Case History	Self-Excited Vibration of Growing Equipment of Wire-Lifting for Silicon Single Crystal	Others
Self-excited Vibration		

Object Machine

Growing equipment of wire-lifting for silicon single crystal (Fig.1)

Observed Phenomena

The wire rope, the bottom end of which is fitted with a seed crystal, is lifted upward at a maximum speed of 6 mm/min while rotating at a constant angular velocity of 25 rpm. A crucible filled with silicon melt located at the bottom rotates in the direction opposite to the wire rope at an angular velocity of 5 rpm and was lifted at a maximum speed of 1 mm/min, so as not to allow the seed crystal to be separated from the melt surface. During the process of producing silicon single crystal in this equipment, a conical vibration of pendulum mode occurred, whose amplitude gradually grew with time.

Cause Presumed

In several hours after starting the lifting operation, the vibration became significant and maintained, then increasing the amplitude quite slowly, until completion of lifting. As the vibration maintained with growing amplitude without any external excitation, it was estimated to be a self-excited vibration.
The estimated causes were:

(1) Parametric vibration due to time changes in the rope length and crystal weight
(2) Friction between the pulley and the wire rope in addition to internal friction of wire rope strands
(3) Hydraulic force between the melt in the crucible and the single crystal

Analysis and Data Processing

As an experiment using the actual machine was difficult, an experimental apparatus representing a simplified system shown in Fig.2 was used. Since the lifting speed of the rope is too slow, we set no lifting motion and only rotation motion of the rope in this apparatus. Our analysis done beforehand has confirmed that the above (1) of the parametric excited vibration was not the case.
Wire rope used: 9 kinds of wires as indicated in Table 1, being the material of tungsten and SUS 304.
An experiment was conducted using five types of the mass ranging from 3.366 kg up to 16.235 kg that were attached to the bottom end of wire ropes which is 1.935 m and 2.375 m in length, respectively. As an example, we show a case study in Fig. 3, using the wire rope of No.1 of Table 1 (2.375 m in length) connected with the bottom mass of 3.366 kg (natural frequency = 2.01 rad/s = 19.16 rpm).
According to several case studies where the rope rotational speed and the direction of whirl of the initial disturbance were changed, the cause of the vibration occurrence was estimated:

Rotational speed:
10 rpm {initial disturbance : forward whirl   damped
                                         : backward whirl   damped
30 rpm {   : forward whirl   growing as self-excited vibration
                                         : backward whirl   damped, but after forward growing as self-excited vibration

★ If self-excited vibration due to internal damping is anticipated, it is important to draw Lissajous curves to determine the direction of whirl, forward or backward.

Fig. 4 gives the test result on instability examined by changing the rotational speed of the rope. For representing the developing magnitude of the instability, an index "*m*" (negative damping coefficient) was measured, that is related to an approximation equation $r = r_o \cdot \exp(mt)$, where "r" is the amplitude of whirl of the rope bottom.
When the rotational speed was close to the system's natural frequency (19.16 rpm), the degree of instability could not be determined because of resonance, but unstable amplitude is seen all for the onset speed ω = 25 rpm or higher.
Fig. 5 shows the negative damping coefficient when changing the bottom mass.
According to the above observations of Fig. 4 and 5, the conclusion is obtained as follows:

－The vibration was a self-excited vibration that maintained when the rope was rotating at a speed exceeding the limit of the onset of the rotational speed.
－Only the forward whirl would grow in self-excited manner, irrespective of how initial

disturbances were applied.
These were in agreement with the behaviors of self-excited vibration of the rotating shaft that occurs due to internal friction.
Conclusion: the wire rope self-excited vibration occurred due to internal friction.

Countermeasures and Results

The system's external damping was increased. In addition, a sleeve was attached on the winding section to increase external friction, but abrasion powder is developed. Materials having small internal friction were recommended, but only the material available is tungsten (large internal friction) at the present.
Thus, the viscous damping force of the silicon melt system in the crucible was enhanced to improve instability. But, the unknown influence of hydraulic force while the crucible is rotating should be more studied.

