Molten Metal Flow Measurement Using Cylinder and Hall Element

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1. Introduction

Precise molten steel flow measurements are required for further development of the current refining processes and continuous casting molds. Much effort has been devoted to developing velocimeters for measuring molten metal flows.1−3) As a result, many types of velocimeters such as a hot film anemometer,4) a Vives probe,5) an ultrasonic Doppler velocimeter,6) a melting probe,7) a reaction probe,8) and a Karman vortex prove9)−11) have been developed and widely used in a variety of engineering fields. Unfortunately, the former three velocimeters are not applicable to molten steel flow velocity measurements because the candidate materials for these velocimeters are not available around 1600°C. The melting probe is sensitive to the change in the molten metal temperature, and the reaction probe is influenced by the temporal change in the meniscus height.9) Accordingly, we focused on the Karman vortex probe in this study. This probe relies on the linear relationship between the shedding frequency of the Karman's vortex streets formed behind a circular cylinder and the velocity of flow approaching the cylinder.

In order to determine the shedding frequency of the Karman's vortex streets, we measure the oscillation frequency of the cylinder as the cylinder oscillates in phase with the shedding of the Karman's vortex streets. The shedding frequency therefore is equal to the oscillation frequency of a circular cylinder. Such a regular vortex shedding pattern is observed when two conditions are satisfied. Firstly, the Reynolds number, Re, has to satisfy the following condition.

\[ Re = \frac{vD}{\nu} = 300 \sim 300000 \] ........................(1)

where \( v \) is the velocity of flow approaching the cylinder, \( D \) is the diameter of the cylinder and \( \nu \) is the kinematic viscosity of liquid. Secondly, the ratio of the immersion depth \( H_i \) to the cylinder diameter \( D \) should be greater than approximately 6.

\[ H_i/D > 6 \] ........................(2)

When this condition is satisfied, the shedding frequency of the Karman's vortex streets is hardly influenced by the immersion depth \( H_i \), even if \( H_i \) changes with respect to time.

The shedding frequency \( f \) can be correlated in terms of the Strouhal number defined by

\[ St = fD/v \] ........................(3)

The Strouhal number, St, remains almost constant in the aforementioned Reynolds number range, and, hence, \( v \) can be determined by measuring the shedding frequency, \( f \), as the cylinder diameter \( D \) is given a priori. The cylinder itself oscillates in phase with the shedding of the Karman's vortex streets. The shedding frequency therefore is equal to the oscillation frequency of the cylinder.

The advantages of the present Karman vortex probe are as follows:

1) This probe is not affected by the physical properties of molten metals,
2) not affected by the change in the temperature of the molten metals,
3) insensitive to the change in the meniscus height,
4) and, even if electromagnetic braking is applied, this probe can be used as long as the shedding of the Karman's vortex streets takes place.

3. Experiment

3.1. Profile of Karman Vortex Probe

Figure 2 shows a schematic of a Karman vortex probe reported in the previous paper.1−3) As mentioned earlier, the oscillation frequency of a circular cylinder was detected with strain gauges. In this study a Hall element is used to detect the oscillation frequency in place of the strain gauges for the enhancement of the accuracy of the frequency measurement. The principle of shedding frequency measurements using the Hall element can be explained in the following manner.7) When electrons pass in a semiconductor placed in a magnetic field, the electrons undergo Lorenz force's influence and the loci of the electrons are bent. As a result, a potential difference appears inside the semiconductor.

\[ \text{Fig. 1. Schematic of Karman's vortex streets.} \]
The potential difference is proportional to the magnetic flux density between two output terminals (Hall effect). The Hall element works based on this effect. If the Hall element oscillates in the magnetic field, the output voltage of the Hall element also oscillates in phase with the oscillation of the Hall element. Therefore, we can detect the shedding frequency of Karman's vortex streets using the Hall element and a fast Fourier analyzer.

The detail of the detection unit equipped with the Hall element is shown in Fig. 3 together with the strain gauge unit. It should be noted that the test cylinder and its supporting rod are the same for the two detection units. The Hall element made of InSb was connected to an amplifier, and the output signal of the amplifier was processed with the same frequency analyzer.

### 3.2. Experimental Apparatus and Procedure

The Karman vortex probe was immersed in a molten Wood's metal bath or in a molten pig iron bath, as shown in Fig. 2. Wood's metal of a melting point of 47°C was melted in a cylindrical vessel having an inner diameter of 360 mm and a height of 220 mm. The bath depth was 150 mm and the temperature was 80°C. Pig iron was melted in a cylindrical crucible with an inner diameter of 170 mm and a height of 300 mm at a temperature of 1400°C using an induction furnace. The bath depth was 220 mm. The densities of the Wood's metal and the pig iron were 9.5 g/cm³ and 7 g/cm³, respectively. The test cylinder is made of sialon, being a kind of ceramics. It has high resistivity against thermal shock and its density is 3.25 g/cm³. The outer diameter of the cylinder is 5.6 mm.

For the calibration of the Karman vortex probe the test cylinder was rotated at a predetermined velocity $v$ in a molten metal bath. Figure 4 shows an example of the output signal of the amplifier and its power spectrum for the molten pig iron bath, where $k$ is a constant. A similar result was obtained when the strain gauge unit was used to detect the oscillation frequency of the test cylinder. The shedding frequency, $f$, was multiplied by the diameter of the test cylinder, $D$, and then compared with the predetermined rotation velocity $v$.

### 4. Experimental Results and Discussion

Figure 5 shows the calibration results for the Wood's metal bath. Agreement between the results obtained with the strain gauge unit and those obtained with the Hall element unit is very good. Although the strain gauge unit cannot detect an oscillation frequency lower than approximately 12 Hz, the Hall element unit can detect the oscillation frequency. The same conclusion was derived for the molten
pig iron measurements, as shown in Fig. 6.

The strain gauges are attached to the notch of the supporting rod. The notch has a rectangular cross section and its surface area is limited. Accordingly, the size of the strain gauge unit is restricted, and its sensitivity is also restricted. When the shedding frequency of Karman’s vortex streets is low, the noises originating from the motor, wave motions on the bath surface and so on distort the output signal of the strain meter. As a result, the accuracy of the sensor using the strain gauges becomes low as the shedding frequency becomes low. Concerning the Hall element unit, however, only a magnet is attached to the supporting rod and the Hall element is attached separately from the supporting rod. It is therefore easy to enhance the sensitivity of the Hall element. This is the main reason why the Hall element unit can detect lower shedding frequency than the strain gauge unit.

Consequently, the Hall element unit would be a more powerful tool for the detection of the oscillation frequency of the test cylinder immersed in molten steel flows than the strain gauge unit.

5. Conclusions

A velocimeter called the Karman vortex probe was developed. A Hall element was used to detect the shedding frequency of the Karman’s vortex streets formed behind a circular cylinder. According to model experiments using a molten Wood’s metal bath and a molten pig iron bath, this velocimeter would be applicable to velocity measurements of molten steel flows on the meniscus of the current refining processes and continuos casting molds.

Nomenclature

- $D$: test cylinder diameter
- $H_i$: immersion depth of test cylinder
- $Re$: Reynolds number
- $St$: Strouhal number
- $v$: velocity of approaching flow
- $\nu$: kinematic viscosity of liquid

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