculated using the finite element method, and the superposition of the values thus obtained is given to derive the total deformation, using the equation:

\[
\begin{bmatrix} A_f \end{bmatrix} \{ F \} + \begin{bmatrix} A_p \end{bmatrix} \{ p \} + \{ U_w \} + \{ U_o \} = 0
\]  

(2)

where,

\( \{ F \} \): nip load vector
\( \{ p \} \): shoe hydraulic pressure vector
\( \{ U_w \} \): self-weight deformation vector
\( \{ U_o \} \): the rigid body displacement vector
\( [A_f], [A_p] \): influence coefficient matrix of nip load and shoe hydraulic pressure, respectively, derived from the finite element method.

Fig. 5 Flowchart of analysis

Calculation flowchart is shown.

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smoothing treatment induces a time lag to the system, particular care is necessary when carrying out such control. As an example of the controll, Fig. 7 shows a simulated result on the stability of system under varied gain condition. The horizontal axis is the data numbers in repetition of control. The vertical axis is the output responding to (0 \( \Delta \) 1) step input. If the control parameters are inadequate [Fig. 7(a)], the system may diverge. After the optimization of gains [Fig. 7(b)], however, the system converges to a stable condition within a very short period of time. The improvement suggests that the system stability strongly depends on the compression rigidity of paper, the gain, and the smoothing factor of the on-line sensor.

5. Practical applications

5.1 Outline of the test stand

Fig. 8 shows an overall view of the test stand, which has a face length of 2 000 mm. The effectiveness of the shoe hydraulic pressure on the shell deformation and the nip pressure profile were verified. Verifications were also made of the adequacy of oil film thickness, the heat generation at shoe, the amount of oil needed, and the force under high speed condition and high nip pressure condition.

5.2 Measurement of oil film thickness

Fig. 9 shows examples of measured oil film thickness at the leading edge and trailing edge of a shoe, with parameters of speed and hydraulic pressure (nip pressure). The oil film at the leading edge becomes thinner as the hydraulic pressure of the shoe increases. The oil film at trailing edge, however, undergoes no change in the thickness above a certain level of the nip pressure. Both the leading edge and the trailing edge show a tendency towards a thinning of the oil film as speed increases. Analytical result of oil film thickness at a nip pressure of 350 kN/m shows good agreement with the observed values.

The thickness of oil film at the leading edge is greater than that at trailing edge because the oil film at leading edge is subjected to a dynamic effect of rimming oil that develops on the inner face of the shell, adding to the oil film thickness determined by the hydrostatic bearing theory. As speed increases, the amount of heat generated in the shoe increases which in turn leads to an increase in oil temperature. This, in turn, reduces the viscosity of the oil, leading ultimately to a reduction in oil film thickness.

In any case, it is understood that the oil film secures sufficient thickness not lower than 80 \( \mu \)m under high speed and high nip pressure conditions.

5.3 Verification of performance on commercial facilities

Fig. 10 shows a caliper profile of newspaper stock before and after the application of automatic control.
Satisfactory oil film formation is attained even under high speed and high nip pressure.

The data are from a soft nip calender stack acquired by applying the multishoe caliper control to a rubber-covered roll. The deviation in caliper of 2 μm seen before application of the automatic control improves from 1.45 μm to 0.3 μm after application of the automatic control.

Fig. 11 shows a converging trend of 2 μm from a liner board. The multishoe caliper controlled roll is used to a hard nip calendar. The horizontal axis is the number of scans of on-line sensor. The figure shows that the convergence is attained within about twenty scans, although the number depends on the smoothing factor and the gain adjustment. This twenty or so scans represents a time scale of about 10 minutes.

The multishoe caliper control system developed here shows at least an shows equivalent or higher performance, and gives equal level of convergence time compared to a conventional system in which the hot roll is equipped with external heating devices at a small pitch, and the temperature of the hot roll is varied in the paper cross direction, thus varying the shell diameter to control the nip pressure profile.

The multishoe caliper control system has already been used in both hard nip and soft nip calenders, and shows satisfactory performance without raising problems, even when no conventional external heating device is accompanied.

6. Conclusion

MHI has developed a multishoe caliper controlled roll that forms an oil film having thicknesses of 80 μm or more even under high speed and high nip pressure conditions. This was done by applying the hydrostatic bearing technology to the shoe of a multishoe caliper controlled roll and to the oil film formation on the inner face of the shell.

The roll has been practically applied to both soft nip and hard nip calenders. The applications demonstrated that a system controlled exclusively by developed control software provides high level of performance with respect to caliper control in the paper cross direction equal or superior to the performance of conventional external heating device system.

The technology has already been introduced to the central roll of a press part.

References