and positions of the load sensors are determined in consideration of the profile and supporting method of the pan. We can easily obtain F_a and F_b by measuring the shearing force with strain gauges pasted on its side when the pan is not so rigid, or measure the pan springing load when the pan is supported at the center or highly rigid to make it difficult to detect strain. The inertia force F_{ine} can be measured with an accelerometer placed on the pan. In actuality, however, it is difficult to measure F_{ine} at high frequencies, since elastic vibration becomes dominant to make it impossible to regard the pan as a rigid body. In the conventional method, therefore, the components at these frequencies are cut with a low pass filter. The cut-off frequency is set at 20 Hz in the European Standard of EN 5031, for example. To solve this problem, we have developed a method to measure the inertial force by calculating the weighted average of the measurements obtained from a plurality of accelerometers installed on the pan. To correctly determine the inertia force when there are n dominant vibration modes in the frequency range to measure the contact force, we measure the values of acceleration at discrete points xj (j = 1 to n), and multiply each value by an appropriate weighted factor. This enables us to measure the inertia force at high precision even in the high frequency range where elastic vibration is dominant.

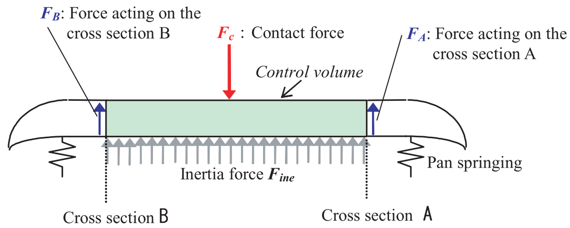

Figure 1. Force equilibrium on a panhead.

PRECISION OF THE CONTACT FORCE MEASUREMENT

Figure 2 shows the precision of the contact force measurement when this technique was applied to the Shinkansen pantograph PS202. The inertia force was measured with three accelerometers attached to the pan bottom. Since the first elastic mode of the pan is at about 80 Hz, the conventional method to use an accelerometer can measure the contact force only up to about 40 Hz. In contrast, this technique enables measurement in the frequency range up to 100 Hz at high precision.

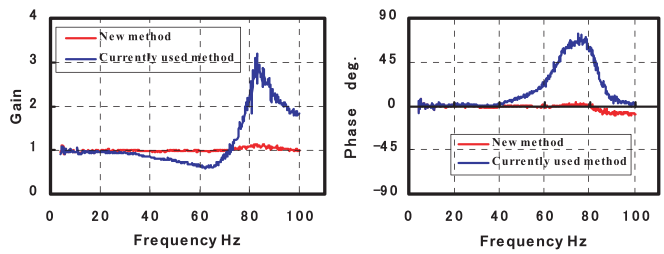

Figure 2. Measurement precision.

APPLICATION TO THE DIAGNOSIS OF CONTACT LINE FACILITIES

The standard deviation of contact force measurements has been used to evaluate the performance of current collection. As a case study of the diagnosis of contact line facilities, however, we will estimate below the wave propagation velocity in trolley wires, which is one of the parameters that determine the performance of current collection. The fluctuation of contact wire is strongly affected by the spatial periodicity of contact line facilities, such as the spans between support poles and between hangers. Since the spatial periodicity depends on train speed, however, it is effective to observe frequency information and time-related information simultaneously, in order to extract the features of contact line facilities. The chart in the middle of Fig. 3 shows the fluctuation of contact force measured in a simple catenary section. The chart at the top displays the contact force processed through short-time Fourier analysis, with the frequency normalized with respect to train speed and converted into the number of waves, or the power spectrum density normalized by a logarithmic scale. The red part indicates the place of high power spectrum density. This chart shows that dominant components exist at the specific numbers of waves, in particular, at the number of 0.2 that corresponds to the hanger interval of 5 m. We can confirm by this chart that the fluctuation of contact force depends on the spatial periodicity of contact line structure. The contact force also fluctuates when the pantograph receives the waves that are excited by the fluctuation of contact force over hanger intervals and reflected at hanger points, as expected by theoretical analysis. The chart also indicates that this phenomenon has occurred in the present case. The number of waves of the contact force fluctuation for the above reason depends on train speed and wave propagation velocity in the trolley wire. Based on this fact, we can also estimate the wave propagation velocity. By comparing the estimated and measured values, we have proved that the wave propagation velocity can be expected at the precision of about 10% (Fig. 4).

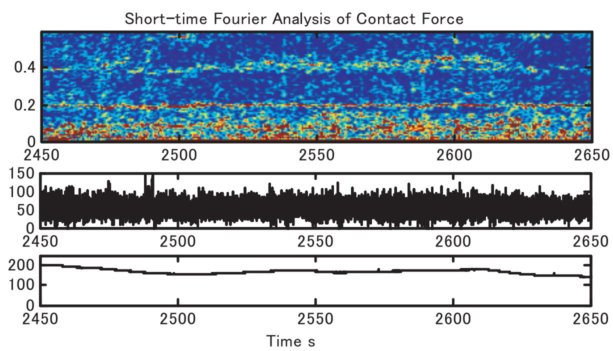

Figure 3. Measurement results of contact force on a line test.

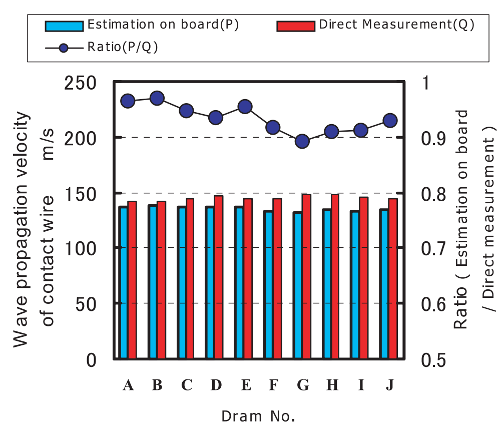

Figure 4. Estimation of wave propagation velocity of contact wires by contact force measurements.

POSTFACE

The method to measure the contact force introduced above can be applied to pantographs of other types. We have already measured the contact force of different pantographs used for Shinkansen and narrow-gauge lines. As a technique to measure the contact force in a wider frequency range than that coped with by the above method, we have also developed a method to estimate the contact force based on the dynamic response of pantograph through the analysis of pantograph vibration, by using sensors more than the number of dominant vibration modes installed on the pantograph and the transmission function from each sensor to the contact force. This method features a high degree of freedom for sensor arrangement. As an expanded version of this method, we have also developed a method to simultaneously measure the contact force not only in the vertical direction but also in the longitudinal direction. We will promote researches focusing on the method to utilize the contact force measurements for the diagnosis of contact lines.