Lesson Learned

Equipment having a rotating wire rope may suffer from self-excited vibration caused by internal friction. Long term operation requires attention to be paid even for a slight instability of the system.

References

Tanabe. *Machine Design*, 28-13 (1984), 47
Ohta; Mizutani; and Fujita. *Transactions of the JSME*, 54-507 (1988), 2544

Keyword

Single crystal growing equipment, wire rope, self-excited vibration, internal friction

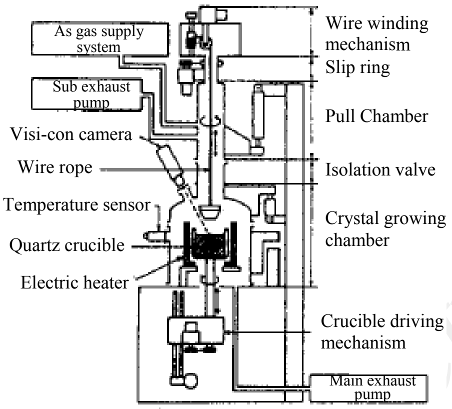


Fig.1: Wire-winding type growing equipment for silicon single crystal

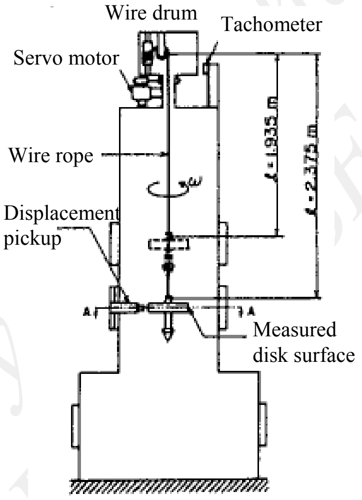
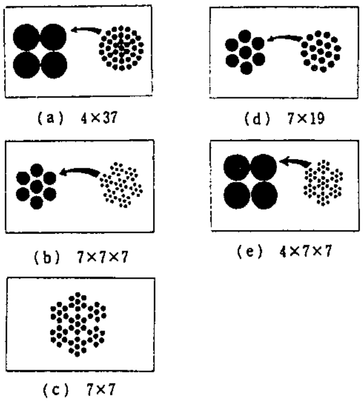


Fig.2: Schematic diagram of experimental apparatus

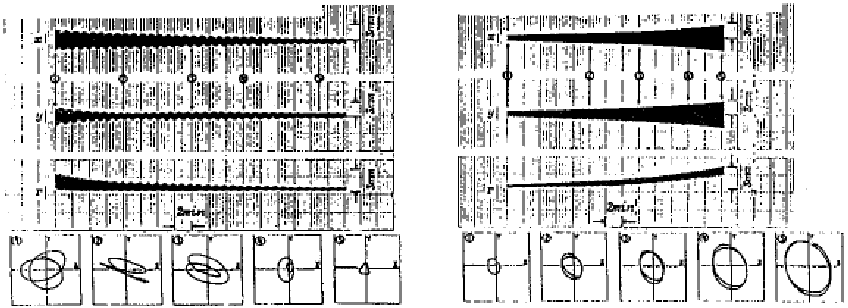
Table 1: Wire rope used for experiment

No.	Construction	Material	Diameter of rope	Diameter of element wire	Tensile strength
1	4x37	W	1.8mm	0.11mm	2793N
2	7x7x7	W	1.89	0.07	2548
3	7x7	W	2.0	0.23	2920
4	7x19	W	1.8	0.12	2430
5	7x19	W	1.5	0.1	2127
6	4x37	SUS304	1.8	0.11	2234
7	4x7x7	SUS304	1.25	0.06	1568
8	7x7	SUS304	2.0	0.23	3234
9	7x7	SUS304	1.2	0.13	1127



