Fluidity of Al-Si Alloy in Metal Mold Casting under Vibration

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Abstract The effect of mechanical vibration on the metal fluidity in thin casting was investigated in this study. The vibration was applied in vertical and horizontal mode during solidification process of aluminum alloy (Al-12\%Si). This was done in the frequency range from (0 to 60) Hz and at two intensities; high intensity at (1.6 Volt, 4Ampere) and low intensity at (0.8 Volt, 2 Ampere). The results indicated that in vertical mode the mechanical vibrations increasingly improve fluidity of thin sections and the maximum percentage of fluidity improvement was equaling to 30.61\% at 60 Hz. For horizontal mode it was found that fluidity also increase with frequency and the percentage of improvement was equaling to 33.35\% at 12 Hz but then it falls at 60 Hz for both intensities, that because at strong vibration castings have an elliptical form rather than circular due to metal flow in the direction of vibration more than the other directions which mean that horizontal mode can operate most effectively at low frequencies only.

1. Introduction
Casting is a manufacturing process in which molten metal flows by gravity or other force into a mold where it solidifies in the shape of the mold cavity. Casting enable many pieces to be combined into a single part, eliminating assembly and inventory and reducing costs by 50\% or more compared to machined parts. It is one of the oldest shaping processes, dating back to 6,000 years [1]. The principles of casting seems simple:
• Melt the metal.
• Pour it into the mold.
• Let it cool and solidify.

Thin wall casting received a lot of attention in the last decades not just for its importance in producing light weight components, but also for its importance in meeting the growing demand for producing thinner section castings having good mechanical properties. On the other hand, thin wall casting face a manufacturing problems associated with mold filling, because sometimes molten metal permanently freeze before it can completely fill the mold. As a result, that will affect the soundness of cast products and deteriorates their final quality. Rejection of the shaped casting may cause because of the incomplete filling of the mold which called Misrun defect. Due to the large production volumes involved in casting processes, it became necessary to control casting defects by improving fluidity and other parameters, because small reductions in the amount of casting defects can give large economical benefits [2][3]. Consequently, various methods have been developed to improve casting characteristics such as electromagnetic vibrations, ultrasonic waves and mechanical vibrations [4]. Application of the mechanical vibrations to the mold during solidification attracts attention because of its simple system.
Experimentation with mold vibration date back to 1868. In one of the earlier investigation Wachter [5] studied the effect of vibration on molten metal and reported that "there was a pumping force generated at the entrance to the vertical passages used to evaluate the fluidity of the molten metal". Abdul-Karem et al. [6] Assessed the effect of vibration, frequency and amplitude on the fillability filling type in thin wall investment castings filled with A356 alloy, the experimental results showed that vibration had a significant effect on the ability of the metal to flow within thin sections increasing the filling capability by approximately 90 % compared with casting without vibration effects. Flemings [7] found that vibrations increased the distance which the metal runs (its fluidity) into small holes in a casting, these effects were found to be greatest with small metal heads and are again attributable to an increased effective metal head. Campbell [8] and Chandraschariah [9] investigate the effect of different factors and they found that (when the temperature of the mold is less than the liquidus temperature) fluidity has a major effect on the filling of the mold which can be improved by controlling factors relating to flow and heat transfer, including superheat, alloy composition and the resultant mode of solidification. Fluidity improvement in thin wall investment casting is another matter; the surface tension is an additional factor which should be taken into account when calculating fluidity (Campbell [8],[10] and Flemings [7]). Analysis of fluid flow and heat transfer are frequently used in modeling to improve the quality and yield of castings by improving their fluidity characteristics (Griffiths and Jones [11]). Waleed et al. [12] analyzed mathematically the rate of heat loss during casting. The objective of the present work is to assess, in the comprehensive approach, the effect of vibration mode and frequency on Al-Si alloy fillability filling in thin sections at two different intensities.

2. Experimental procedure
Shaker or vibration exciter type (4808Brüel & Kjær) which converts electrical signal to mechanical vibrations was coupled to the target mold and driven through a power amplifier by a sinusoidal signal generator. Figure 1 shows the instrumentation set up, additional information about each instruments are listed in appendix A table A1.

![Figure 1. Vibration system instruments.](image)

The vibrator was set in vertical position to produced a vertical vibration and in horizontal position to produce a horizontal vibration. The melt was produced in a mild steel mold with a special design consisting of four thin sections with critical angels as shown in figures 2 and 3.
The first section is the top section makes an angle (10°) with the horizontal level, while the second section makes an angle (7.5°) and the third section makes an angle (5°) with horizontal level and they both divided into two parts. The fourth section is the base of the mold at (0°).

