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TOWING TANK TESTS OF THE ACCUSONIC ACOUSTIC FLOW METER

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MANAGEMENT PERSPECTIVE

The Water Survey of Canada is pursuing a hydrometric instrumentation development program which will lead to enhanced automation of its data acquisition activities. Of the two main activities, the measurement of stage and discharge, the latter requires by far the larger amount of manual input. To reduce the requirement for human intervention in remote areas, the acoustic method of unattended flow measurement is being evaluated. Tests on newly developed prototypes of acoustic flow meters are being conducted jointly by the Water Survey of Canada and the National Water Research Institute. Successful development of an acoustic flow meter for long term, unattended deployment, will produce significant savings in the national flow measurement program of the Water Survey of Canada.

Dr. J. Lawrence
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PERSPECTIVES DE GESTION

La Division des relevés hydrologiques du Canada poursuit son programme de développement dans le domaine de l'instrumentation hydrométrique, qui conduira à une plus grande automatisation de ses diverses activités d'acquisition de données. Des deux principales de ces activités, soit les mesures de niveau et de débit, c'est la dernière qui requiert de loin le plus d'apport manuel. On évalue actuellement la méthode acoustique de mesure automatique de débit de façon à réduire les besoins en personnel dans les régions éloignées. Des essais avec des prototypes de débitmètres acoustiques, récemment mis au point, sont effectués conjointement par la Division des relevés hydrologiques du Canada et par l'Institut national de recherche sur les eaux. La mise au point d'un débitmètre à fonctionnement durable, sans intervention humaine, permettra de réaliser d'importantes économies dans le cadre du programme national de mesure des débits, de la Division des relevés hydrologiques du Canada.

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SUMMARY

The Water Survey of Canada is in the process of acquiring a reliable, low cost, ultrasonic flow meter to measure river discharge at remote locations on a real time basis. Tests were conducted on the ACCUSONIC flow meter used by the United States Geological Survey (USGS). Analysis of the test data shows that measurements made with the USGS flow meter were lower than the reference velocity and this velocity deficit was found to increase gradually with increase in towing speed in the range from 0.6 m/s to 3.0 m/s. The reason for this cannot be determined conclusively from the present test, but is thought to be attributable to the space limitations in the towing tank and the flow meter. The low variability in velocity measurements was considered to be excellent considering the uncertainties as a result of the towing tank environment. A dimensionless flow meter coefficient was developed using dimensional analysis.

RÉSUMÉ

La Division des relevés hydrologiques du Canada est sur le point d'acquérir un débitmètre à ultrasons, peu coûteux et sûr, permettant de mesurer le débit des rivières à des endroits éloignés, en temps réel. Des essais ont été effectués avec le débitmètre ACCUSONIC, utilisé par l'USGS (United States Geological Survey). L'analyse des résultats des essais montre que les valeurs obtenues avec le débitmètre USGS étaient inférieures à la vitesse de référence, l'écart augmentant graduellement avec la vitesse de touage dans l'intervalle de 0.6 à 3.0 m/s. Ces essais ne permettent pas d'expliquer de façon certaine l'écart noté, mais on pense qu'il serait dû aux limitations de nature spatiale, inhérentes au réservoir de touage et au débitmètre. La faible variabilitié lors des mesures de vitesse était considérée comme excellente, si on tient compte des incertitudes résultant de l'environnement propre au réservoir de touage. Un coefficient sans dimensions a été déterminé pour le débitmètre à partir d'une analyse, elle aussi sans dimensions.

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1.0 INTRODUCTION

The Water Survey of Canada (WSC), through private industry, is in the process of developing a reliable, low power, low cost, ultrasonic flow meter to measure river discharge in remote areas. At the request of WSC, the Research and Applications Branch (RAB) of the National Water Research Institute NWRI), conducted performance tests on the ACCUSONIC flow meter used by the United State Geological Survey (USGS). These tests were conducted jointly by staff of WSC, RAB and Accusonic. This report presents the complete results of these tests.

