# 温度差マランゴニ対流における振動流の制御

塩見淳一郎（東大工）

# Control of oscillatory thermocapillary convection

J. Shiomi
Dept. of Mech. Eng., The University of Tokyo

**ABSTRACT**

Possibility to stabilize the oscillatory thermocapillary convection is demonstrated using a proportional feedback control. The feedback control is realized by locally modifying the surface temperature by using the local temperature measured at different locations fed back through a simple control law. The control method was applied in simplified geometries such as the annular configuration and the half-zone for high Prandtl number liquids by means of experiments, numerical simulations, and formulation of a simple model equation system. Successful suppression of the oscillation was obtained especially in the weakly nonlinear regime where the control completely suppresses the oscillations. With a right choice of actuators, even with the local control, it was shown that it is possible to modify the linear and weakly-nonlinear properties of the three-dimensional flow system with linear and weakly nonlinear control.

Key Words:Thermocapillary convection, feedback control, annular configuration, half-zone

## 1. Introduction

In a crystal growth method called floating-zone technique, the time dependent state of the convection is blamed for detrimental striations in the chemical composition of the finished crystal. The industrial need has motivated a number of theoretical, experimental and numerical studies to clarify the onset mechanism of the instability and the structure of the resulting oscillation. Many studies on the convective flow were carried out in various simplified model problems where generic convection similar to that of the flow in the floating-zone melt is realized. Recently, further development in the field of study has contributed on understanding important characteristics of supercritical behavior of the oscillatory flows. Most of the ground-based experiments are carried out in geometries with scales of several millimeters in order to have thermocapillary forces dominant over buoyancy forces. With the demand for experiments in micro-gravity conditions, this problem has been caught in the limelight as a candidate for space-based projects.

Based on the knowledge obtained from these extensive researches, the ultimate goal of this field of study would be to stabilize the instability to improve the quality of semiconductors. In the industries, the control problem of the crystal growth process has been around for years. For example, in the floating-zone technique with radio frequency heating, because of the asymmetric thermal field of the radio frequency coil, the growing crystal is subjected to a rotation to obtain a symmetric single crystal. The rotation is also often applied to the system to maintain the cylindrical shape of the melted zone. Since the oscillatory state of the convection was found to be the prior cause of the detrimental striation, the microscopic inhomogeneity of dopant and impurity distribution, in the finished product, there has been an increasing interest in suppression of the oscillation. Most of the works done thus far aim to reduce or alter the steady state, in other word, to decrease the effective Marangoni number, and thus to attenuate the fluctuation. For example, a well known method is to apply a magnetic field to an electronically conductive melt. Others are counteracting the surface flow by generating a stream by end-wall vibration or directing a gas jet parallel to the surface. A drawback of these methods is that the damping of the base convection enhances the macro-segregation of the chemical compositions due to the weakening of the global mixing.

An alternative way to attenuate the oscillation would be to act only on the thermocapillary instability. If one could stabilize the instability without influencing the base flow appreciably, it might be beneficial in terms of both microscopic and macroscopic homogeneity of the final single crystal. When it comes to this type of method to control the oscillatory thermocapillary convection, there has been only a limited number of works reported. The idea originates in that if the surface temperature distribution plays a key role in the instability mechanism, the property of the oscillation should be able to be altered by modification of the temperature. The objective is to suppress only the fluctuation without altering the base flow by modifying the stability characteristics. [1)] Knowing the structure of the oscillation, a few sensors and actuators are strategically positioned to realize the feedback control. With the help of feedback control, an attempt can be made to minimize the cost of control.

The attraction of the current study in the academic point of view should also be noted. This problem contains rich fundamental physics with nonlinear dynamics which can lead the flow to chaotic states. At the same time, the problem has a few advantages to be subjected for active flow control. Firstly, since only a limited number of spatial modes play a role in the instability, the flow can be possibly controlled with a small number of controllers. Secondly, the flow can be altered by modifying the temperature which is usually experimentally accessible. Finally, being a rather slow phenomenon compared to other popular targets of flow control, for instance flows on airfoils, the instability could be a suitable target for a control scheme which involves real-time computation of system equations.

## 2. Global suppression of the oscillation

The local feedback control was experimentally applied in an annular configuration and a half-zone model [2, 3, 4]. The details of the control method and the experimental realization are described in the referred articles. In both geometries, significant attenuation of the oscillation was achieved in a range of supercritical Ma (Marangoni number) and the global stabilization of the oscillation was achieved. Especially, in the half-zone experiment, the control was performed together with flow visualization and the transitional process of global flow field stabilization was captured [4]. On applying the control, the mode-2 standing wave with the visualized elliptical particle-free area gradually reaches a steady axisymmetric state.