The permanent casting process started when the melt placed in a graphite crucible and placed within the electric furnace chamber at 720°C. Melting the alloy was carried out in a temperature of 670°C. The first melt was poured into non-vibrating mold that previously preheated to 150°C. The subsequent melt was poured into preheated mold being vibrated at various frequencies ranging from (0-60)Hz and two different vibration intensities (1.6 volt peak to peak and 0.8 volt peak to peak). Aluminum cast alloy (Al-Si alloy) was used in this work. This alloy is classified with good castability but it is difficult to machine due to the high Si content [13]. This alloy has been used a lot in the production of castings at the State Company for Electrical Industry in Baghdad. Chemical composition of the aluminum alloy used in the current research is shown in table 1.

### Table 1. Chemical composition of Al-Si alloy.

|        | Si    | Mn    | Cu    | Fe    | Mg     | Ti    | Zn     | Others |
|--------|-------|-------|-------|-------|--------|-------|--------|--------|
| max    | 0.15  | 0.001 | 0.10  | 1.0   | 0.05   | 0.15  | 0.1    | 0.15   |
| max    | 0.05  | 0.15  |       |       |        |       |        |        |
| max    | 1.0   |       |       |       |        |       |        |        |
| max    | 0.1   |       |       |       |        |       |        |        |

To measure fluidity two tests were made for the first time in 1902, the most common fluidity tests were the spiral-shaped mold test and the vacuum fluidity test. The first method measured the length the metal flows inside a spiral-shaped mold. The second method measured the length of the metal flows inside a narrow channel when sucked from a crucible by using a vacuum pump [14]. Traditionally, the spiral test has been widely used because it is compact and portable, and hence can be used easily in the foundry.

3. Results and discussions

To measure fluidity two tests were made for the first time in 1902, the most common fluidity tests were the spiral-shaped mold test and the vacuum fluidity test. The first method measured the length the metal flows inside a spiral-shaped mold. The second method measured the length of the metal flows inside a narrow channel when sucked from a crucible by using a vacuum pump [14]. Traditionally, the spiral test has been widely used because it is compact and portable, and hence can be used easily in the foundry.

**Figure 2.** Mold design.  
**Figure 3.** The metallic mold.
In this work, fluidity of melt before solidification was measured for each casting at the three mold sections at \((5^\circ, 7.5^\circ, 10^\circ)\) to investigate the effect of mechanical vibration on the capability of liquid metal to fill thin sections and produce castings without Misrun in permanent mold casting. Thirteen pieces had been cast successfully in different work conditions. The essential work variables were:

- Vibration mode
- Frequency of vibration
- Intensity

Since castings disks were not uniform in shape, fluidity per diameter calculated by dividing the disk at each section to four lines (A-A, B-B, C-C, D-D) where each line represent diameter as shown in figure 4 (a and b). The calculations depended on measuring lines length by using measuring instruments and took the average value between them. The fluidity measurements divided into two parts:

![Image](image1.jpg)

(a) The casting  
(b) Method of dividing the casting

**Figure 4.** The casting and method of division.

### 3.1. Part One: Fluidity measurements in vertical vibration mode

The first part of experimental work includes the measure of the propagation of molten metal under the effect of vertical vibration, the data has been shown in table 2.

| Frequency Hz | Vibration intensity1 (1.6V&0.4Amp.) | Vibration intensity2 (0.8V&0.2Amp.) |
|--------------|-------------------------------------|-------------------------------------|
|              | Average at 10° Cm | Average at 7.5° Cm | Average at 5° Cm | Average at 10° Cm | Average at 7.5° Cm | Average at 5° Cm |
| 0            | 15.15 | 13.475 | 13.975 | 15.15 | 13.475 | 13.975 |
| 2.3          | 17.2 | 13.8 | 15.175 | 18.45 | 11.725 | 15.3 |
| 12           | 18.1 | 17.575 | 15.4 | 18.55 | 16.95 | 15.425 |
| 60           | 18.225 | 17.6 | 16.375 | 19 | 17.35 | 15.625 |
Table 2 shows the results obtained from the fluidity measurements carried out on various castings of the Al-Si alloy at vertical vibration mode. The results showed an improvement in fluidity when vibration was used during the pouring temperature (720°C) and mold temperate (150°C), because vibration generates additional acceleration and pressure to improve the filling capability to force the melt into thin sections, thereby improving the fluidity [6].