2.0 PRINCIPLE OF THE FLOW METER

The measuring principle applied is the time of flight method which has been successfully applied with other acoustic flow meter systems. In this method sound pulses are transmitted through the water between two opposing transducers, say A and C, in both directions as shown in Figure 1. Proper installation of the transducers allows the determination of the mean flow velocity at the elevation of the acoustic path, by measuring the difference in the travel times of the sound pulses moving in both directions along a path of known length and diagonal orientation to the flow.

If the time of travel for the sound pulse from A to C is designated by t_{AC} and on the return from C to A by t_{CA}, then for zero flow one obtains

$$t_{AC} = t_{CA} = L/C \qquad (1)$$

where: L = the length of the acoustic path in metres (m) and C = the velocity of sound in water which, depending on water temperature varies between 1400 m/s and 1500 m/s. If there is a flow as shown in Figure 1, the travel time of the sound pulse A to C will be smaller than from C to A. These times are given as

$$t_{AC} = \frac{L}{C + V_A \cos\theta} \quad (2)$$

and

$$t_{CA} = \frac{L}{C - V_A \cos\theta} \quad (3)$$

where V_A, θ and L are identified in Figure 1. If one now assumes that the velocity of sound C is the same for both pulses, the flow velocity can be obtained from equations (2) and (3) as

$$V_A = \frac{L}{2\cos\theta} \left[\frac{1}{t_{AC}} - \frac{1}{t_{CA}} \right] \quad (4)$$

The two sound pulses are transmitted simultaneously, thereby assuring transmission through water having the same temperature and thus the same speed of sound. The two transit times are individually measured using acoustic pulses with unique signatures. Each individual flow measurement is automatically computed and checked by a computer using the established values of L and θ. A measurement is rejected when the measured flow velocity or velocity of sound does not lie between predetermined upper and lower limits. Direct digitalization and the programming of "time windows" for the reception of the pulse signals greatly improves the reliability and accuracy of the measurements.

3.0 EXPERIMENTAL EQUIPMENT AND PROCEDURE

3.1 Towing Tank

The towing tank used to test the meter is constructed of reinforced concrete, is founded on piles and is 122 metres long and 5 metres wide. The full depth of the tank is 3 metres, of which 1.5 metres are below ground level. Normally the water depth is maintained at 2.7 metres. Concrete was chosen for its stability and to reduce possible vibrations and convection currents.

At one end of the tank is an overflow weir. Waves arising from towed current meters and their suspensions are washed over the crest, thereby reducing wave reflections. Parallel to the sides of the tank perforated beaches serve to dampen lateral surface wave disturbances.

3.2 Towing Carriage

The carriage is 3 metres long, 5 metres wide, weighs 6 tonnes and travels on four precision machined steel wheels. The carriage is operated in three overlapping speed ranges:

0.005 m/s	-	0.06 m/s
0.05 m/s	-	0.60 m/s
0.50 m/s	-	6.00 m/s

The maximum speed of 6.00 m/s can be maintained for 12 seconds. Tachometer generators connected to the drive shafts emit a voltage signal proportional to the speed of the carriage. A feedback control system uses these signals as input to maintain constant speed during tests.

The average speed data for the towing carriage is obtained by recording the voltage pulses emitted from a measuring wheel. This wheel is attached to the frame of the towing carriage and travels on one of the towing tank rails, emitting a pulse for each millimeter of travel. The pulses and measured time are collected and processed to produce an average towing speed with a micro computer data acquisition system. Analysis of the towing speed variability by Engel (1989), showed that for speeds between 0.2 m/s and 3.00 m/s, the error in the mean speed was less than 0.15% at the 99% confidence level. Occasionally, these tolerances are exceeded as a result of irregular occurrences such as "spikes" in the data transmission system of the towing carriage. Tests with such anomalies are automatically abandoned.