In both geometries, the linear control performs best in the weakly nonlinear regime, where the amplitude of the uncontrolled oscillation is predictable by the weakly nonlinear theory. In this regime, the oscillation could be suppressed to the background noise level as shown in Fig.1. Having the saturated oscillatory state as the initial condition, with a proper choice of the control gain, the system with the control loop exhibits an exponential decay which clearly indicates that the linear stability of the target mode was modified without influencing the stability of other modes. The heater output plotted bellow shows that, though the output initially overshoots, the power needed to maintain the stabilization is less than 1 mW, which is in the order of a hundredth of the driving power of the base convection. This state could be maintained for infinite time and was quantitatively repeatable. On turning off the control, the fluctuation grows exponentially until it reaches the nonlinear saturation. Similar results were obtained from the

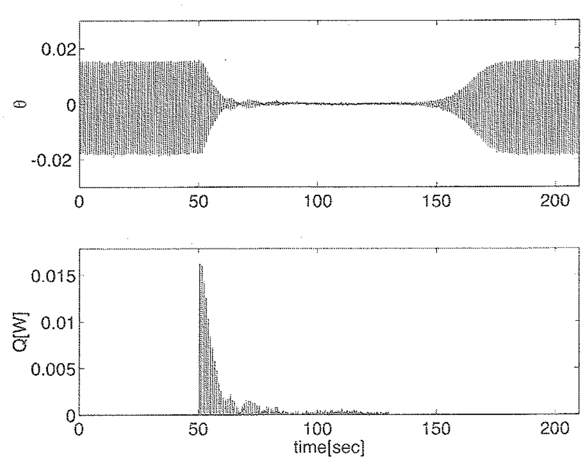



Fig. 1. The typical picture of successful control of oscillation with weakly nonlinearity. Top: Time history of the dimensionless temperature. Bottom: Simultaneously measured heater output power.

numerical simulation of annular flows for the values of ε = $(Ma-Ma_{cr})/Ma_{cr}$ very close to the critical one [7].

## 3. Limitations of control

Although successful suppression of the oscillation was demonstrated for small ε, the control also exhibited limitations as nonlinearity becomes stronger. At these values of ε, maximum suppression is reduced, where the shortcoming is accompanied with a distortion of the temporal signals. There seems to be different scenarios causing the limitation, depending on the geometry and configuration of the controllers.

### 3.1. Destabilization of linear modes

It was experimentally observed that, beyond the limitation of control, the time signal exhibits clear modulation which suggests the appearance of other spatial modes with close-by critical frequency as the original one. In the half-zone experiment [4], the flow visualization captured a clear process of waves with new azimuthal wavenumber (mode), taking the value of 1 for this case, being destabilized. As increasing the linear control gain, the new mode is amplified and eventually dominates the flow as shown in Fig.2 where excited mode-1 standing wave is visualized by the number of symmetries of the particle-free zone in core region of the liquid bridge [4].

The results from the annular configuration experiments [3, 6] show that the control can amplify both or either of the frequency peaks in the close-by frequency to the fundamental one as in the half-zone experiment, and the first harmonic frequency. For the former case, temperature measurements at multiple locations suggested that the newly appearing oscillation was mode-2. This was confirmed by carrying out a numerical simulation for the annular geometry [7], where the results show transition from mode-3 to mode-2 dominated flow as increasing the control gain. For the latter case, the toy model shows that an attempt to target the fundamental mode with current local proportional control can result in the destabilization of the first harmonic mode [3]. In the numerical simulation, this type of destabilization was not evident for the limited range of ε.

The controlled oscillation always appeared to be a standing wave with nodes nearby sensors and heaters. Therefore, on turning off the control, when the original uncontrolled oscillation has a traveling nature, the symmetry of the problem gives equal possibilities for

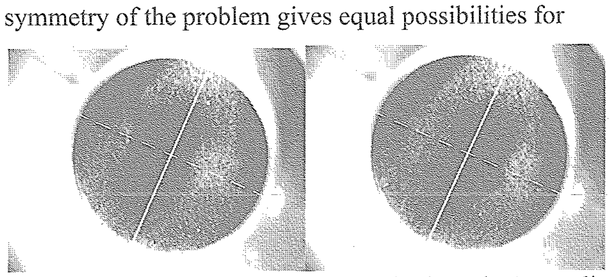


Fig. 2. Flow visualization of excited mode-1 standing wave in a half-zone.

