Pulsating Flow Characteristics of Hot-Wire Air Flow Meter for Gasoline Fuel-Injection Systems*

Yoshishige OHYAMA**, Kotarou HIRASAWA**, Yutaka NISHIMURA**, Minoru OHSUGA** and Mamoru FUJIEDA**

Pulsating flow characteristics of the hot-wire air flow meter for gasoline fuel injection systems were investigated to analyze simple methods for processing measured data. It was clarified that backward flow components due to pulsation are detected as forward flow by the probe in conventional meters, which increases errors. The errors due to pulsation can be reduced by using a meter with a hot-wire probe located in a bypass passage, which aerodynamically compensates forward and backward flow components.

**Key Words:** Fuel Injection, Intake System, Air Flow Meter, Hot Wire, Pulsation

1. Introduction

Since the hot-wire air flow meters11–13 now being widely employed in gasoline fuel injection systems are designed to output the same measured values in both backward and forward flows, the average of the measured values is apt to be larger than the actual air flow when backward flow occurs in the suction air passage equipped with a flow meter, because of pulsation caused by repetitive and columnar vibrations14. In addition, if the air flow meter is mounted apart from the throttle valve, a time-lag difference is produced between the two flows due to influences of pulsating components15. For the case where noticeable pulsations occur, there are methods to compensate for the time-lag difference by mounting pressure sensors and separating the forward and backward pulsating components from each other using software, but these methods are still confined to laboratory analyses.

In this paper, we offer a handy processing method to analyze the pulsating flow characteristics of a hot-wire air flow meter applicable to gasoline fuel injection systems.

2. Analysis

2.1 Backward flow due to pulsating flow

Velocity fluctuations due to columnar vibrations may sometimes reach ±20 m/s17. Since an air flow meter is normally mounted on the air-filter side and separated from the suction valve, it is affected by velocity fluctuations. This is shown for a simple model in Fig. 1. Assuming $p_1$, $p_2$, and $p_3$ are pressures at each part and $u_1$ and $u_2$ are velocities, then we obtain

$$p_1 = a_1 \frac{du_1}{dt} + b_1 u_1 + p_2$$  \hspace{1cm} (1)

![Fig. 1 Suction system model](image)

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\[ p_s = a_3 \frac{du_s}{dt} + b_3 u_s + p_s \]  
\[ \frac{dp_s}{dt} = k(u_1 - u_3) \]

where \( a_i, b_i, a_s, b_s, \) and \( k \) are constants. Furthermore, assuming that \( p_s = \) constant, \( p_s = \) constant, \( a_1 = a_s, b_1 = b_s, \) and \( u = u_1 - u_3, \) we obtain

\[ a_t \frac{d^2 u}{dt^2} + b_t \frac{du}{dt} + ku = -a_t \frac{d^2 u_3}{dt^2} - b_t \frac{du_3}{dt} \]  

Figure 2 shows the calculation results for a change of \( u_1 = u + u_3 \) when \( b_1 = 0 \) and \( u_3 \) changes in the form of a sine wave in Eq. (4).

Velocity fluctuations \( u \) caused by columnar vibrations are superimposed on the change of speed \( u_3 \) due to the reciprocating motion of the pistons which produces the velocity \( u_1 \) at the flow meter. If the vibration frequency \( \omega \) of \( u_3 \) is smaller than the natural vibration frequency \( \omega_n, \) waveforms are obtained as shown in Figs. 2 (a) and (b), while if \( \omega > \omega_n, \) waveforms are obtained as shown in Fig. 2 (c). When \( \omega = \omega_n, \) the amplitude of \( u_1 \) increases due to that of the resonance. It is possible that \( u_1 \) (velocity in the air flow meter passage) may become negative, even if the reciprocating velocity \( u_3 \) does not (due to the absence of backward flow).