3.3 Transducer Suspension and Alignment

Each of the two transducers was suspended with a cylindrical rod, having a nominal diameter of 1 in(2.54 cm), attached to the end of a cantilevered beam which was clamped to the deck of the towing carriage as shown schematically in Figure 2. The transducers were set at a depth of 0.70 m which was sufficient to avoid any surface effects while at the same time minimizing the drag on the vertical suspension rods. The drag on these rods was further reduced by fitting plastic fairings over the submerged lengths. The beams and suspension rods were sufficiently braced to keep mechanical vibrations at a minimum. The test set-up given in Figure 2 resulted in an alignment of the sound beam with the towing direction of 24.3 degrees and a path length of 8.0 meters. The towing carriage with the suspension system is shown in Figure 3 and 4.

3.4 Test Procedure

The test procedure consisted of towing the suspended transducers through the water at a pre-set constant speed. As the towing carriage traveled along the tank, pairs of acoustic pulses were collected continuously with the flow meter's data acquisition system. Tests were conducted to:

(a) Provide five sets of data in order to directly compare the measured velocities with the reference velocities over the full range of velocities from 0.20 m/s to 3.00 m/s at intervals of 0.20 m/s.

(b) Obtain ten pairs of velocity data (V_A and V_C) (V_C = towing speeds) at specific towing speeds in order to assess the repeatability in the flow meter's performance. These pairs were obtained at towing speeds of 0.20 m/s, 0.60 m/s, 1.00 m/s, 1.60 m/s, 2.00 m/s, 2.60 m/s and 3.00 m/s.

All tests were conducted so that sampling of the acoustic pulses always began when the carriage passed the same pre-determined location in the towing tank in order to keep all characteristics unique to the towing carriage system constant. The tests were always made after sufficient time, usually from 4 to 10 minutes, had passed to allow disturbances in the water to subside. At the end of the waiting period the average measured residual velocity was about 0.009 m/s and the general direction was toward the head end of the tank. This meant that the meter would sense the towing velocity plus the net residual velocity toward the head end of the tank. Several tests with potassium permangenate crystals dropped into the stilled water while the towing carriage was at rest confirmed this behavior.

4.0 SOURCES OF ERRORS

The errors and uncertainties involved in determining the flow velocity with the flow meter can be attributed to the following sources:

(a) Errors and uncertainty as a result of determining the length of the acoustic path L, the angle of orientation θ, and the difference in the travel times of the acoustic pulse, say, Δt.

(b) Uncertainties related to the towing tank environment.

4.1 Errors due to Measurement of L, θ and Δt.

To facilitate the determination of the effect of measurement errors it is convenient to combine equations (1) and (2) to give the computed flow velocity as

$$V_A = \frac{C^2 \Delta t}{2L\cos\theta} \qquad (5)$$

The error in the computed flow velocity can be obtained from the total differential of equation (5) given as

$$dV_A = \frac{c^2}{2} \left[\frac{\partial V_A}{\partial L} dL + \frac{\partial V_A}{\partial \theta} d\theta + \frac{\partial V_A}{\partial \Delta t} d\Delta t \right] \qquad (6)$$

After determining the partial derivatives, substituting them into equation (6), combining equations (6) and (5) and simplifying, one obtains the relative error in the flow velocity as

$$\frac{dV_A}{V_A} = \frac{d\Delta t}{\Delta t} - \frac{dL}{L} + \tan\theta d\theta \qquad (7)$$

Equation (7) shows how the relative error in the flow velocity depends on the relative errors in the measurement of the acoustic path length, the angle of the acoustic path orientation and the difference in the pulse transit time from transducers A to C and C to A.