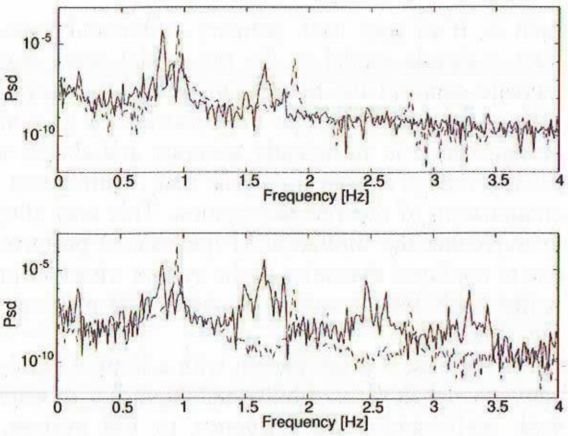



Fig. 3. Broadening of the spectra of the oscillation subjected to the linear control. The temporal spectra of the oscillation without (dashed lines) and with (solid lines) control at two different azimuthal positions. Heater length, Lh=0.5 mm. ε=0.24.

both clockwise and counterclockwise wave to take over. This could be seen in switch of the direction of rotation before and after applying the control.

3.2. Nonlinear limits

The control can certainly enhance nonlinear features of the oscillation. Experiments have shown that an excess of control gain and Ma can result in the broadening of the temporal spectra which would eventually make the state to chaotic. Since the actuation employed in the current control method has definite length, the actuator (or heater) influences a broad range of modes whose width depends on the geometry of the actuator. In spite of our original hope for the generated higher modes to diffuse away, they have a strong influence for high control gain and Ma. As shown in Fig. 3, temporal spectra from the experiment in the annular configuration depict the broadening of the peak. Further increase of the control gain forces the system to a chaotic state. The numerical simulation supports these observation where broadening in the spatio-temporal spectra is observed as shown in Fig. 4.

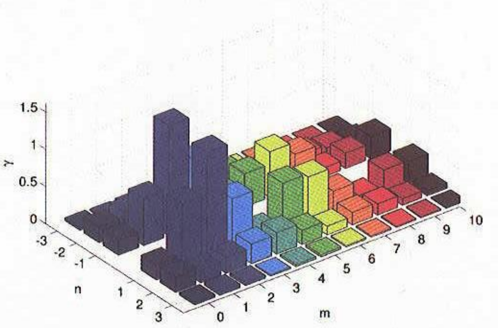
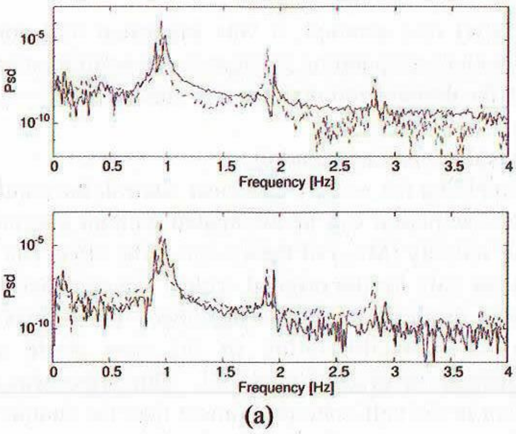
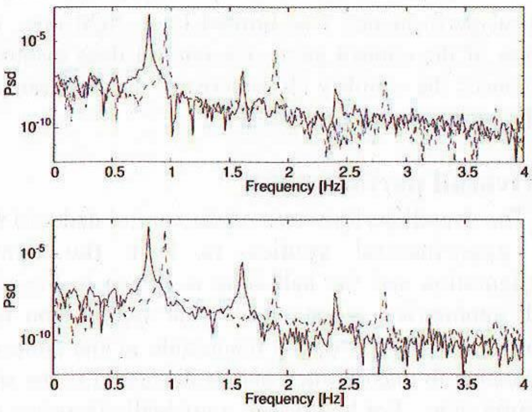



Fig. 4 Broadening of the spectra of the oscillation subjected to the linear control. The spatio-temporal decomposition of the oscillation in the numerical simulation. γ is the suppression ratio. ε = 0.07.




(a)




(b)

Fig. 5. The power spectrum density for the nondimensional temperature signal for both sensors. Dashed lines: without control. Solid lines: subjected to the linear control with, Gain=-0.155W (a) and Gain=-0.503W (b). Heater length, Lh = 1.5 mm. ε=0.24.