3.1.1. Fluidity at intensity 1. Figure 5 shows the effect of the frequency at high intensity of vertical vibration on the fluidity per diameter of the castings. It is observed from the figure that the propagation of metal along the diameter of castings has increased and reaching a maximum value as the frequency increases to 60 Hz; Abdul-Karem and Khalid confirm this observation and states that "The higher the vibration action during solidification of molten metal the higher will be the velocity thereby improving fluidity"[15]. It is conspicuous from the figure that fluidity at 10° has values higher than sections (2,3) at 7.5° and 5° between (0 and 60)Hz; because it is the biggest angle and the molten metal can easily overcome the surface tension and fill the part due to the high internal pressure[6]. Also, the fluidity at 7.5° starts lower than 5° only between (0 and 2.3)Hz but then it increase to reach higher values close to the values of 10° between frequency ranging from (12-60)Hz, it is clear also that the fluidity at 5° seems to be lower than those into Sections (1,2) at 10° and 7.5°; because this section is very thin and the metal loses its heat so fast accelerating the solidifying before filling the part completely.

![Vertical, Intensity 1](image)

**Figure 5.** Effects of vertical vibration on the fluidity at high intensity.

3.1.2. Fluidity at intensity 2. Figure 6 reveal the effects of the frequency at low intensity of vertical vibration on the fluidity per diameter of the castings. It is observable from the figure that the fluidity along the diameter of the castings increases with the frequency reaching the maximum value at 60 Hz. Also fluidity increasing with angles and reaches the maximum values at 10° and the lowest values at 5° as in high intensity. It is conspicuous that the intensity 2 has the higher values of fluidity per diameter at 10° and 60 Hz equaling to (19) cm and more than intensity 1 for the same conditions; the metal flow nature under vertical vibration was oscillating motion and shape of the wave varied according to the vibration intensity. In case of high intensity the oscillation was strong, as a result most of solidification time dissipated due to this motion where the surface wave was with short wave length and high wave height. Since solidification is a function of time, the metal freeze before filling the casting part. While in case of low intensity the oscillating motion was smoother and the surface wave was with high wave length and short wave height also, thus the metal will flow regularly and fill large space than in high intensity case before solidifying.
3.1.3. Fluidity improvement for intensity 1. Figure 7 demonstrates how the fluidity improved with increasing frequency. It is observed from the figure that percentage of fluidity improvement reaches maximum value at 7.5°, where it equal to 30.42% at 12 Hz and remain with this percent at 60 Hz equalling to 30.61%. At 10° the percentage of improvement increase and also reach high value at 12 Hz equal to 19.47% and then it increase to 20.29%. At 5° the percentage also increase with frequency and at 60 Hz it reach value close to the 10° value equalling to 17.17% although it was very thin section. These results support the thought that vibration improves fluidity even in thin sections.

3.1.4. Fluidity improvement for intensity 2. Figure 8 shows the effects of vertical mode vibration on the percentage of fluidity improvement at low intensity. It is obvious that the percentage of improvement increase with vibration, best results obtained only in high frequency where at low frequency the present started with negative value equalling to -12.98% at 2.3 Hz. As in section (3.1.3) the fluidity improved at 7.5° more than the other sections reaching a maximum value equalling to 28.75% at 60 Hz.
3.2. Part Two: Fluidity measurements in horizontal vibration mode

The second part of fluidity measurements specialized to study the effect of applying vibration horizontally on the ability of molten metal to fill thin sections. The measured data shown in table 3:

**Table 3. Fluidity per diameter at different frequencies of horizontal vibration.**

| Frequency Hz | Vibration intensity1 (1.6V & 0.4Amp.) | Vibration intensity2 (0.8V & 0.2Amp.) |
|--------------|---------------------------------------|---------------------------------------|
|              | Average at 10° Cm | Average at 7.5° Cm | Average at 5° Cm | Average at 10° Cm | Average at 7.5° Cm | Average at 5° Cm |
| 0            | 15.15           | 13.475           | 13.975           | 15.15           | 13.475           | 13.975           |
| 2.3          | 17.65           | 17.55            | 17.1             | 15.375          | 14.75            | 14.55            |
| 12           | 17.45           | 17.97            | 17.55            | 17.675          | 16.25            | 15.5             |
| 60           | 17.125          | 17.35            | 15.275           | 17.17           | 17.07            | 13.875           |

Table 3 shows the results obtained from the fluidity measurements carried out on various castings of the Al-Si alloy under the effect of horizontal vibration. The results showed an improvement in the fluidity when vibration was used during pouring temperature (720°C) and mold temperature (150°C) but then the results droop at high frequency for both intensities.

3.2.1. Fluidity at intensity 1: Figure 9 depicts the effects of applying vibration horizontally at high intensity on the fluidity per diameter of the castings. It is observable from the figure that the fluidity per diameter increases with increasing the frequency of vibration between (0 and 12) Hz; vibration generates pumping force on the metal flows horizontally [16]. With increasing frequency and intensity this force increase and applying additional pressure on the metal flow within the mold. Thus, the metal fill large space before freezing. At 60Hz the fluidity decrease at low intensity more than high intensity.