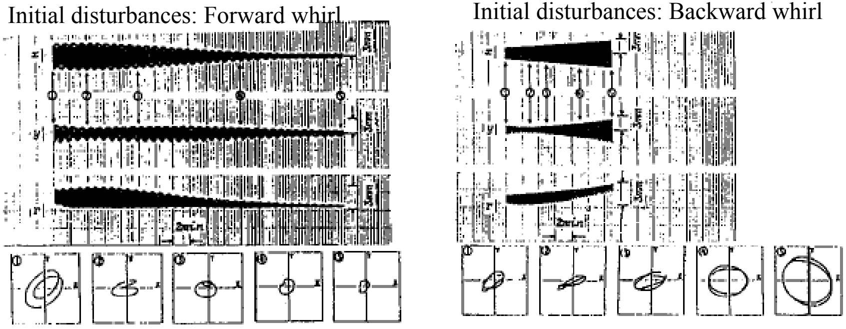
Initial disturbances: Backward whirl

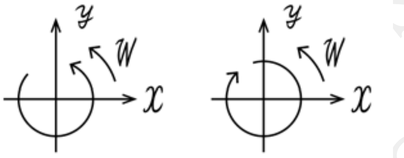
Initial disturbances: Forward whirl



Initial disturbances: Forward whirl

Initial disturbances: Backward whirl





Forward whirl Backward whirl

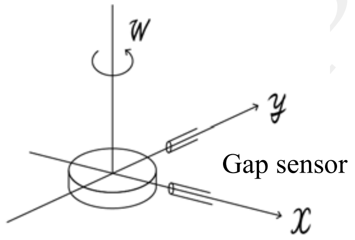


Fig.3: Vibration waveforms for various initial disturbances

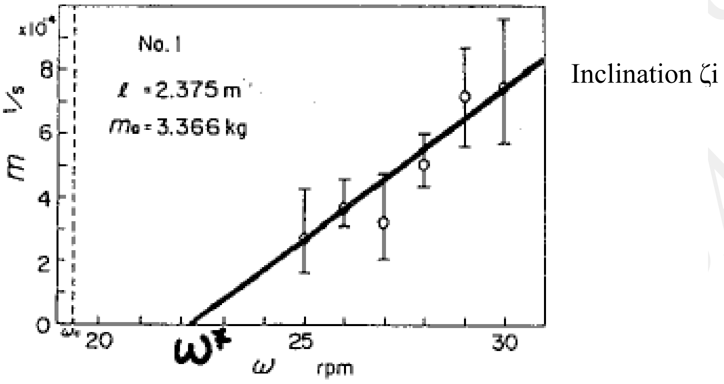


Fig.4: Effect of rotational speed on instability

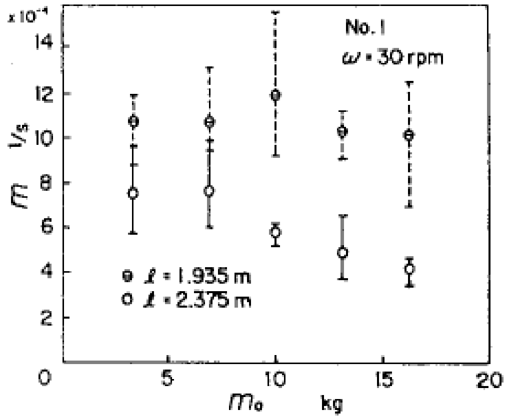


Fig.5: Effect of bottom mass on instability

Let internal and external damping ratios be ζi, ζo, rotational speed ω, and natural circular frequency ω_n,

$$\begin{aligned} m &= \zeta_i(\omega-\omega_n) - \zeta_o\cdot\omega_n \\ &= \zeta_i\cdot\omega - (\zeta_i+\zeta_o)\,\omega_n \end{aligned}$$

Let the onset speed ω for m = 0 to be ω*,

$$\omega^* = (1+\zeta_o/\ \zeta_i)\,\omega_n$$

so that, the instability limit is determined by the ratio of internal damping and external damping;
where *m* = real part of the system's eigenvalue.

★ Due to the presence of internal damping, the vibration diverges only for the rotational speed larger than the natural frequency (self-excited vibration occurs), resulting in only the forward whirl.