2.2 Propagation of pressure and velocity in a suction pipe

When the velocity at the outlet end of a suction pipe changes stepwise, pressure \( p \) and velocity \( u \) change at \( L/2 \) from the inlet end, as shown by the model in Fig. 3. Velocity \( u \) is deflected, becoming positive or negative as velocity \( w \) changes. Accordingly, when \( w \) changes from \( w_0 \) to zero, a backward flow is produced (\( u < 0 \)) as shown in Fig. 3 (b). By assuming that \( L \) is the pipe length and \( a \) is acoustic velocity, the vibration cycle is \( 4L/a. \) Regarding pressure \( p \) and velocity \( u, \) we see that the following relation holds true.

\[ \frac{\partial p}{\partial x} = \rho \frac{\partial u}{\partial t} \]  
\[ \rho \frac{\partial u}{\partial x} = \frac{1}{a^2} \frac{\partial p}{\partial t} \]  

\( t \) : Time
\( x \) : Distance from the pipe inlet
\( \rho \) : Density
\( a \) : Acoustic velocity

If a hot-wire probe is mounted in the bypass passage, branching from the main passage as shown in Fig. 4, Eq. (6) holds true on surfaces \( S_1 \) and \( S_2 \) in front of and behind the throttle. A pressure loss component

![Diagram of pressure and velocity changes](image)

*Fig. 2 Change of \( u_1 \) and \( u_2 \) with time*

*Fig. 3 Change of \( p \) and \( w \) with time when \( w \) changes stepwise*

*Fig. 4 The model with a probe in the bypass passage*
By substituting Eq.(12) into Eq.(11), we obtain
\[ v_b = \beta_1 \cdot U + (\beta_2 \cdot \nu_t - V_1 \cdot \frac{d \nu_t}{dt}) \]  
(13)
By arranging the probe in the bypass passage such that \( \beta_2 \cdot \nu_t = V_i \), we obtain \( v_b = \beta_2 U \). Thus, \( v_b \) becomes a function of outlet velocity \( U \) of the suction pipe without being affected by the forward or backward flow caused by the pulsating flow. As a result, \( U \) can be measured correctly by the probe owing to the aerodynamic compensation for the influences of the pulsating flow.

3. Experimental Study

3.1 Experimental apparatus
We tested an engine with the specifications listed in Table 1. The hot-wire air flow meter was mounted at the position where the carburetor is conventionally mounted (See Fig.5). An ordinary air filter as used for a carburetor was also mounted in the apparatus. A probe consisting of a tungsten wire (5 μm diameter) or a ceramic bobbin (0.6 mm diameter), both conventionally available, was used as the hot-wire probe. The bypass passage was 8 mm in diameter and 50 mm in length, while the throttle was 45 mm in diameter.
For bench-top experiments, a vacuum pump was used instead of an engine to rotate a butterfly valve which produced the pulsating flow\(^{11}\).

3.2 Fluctuations of pressure and velocity
Figure 6(a) shows the pressure in the air filter when the engine speed was 1 000 rpm. Unlike the pressure values without a filter, the pressures are sometimes positive when the air filter is used, because pressure fluctuations caused by the columnar pulsation are superimposed on those caused by the velocity fluctuations. Figure 6(b) shows an example of measured results of velocity fluctuations in the main passage. The superimposition of the velocity

<table>
<thead>
<tr>
<th>Engine specifications</th>
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<tr>
<td>4 cycle 4 cylinder</td>
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<td>Swept volume 1952cm(^2)</td>
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<tr>
<td>Bore X stroke 85 x 86mm</td>
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<td>Compression ratio 8.5</td>
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</tbody>
</table>

Fig. 5 Experimental apparatus

\[ u_t = \beta_3 (u + \nu_t \cdot \frac{d \nu_t}{dt}) \]  
(11)
As is understood from Eq.(11), the flow in the bypass passage is affected by the fluctuations of pressure \( \nu_t \) in the suction pipe, in addition to the velocity at the suction pipe outlet.

Now we assume \( \nu_t \) is the velocity at an optional point inside the bypass passage; then Eq.(12) holds true between velocity \( u_t \) at the bypass passage inlet and velocity \( \nu_t \) at the optional point inside the bypass passage.

\[ v_b = u_t - V_1 \cdot \frac{d \nu_t}{dt} \]  
(12)
fluctuations caused by the pulsation and backward flow at \( S_3 \) is indicated. Also, backward flow is produced every two cycles of fluctuations, similar to the behavior in Fig. 2(a).