3.2.2. Fluidity at intensity 2: Figure 10 shows the effects of frequency at low intensity on the fluidity per diameter of the castings. It is observable from the figure that the fluidity per diameter of the castings increases with the frequency of vibration between (2.3 and 12) Hz but it decrease at 60Hz at 10° and 5°, as in section (3.2.1). It is clear from the figure that the fluidity reach its maximum value at 10° and then
matching the 7.5° at 60Hz. The fluidity at 7.5° section starts low than the 5° but then increase. Also, the fluidity droop at 5° more than the other angles.

![Figure 9](image-url). Effects of horizontal vibration on the fluidity of samples at high intensity.

![Figure 10](image-url). Effects of horizontal vibration on the fluidity of samples at low intensity.

Comparing the fluidity measurements at both intensities, it is clear that the fluidity droops at 60 Hz. The experimental results in table 4 shows that castings at strong vibration have an elliptical form rather than circular, this because the metal flow in the direction of vibration more than the other directions. This confirm what Campbell state that "horizontal mode can operate most effectively at very low frequencies, typically 0.1–10 Hz" [17].

| Fluidity along the ellipse diameters Cm | Vibration intensity1(1.6V.,4Amp.) | Vibration intensity2(0.8V.,2Amp.) |
|---------------------------------------|----------------------------------|----------------------------------|
|                                       | 10°     | 7.5°    | 5°       | 10°     | 7.5°    | 5°       |
| Large diameter A - A                  | 13.6    | 13.2    | 11       | 13.2    | 13.2    | 9.3      |
| Small diameter C - C                  | 10.9    | 11.4    | 10.2     | 11.1    | 11.5    | 8.5      |
3.2.3. Fluidity improvement for intensity 1. Figure 11 shows the fluidity enhancement under the effect of horizontal vibration at high intensity. It is obvious that the percentage of improvement increased gradually at 7.5° and 5° with vibration and reaches maximum value at 12 Hz equalling to 33.35% and 25.58% respectively even at 10° in spite of it decrease from 16.5% at 2.3 Hz to 15.18% at 12 Hz but this drop considered very small. Also from the figure it observable that the percentage at all frequencies droop at 60 Hz that because the metal flow in the direction of vibration more than the other which affect the total improvement percentage.

3.2.4. Fluidity improvement for intensity 2. Figure 12 reveal the effects of horizontal mode vibration on the percentage of improvement. It is obvious that the points take the same behaviour of points in high intensity (paragraph 3.2.3.) where it all increase at 12 Hz that because the pumping force generated at the entrance to the vertical passages used to evaluate the fluidity of the molten metal and then falls at 60 Hz that because the metal flow in the direction of vibration more than the other as mention before. At 7.5° the fluidity increase with frequency even at strong vibration which agree with what Campbell said that "horizontal mode can operate most effectively at very low frequencies typically 0.1–10 Hz" [17].

Figure 11. Effects of horizontal vibration on the percentage for fluidity improvement at high intensity.

Figure 12. Effects of horizontal vibration on the percentage for fluidity improvement at low intensity.
4. Conclusions
The major conclusions that can be obtained are as follows:

- The mechanical mold vibrations increasingly improve fluidity of thin sections.
- Vertical vibration mode was better than horizontal vibration mode in terms of fluidity.
- Fluidity is increased with increasing frequency in vertical vibration mode and it reaches its maximum value at (60 Hz).
- At vertical mode the low intensity has the higher values of fluidity per diameter and more than high intensity for the same conditions.
- Horizontal vibration mode can operate most effectively at low frequencies (2.3 and 12) Hz and droop at high frequencies (60 Hz).
- The experimental results in horizontal mode shows that castings at strong vibration had an elliptical form rather than circular form.

Acknowledgments
The authors thank Dr. Sadiq Hassan, head of Mechanical Engineering Department / The Technical Institute in Al-Muthanna as well as the Engineering Workshop staff for their extreme help in manufacturing the mold. The authors would like to acknowledge also all the staff of the Engineering Workshop at University of Baghdad, whom generously gave their time and expertise to help us during the experimental work especially Mr. Talib H. Rashid, supervisor of Mechanical Workshops. At University of Technology, the authors would like to thank Dr. Adil M. Salih, head of Cars Department and Dr. Alaa Abdul-Hassan, head of Material Engineering Department for their generosity.

Appendix A:

| No. | Equipment                  | Origin     | Model        |
|-----|----------------------------|------------|--------------|
| 1   | Function Generator         | China      | ATTEN AT8620 |
| 2   | Power Amplifier            | Denmark    | 2719 Brüel & Kjær |
| 3   | Vibration Exciter          | Denmark    | 4808 Brüel & Kjær |
| 4   | Electrical furnace         | China      | KJ-1200X     |

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