The uncertainty in the measurements of L over the length of 8 m should be no greater than about .010 m and therefore dL/L = 0.10%. The angle θ was determined by indirect means from measurements of the distance L and the distance x as shown in Figure 2. The error in the angle θ therefore depends on the error in the measurements of x and L. The angle θ is equal to the arc sin of x/L and the error in θ can be determined from the total differential given by

$$d\theta = \frac{\partial\theta}{\partial x}dx + \frac{\partial\theta}{\partial L}dL \qquad (8)$$

After determining the partial derivatives, substituting them into equation (8) and simplifying, one obtains the relative error in the angle θ given as

$$d\theta = \pm \frac{\frac{x}{L}\left[\frac{dx}{x} + \frac{dL}{L}\right]}{\sqrt{1 - \left(\frac{x}{L}\right)^2}} \qquad (9)$$

Equation (9) shows that the error in the angle θ depends on the ratio x/L and the relative errors of L and x. For the present tests x/L = 0.411. It is also clear from equation (9) that the largest value of dθ occurs when dL/L and dx/x are of the same sign. One can expect that the measurement of the length x is less accurate than the measurement of the length L because it requires the correct location of the point P in Figure 5 to ensure a right angle APC. However, the error in measuring x should be no greater than 0.2%. Therefore, taking dL/L = 0.1% and dx/x = 0.2% the maximum error in the angle θ is about 0.00136 radians. Substituting the values for dL/L and dx/x into equation (7) and considering that the nominal angle θ = 24.3, one obtains

$$\frac{dV_A}{V_A} = \pm \left[\frac{d\Delta t}{\Delta t} + 0.039\right] \qquad (10)$$

Equation (10) expresses the maximum relative error in the flow velocity as the sum of the errors due to the positioning of the transducers and the relative instrument error $d\Delta t/\Delta t$ which is a function of the electronics of the instrument. The error due to positioning of the transducers is a fixed quantity once the transducers are secured in their place and is a systematic error for these tests.

The timing accuracy of the flow meter depends on the following factors:

(a) Unknown signal delay

Signal delay is the sum of all non-water time delays in the system. They are constant and, in this application, equal in both the forward and reverse direction (ie: A to C and C to A). The forward and the reverse signal delay correct the measured travel time such that the results reflect the in-water travel time only. The maximum error due to this signal delay is +/- 0.037% of the measured velocity.

(b) Time base accuracy

Both forward and reverse travel time is measured using a digital counter driven by a precise and stable oscillator. The error in the time measurement is about +/- 0.005% of the measured velocity.

(c) Digitizing Error

Since travel time is measured using a digital counter, each travel time measurement is accurate to -1, +0 counts. Averaging over 10 measurements indicates an insignificant error of +/- 0.00028% of measured velocity.

(d) Signal to noise ratio.

The sonic signal to noise (from all sources) ratio is at least 40 decibels or greater. The very small variations in received signal detection time will be canceled through averaging.

(e) Zero offset

The zero offset occurs because a signal delay occurs in one direction and not in the other. This effect is usually attributable to small differences in transducers. The error is based on tests with randomly paired transducers using a +/- 20 nanosecond time difference between transducers. This effect accounts for a constant offset of about 0.003 m/s. Clearly percent error is largest at the lowest velocities, decreasing as flow velocities increase.

The relative error $d\Delta t/\Delta t$ from the above five sources, after some conversion to percentages, can therefore be expressed as

$$\frac{d\Delta t}{\Delta t} = \pm \left[0.042 + \frac{0.3}{V_C} \right] \qquad (11)$$

Finally, combining equations (10) and (11) the total maximum relative percent error dV_A/V_A can be expressed as

$$\frac{dV_A}{V_A} = \pm \left[0.081 + \frac{0.3}{V_C} \right] \qquad (12)$$

It is clear from equation (12) that the most significant component in the total maximum relative error is that due to the zero offset, which is greatest at low velocities and decreases as velocities increase. The total effect of the other error components is quite small and should not affect the velocity measurement significantly. When the stream velocity is 0.20 m/s, the maximum expected error in the velocity measurement is about +/- 1.6% and this decreases to about +/- 0.2% when the stream velocity is 3.0 m/s.