## 4. Remedies

4.1 Actuator size

The broadening of the spatio-temporal spectra caused by the local heating can be reduced by increasing the azimuthal length of the actuator. The idea is to attenuate the generation of the broad wavenumber waves in order to reduce the enhancement of nonlinear events. The modification resulted in a significant change in the controlled oscillation where original broad spectra are reduced to clear peaks of two fundamental modes. The change can be observed in the difference between Fig. 3 and Fig. 5. The limitation of the control is now due to clear destabilization of a linear mode which can be delayed with the following methods. This feature of the controlled oscillation for difference actuator length was also observed in the numerical simulation [7].

4.2 Configuration of the controllers

In case that the limitation of the control is due to the destabilization of a new linear mode, once we have an idea of which mode is amplified, it is possible to delay the destabilization by changing the configuration of the sensors and the actuators. The original series of experiment were carried out with negative control gain. Taking the two close-by fundamental modes (original and new) into account, it was suggested that positive gain with corresponding changes in the configuration can delay the destabilization of the new modes [4, 6, 7].

4.3 Weakly nonlinear control

Applying the weakly nonlinear control, the amplitude of the oscillation can be attenuated without altering the linear stability ($Ma_{cr}$) of the system. The effect can been seen not only for the original critical wavenumber waves but also for the newly appearing mode. This allows us to delay the destabilization of the new mode while attenuating the original mode [4,6]. This effect was more evident in the half-zone experiment than the annular one. In the annular configuration, the improvement of the control performance was limited to a slight one. With excess of the control gains, the control does eventually influences the stability characteristics and the transition to the new mode takes place.

## 5. Overall performance

The overall performance of the control deduced from the experimental studies in both the annular configuration and the half-zone is shown in Fig. 6. In both geometries, when $\varepsilon < 1$, the suppression ratio, defined as the ratio of the magnitude of the controlled fluctuation to uncontrolled one, is decreased to the signal to noise ratio. For both cases, $\gamma$ gradually increases with $\varepsilon$ with the steepest increment around $\varepsilon \sim 0.45$. In overall, a significant attenuation was observed in a wide range of $\varepsilon$ ($< 1$). Comparing the two cases, control shows better performance for the half-zone than for annular geometry. One of the reasons could be due to the higher signal to noise ratio in the half-zone owning to more volatile oscillation.

## 6. Conclusions

In the series of studies presented in this report, we proposed a proportional control method where the controllers are strategically placed using the knowledge of the modal flow structures. It was shown that the method can be used to attenuate the oscillation in a range of supercritical Ma. Especially in the weakly nonlinear regime, the control completely suppresses the oscillations. With the right choice of the actuators, even with a local control, it is shown that it is possible to modify the linear and weakly-nonlinear property of the three-dimensional flow system with linear and weakly nonlinear control.

The actuation of the system using the local boundary heating can also destabilize different mode structures, which increases the dimension of the problem. However, it was shown that, having an idea of the newly appearing modes and the fact they are likely to be standing waves, the destabilization can be delayed by optimizing the configuration of sensors and heaters.

The validity of the qualitative analyses presented in this work suggests that the experimental system is clean and simple so that, despite the complexity of three-dimensional system with local actuations, the control problem could be reduced to a lower dimensional model, such as, if all goes well, ordinary differential equations. Such a simple model as the toy model study [5] could recreate many of the features of the controlled system. This encourages the hope for construction of a model system which is sufficiently accurate and simple to be used to realize a control scheme that requires real time computation of the system equation. This may allow us to overcome the limitation of the control performance due to nonlinear dynamics of the system whose influence is inevitable for the current linear control method when Ma is high.

Being a slow phenomenon with a limited number of active modes in the instability and the means of actuation with well-understood influence to the system, the problem may be one of the most suitable problems for experimental realization of the recent development in the art of flow control theories. This problem can be the bridge between two communities of experimental and theoretical control as the problem of thermal convection loop, but with a strong connection with the practical application.

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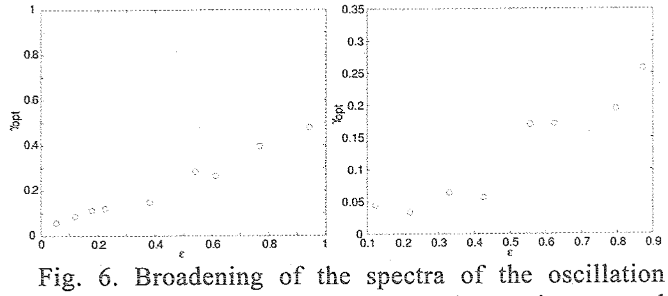


Fig. 6. Broadening of the spectra of the oscillation subjected to the linear control. The spatio-temporal decomposition of the oscillation in the numerical simulation. $\gamma$ is the suppression ratio. $\varepsilon = 0.07$.