Figure 7 shows an example of measured results of velocity fluctuations in the main passage and bypass passage during bench-top experiments (The condition that there was a capacitance at the bypass passage outlet was set). When the bypass passage is as short as about 50 mm, the velocity fluctuation phases of the main passage and bypass passage equal other each, as is predictable from Eqs. (9) and (10).

### 3.3 Averages of measured values

Figure 8 shows an example of results obtained by the experimental apparatus using a vacuum pump. The average measured values of the vibration frequency increase at a vibration frequency equivalent to 1/2 of the natural vibration frequency, as well as at the natural vibration frequency. This ratio of change increases when the probe, with a bobbin, is mounted in the bypass passage, as compared with the ratio of change obtained by mounting the wire in the main passage, but the two tendencies are similar.

Even if no gas return is caused by the vacuum pump, backward flow is produced in the air flow meter passage due to the pulsating flow, and the hot-wire probe measures it as positive, causing the measured values to be larger. The measured values in the bypass passage increase because the air in the passage respires to move forward and backward; this phenomenon is detected by the hot-wire probe mounted at the inlet of the bypass passage. Since the velocity changes according to differentiation of the pressure with time, the phase remains unchanged.

As described above, we clarified that the measured values increase even if no gas return occurs, and the flow meter combined with a probe mounted in the bypass passage is affected by the pulsating flow, unless the mounting position of the probe is selected properly.

### 3.4 Effects of an orifice in the bypass passage

Figure 9 shows the effects of the probe-to-orifice distance on the probe output. If the orifice diameter is zero, a backward flow is detected even if the average value of the velocity is zero, and the output average increases correspondingly as the distance increases. When the orifice diameter is about 1.4 mm, the output average is not affected by the distance, because the velocity caused by compression of the air from both inlet and outlet sides of the bypass passage is balanced at the probe position.

Figure 10 shows the effects of the orifice in the bypass passage. As the orifice diameter becomes smaller, the average of the measured values becomes larger as compared with the air flow due to the effects.
of the backward flow. When the engine speed is 1,000 rpm, measured values become larger due to the effects of the backward flow caused by spitting, even if the orifice diameter is large. In the case of Fig. 10, a surge tank with a volume of 5.2 cm³ was mounted on the outlet side of the bypass passage. Since balancing of the inlet and outlet pressures is delayed due to the presence of this surge tank, the velocity fluctuations increase. Accordingly, the orifice diameter should be 4 mm or more if the error is to be reduced.

3.5 Effects of probe mounting position

When the surge tank is mounted downstream, averages of measured values increase for engine speeds of 2,000 and 3,000 rpm, as shown in Fig. 11. If the bypass passage is lengthened, the measured values increase at 2,000 and 4,000 rpm. At 3,000 rpm, the phase deviates to suppress the backward flow, and the measured value becomes close to 1.

If the probe is mounted at the center of the passage without mounting any surge tank at the outlet, averages of measured values almost coincide with those of the air flow, as shown in Fig. 12. Figure 13 shows fluctuations of the probe output. When the
surge tank is included, fluctuations are conspicuous. By removing the surge tank, fluctuations decrease.

Measurement errors become small at engine speeds of 2,000 rpm or higher, as shown by the circles in Fig. 12, by suitably selecting the mounting position of the probe. However, spitting of the engine at low revolutions is detected as a positive signal by the probe, which causes the average of measured values to increase, although the effects of pressure and velocity fluctuations due to pulsation can be avoided. Measured values can be corrected by averaging them after making the output of the gas return component negative.

4. Conclusions

We investigated the effects of pulsating flow on values measured by a hot-wire air flow meter for gasoline fuel injection systems.

1. The flow in the bypass passage was affected by the pressure of the suction pipe in addition to the velocity at the suction pipe outlet.

2. Backward flow may be produced in the flow meter passage due to pulsating flow, even if spitting did not occur, and the hot-wire probe may measure it as positive, which increases the measurement error.

3. As the orifice diameter of the bypass passage was decreased, errors increased due to the effects of the backward flow.

4. By mounting the probe at the center of the bypass passage, the effects of the pulsating flow could be avoided.

5. Spitting of the engine at low revolutions was measured as positive by the probe, resulting in a measurement error.

References