4.2 Factors Related to the Towing Tank Environment

4.2.1 Effect of Vibrations

Vibrations which may be set up in the mounting system of the flow meter may result in additional error in the flow velocity because such vibrations cause a change in the length of the acoustic path length L. This is reflected through the change in the measured value of Δt. The vibrations in the transducer supports were not measured and their effect is not known. However, the vibrations were kept as small as possible by minimizing the length of submersion of the transducer supports and fitting the latter with plastic fairings as shown in Figure 4.

4.2.2 Effect of Streamline Pattern

The streamline pattern as a result of the wake behind the leading transducer, can have a significant effect on the performance of the flow meter in the towing tank. Due to the non-hydro dynamic shape of the transducers, there is some mounding of the free water surface in their vicinity, resulting in small lateral velocities which affect the flow field along the sonic path. In addition, at each transducer face there is a small zone of stagnation, which yields zero velocity for that small segment of the acoustic path. The net effect of these influences will tend to result in velocities lower than the true velocity. Results from tests in closed conduits and flumes have shown differences up to 3%. These influences depend on the acoustic path length and decrease as path length becomes larger. For a given path length and transducer shape, the error due to the flow patterns can be expected to increase somewhat as velocity increases. To minimize this effect during the present tests, the lateral spacing between the transducers was made as large as possible (about 3.3 m).

4.2.3 Propagation of Surface Waves

Surface waves generated by towed objects in the towing tank have wave lengths which are small enough relative to the towing tank depth, to be considered as deep water waves. Although the wave lengths were not measured, the velocities created by any probable surface waves, at the depth of submergence of the transducers, should be considered to be negligible. Therefore, the effect of surface waves is not likely to contribute significantly to the uncertainty in the velocity measurement with the flow meter.

4.2.4 Effect of Residual Velocities

One of the most persistent sources of error that can be ascribed to the towing tank itself, is that due to residual movement of the water. Part of the difficulty may be caused by density currents and part by the disturbance of the previous run. The towing tank at NWRI is partly above ground and therefore is subject to density currents which arise from changes in temperature which do not occur simultaneously at all parts of the tank. The temperature distribution was not measured during the tests. However during the winter months, the vertical temperature gradients in the towing tank are very small. Although temperature gradients in the summer time can be expected to be larger, it is expected that thermally driven velocities in the tank should be very small. In addition, it is expected that the disturbance created by the transducers and their rod suspensions when towed at the high speeds will create enough mixing to remove any significant movement of water as a result of thermal gradients.

Residual velocities as a result of disturbances of the previous run are most troublesome at the low speeds because of their relative magnitude even after considerable time has expired before the next test is begun. As the towing speeds increase, the magnitude of the residual velocities increase, but they decay faster, and after a relatively short time their magnitude relative to the towing speed is small. However, one may expect that the residual velocities are not uni-directional but instead occur in cellular circulation patterns along the tank. Therefore, the effect of these residual velocities is not likely to be accumulative but rather be reduced by the canceling out of circulations going in different directions. Nevertheless, care was taken during the tests to allow the water in the towing tank to settle down as much as possible, especially at the low speeds,to ensure that the effect of residual velocities was eliminated as much as possible. Typically, residual velocities measured with the flow meter, while the towing carriage was at rest at the head end, were of the order of 0.01 m/s.

4.2.5 Uncertainty in Towing Carriage Speed

The uncertainty in the towing carriage speed is less than 0.15% at the 99% confidence level (Engel, 1989). This performance is based on data obtained while the transducers were being towed. This shows that the towing carriage was not significantly affected by any vibrations that may have been set up as a result of towing the transducers through the water. Therefore, any errors due to the towing carriage are small.

5.0 DATA ANALYSIS

The final velocity obtained with the flow meter is the average of all the velocity samples collected at a given towing speed. However, because the data acquisition system produces an output of velocity samples every 10 seconds, there were up to 37 samples at a towing speed of 0.20 m/s. This number of samples decreased as towing speed increased. As a result, the flow meter produced only from two to three velocity samples at the towing speed of 3.00 m/s. This imbalance in sample size to compute the average velocities obtained with the flow meter could not be avoided within the time limit of this study.

The average velocities were computed from the data samples of the flowmeter. The results are given in Table 1 to 12.

5.1 Measured Velocity Versus Carriage Velocity

The agreement between the velocity determined with the flowmeter and that obtained with the towing carriage was examined by plotting the measured velocity versus the carriage velocity from Tables 1 to 5 in Figures 5 to 9. For perfect agreement the plotted points would fall along the 45° line which is also shown in the plots. Examination of the plots reveals that the measured values tend to agree well at very low velocities. As velocities increase above 0.2 m/s the measured velocities underestimate the reference velocity and this deficit increases gradually as the latter increases. When the carriage velocity is 3.0 m/s the deficit in the measured velocity varies from - 2.1% to - 3.2%.

The relationship between the measured velocity and the carriage velocity appears to be quite linear. This can be demonstrated by a linear regression equation for the data in Figures 5 to 9 given by

$$V_A = 0.9726\ V_C + 0.0048 \qquad (13)$$

The mean intercept is 0.0048 m/s. This positive departure from the expected value of 0.0 is largely due to small residual currents in the towing tank, the effect of which is greatest at the lowest velocities. The mean slope of 0.9726 is slightly less than the expected value of 1.0 and reflects the rate of change in the size of the deficit in the measured velocity. When the carriage velocity is 3.0 m/s, equation (13) underestimates the reference velocity by 2.6%. The gradual increase in the velocity deficit is in keeping with the flow pattern effects that can be expected as a result of the size and shape of the transducers. However, it is not known whether the departures of the intercepts and slopes from their expected values is entirely due to this cause.

5.2 Velocity Residuals

The velocity residuals are defined as the difference between the velocity measured with the flowmeter and the corresponding velocity of the towing carriage. The residuals are expressed in percent of the towing velocity given by

$$R_V = \left[\frac{V_A - V_C}{V_C} \right] 100\% \qquad (14)$$

where R_V is the dimensionless residual at a particular towing velocity, and the remaining variables have already been defined.

The values of R_V were plotted for each of the five data sets given in Tables 1 to 5 versus V_C in Figure 10. The plot shows that when velocities are at 0.2 m/s the flowmeter tends to over and under estimate the reference velocity. For velocities greater than 0.2 m/s, the meter consistently under estimates the reference velocity and this deficit increases, with the rate of change decreasing, as the reference velocity increases, reaching a maximum of about - 3.2% at a velocity of 3.0 m/s. The grouping of the plotted points is quite consistent and the scatter is probably due to conditions in the towing tank, such as residual currents and wakes created by towing the transducers through the water. The fact that the scatter is quite small indicates that great care was taken in assuring that the tank conditions were stable before each test was conducted. This general trend was also revealed in Figures 5 to 9.

The relative expected error given by equation (12) is superimposed on the plot in Figure 10 as upper and lower envelopes. These envelopes give the limits in the errors that can be expected due to the positioning of the transducers and flowmeter characteristics. When the carriage velocity is 0.2 m/s, the expected error should be within +/- 1.6%. This decreases to about +/- 0.2% when the carriage velocity is 3.0 m/s. It can be seen from Figure 10 that for velocities greater than 0.4 m/s, the velocity deficit exceeds the expected error. This excess can probably be largely attributed to the influence of the flow dynamics around the transducers as described in section 4.2.2.

5.3 Variability at a Given Towing Speed

The variability in the flow meter's ability to determine the towing velocity was examined by using values of R_v obtained from data in Tables 6 to 12 for a given nominal towing velocity repeated ten times. Values of R_v were used because it was not possible to repeat exactly the same towing velocity for each of the ten tests conducted. The effect of this discrepancy is minimized by using normalized velocities given as residuals. At each nominal velocity, means and standard deviations of the residuals were computed and these were used to determine the upper and lower confidence limits at the 95% level. The results are given in Figure 11, in which the mean residuals $\bar{R}_v$ are plotted as a function of the nominal towing speed. The plotted values of $\bar{R}_v$ confirm the general tendencies of the meter reflected in Figure 5 to 9 and Figure 10. The variability is greatest for $V_c = 0.2$ m/s and decreases as the velocity increases up to a value of 1.6 m/s. Thereafter, the variability starts to increase again slightly with an increase in velocity up to 3.0 m/s. The greater variability at the lower velocities is probably influenced by the residual currents in the towing tank. The variability for velocities greater than 1.6 m/s can be attributed to the fact that the number of velocity samples obtained with the meter decreased as the towing speed increased.

5.4 Flow Meter Coefficient

The behavior of a flow meter can often be best characterized by developing a performance coefficient which can then be evaluated over the operating range of the meter. Such a coefficient can be developed by using dimensional analysis. For a given flow meter, the measured time difference Δt should depend on the flow velocity, the length and orientation of the path length and the velocity of sound in the fluid medium. This can be expressed in a functional form by writing

$$\Delta t = f\,(V_c,\ L,\ \theta,\ C) \qquad (15)$$

where f denotes a function unique to a particular flow meter and all other terms have already been defined. Using the Buckingham Pi theorem equation (15) can be written in dimensionless form as

$$\frac{\Delta t C^2}{V_c L \theta} = F\left[\frac{V_c}{C},\ \theta\right] \qquad (16)$$

where F denotes another function unique to a particular instrument. The dependent dimensionless variable in equation (16) can be considered to be the flow meter coefficient, say K. By comparing equation (16) with equation (5) it is evident that a more meaningful coefficient can be obtained by replacing the parameter θ by the equivalently valid parameter cos(θ) and thus the coefficient can now be written as

$$K = \frac{\Delta t C^2}{V_c L \cos\theta} = F_1 \left[\frac{V_c}{C}, \cos\theta \right] \qquad (17)$$

It is also clear from comparison with equation (5) that, for an ideal flow meter, the value of K should have a value of 2.0. Any departure from this value of 2.0 is a measure of the performance characteristics of the flow meter and/or the effect of the environment in which the meter is operating. Equation (17) is plotted as K versus V_c/C for the test condition of θ=24.3 degrees in Figure 12. A curve was fitted through the plotted points to represent the average trend in the value of K. The plot shows that K is always less than the ideal value of 2.0 for values of V_c/C greater than about 0.00015, decreasing relatively quickly until V_c/C has reached a value of about 0.0005. Thereafter, the value of K declines gradually in an approximately linear fashion until the minimum value of K = 1.95, representing a deficit of 3.0%, has been reached at the maximum velocity tested. This trend in the value of K, as observed in the previous sections, reflects the effects of the towing tank environment and the characteristics of the flow meter.

6.0 CONCLUSIONS

6.1 Data plotted as flow meter velocity versus towing velocity indicate that the measured velocities tend to underestimate the towing carriage velocity. The relationship appeared to be quite linear. Linear regression with a coefficient of correlation of 0.99999 resulted in an intercept and slope of 0.0048 m/s and 0.9726 respectively, differing from the expected values of 0.0 and 1.0. The intercept is of the order of magnitude of the residual currents observed. The deficit in the slope of the regression equation is attributed largely to the effects of the flow dynamics around the transducers. These effects are expected to increase slightly with increase in velocity. The results show that the average maximum deficit in the measured velocity at the towing velocity of 3.0 m/s is about ≈ 2.6%.

6.2 The velocity residuals for the data in Figures 5 to 9 again reveal that the measured velocities consistently underestimate the towing carriage velocity for velocities greater than about 0.6 m/s and this deficit increases as the towing velocity increases. When the towing velocity is 3.0 m/s, the measured velocities underestimate by as much as about 3.2%. The velocity residuals exceed the error envelope, based on errors in measuring the acoustic path length, the orientation of the acoustic path and the characteristics of the flow meter, for all towing velocities greater than 0.4 m/s. The gradual increase in the velocity deficit with increasing towing speed is thought to be due to the flow field near the transducers. This effect would diminish with increasing length of acoustic path.

6.3 The variability of the velocities obtained with the flowmeter at the 95% confidence level are greatest when V_c = 0.2 m/s. The variability decreases as the towing speed increases until a value of 1.6 m/s has been reached. This is probably due to residual velocities in the towing tank. For towing speeds greater than 1.6 m/s variability increases gradually with the towing speed, because the number of velocity samples decreases as towing speed increases.

6.4 Using dimensional analysis a coefficient was developed, which for an ideal flow meter should have a value of 2.0 regardless of acoustic path length and orientation. For the present test data values of K were always less than 2.0 and this deficit increased as the towing velocity increased, reaching an average minimum value of 1.95, which represents a relative departure of about -2.5% from the ideal value of 2.0. These values of K again reflect the towing tank environment as well as the flow meter characteristics.

ACKNOWLEDGEMENT

The towing carriage was operated by B. Near. D. Doede prepared the photographs shown as Figure 3 and 4. The writers are grateful for their dedication and support.

REFERENCES

Engel, P. 1989. Preliminary Examination of the Variability in the Towing Carriage Speed. NWRI Contribution 89-89, National Water Research Institute, Burlington, Ontario, Canada.

TABLE 1

Data Summary for Calibration No.1

Test	V_C m/s	V_A m/s	V_{AMAX} m/s	V_{AMIN} m/s	n
1	0.2009	0.1997	0.2040	0.1943	14
2	0.4008	0.3946	0.3994	0.3892	12
3	0.5998	0.5890	0.5939	0.5824	9
4	0.7941	0.7806	0.7866	0.7758	4
5	0.9981	0.9790	0.9844	0.9754	5
6	1.2005	1.1693	1.1718	1.1642	5
7	1.4078	1.3763	1.3825	1.3710	3
8	1.6047	1.5677	1.5717	1.5641	3
9	1.8022	1.7547	1.7644	1.7428	3
10	1.9991	1.9545	1.9599	1.9517	3
11	2.2098	2.1598	2.1609	2.1585	2
12	2.4070	2.3423	2.3470	2.3392	3
13	2.6102	2.5348	2.5370	2.5326	2
14	2.8061	2.7230	2.7348	2.7111	2
15	2.9975	2.9149	2.9160	2.9137	2

V_C = average velocity of towing carriage

V_A = average velocity obtained with flowmeter

n = number of velocity samples to compute V

V_{AMAX} = maximum velocity obtained with flowmeter

V_{AMIN} = minimum velocity obtained with flowmeter

TABLE 2

Data Summary for Calibration No.2

Test	V_C m/s	V_A m/s	V_{AMAX} m/s	V_{AMIN} m/s	n
1	0.2006	0.2022	0.2096	0.1954	35
2	0.4005	0.3898	0.3988	0.3840	16
3	0.6011	0.5829	0.5912	0.5755	12
4	0.8102	0.7862	0.7917	0.7801	8
5	1.0040	0.9835	0.9899	0.9790	7
6	1.2057	1.1795	1.1840	1.1756	6
7	1.4124	1.3788	1.3816	1.3750	5
8	1.6104	1.5703	1.5748	1.5633	4
9	1.8046	1.7630	1.7695	1.7517	3
10	2.0073	1.9537	1.9645	1.9452	3
11	2.2140	2.1501	2.1720	2.1364	3
12	2.4102	2.3617	2.3704	2.3514	3
13	2.6124	2.5505	2.5691	2.5362	3
14	2.8067	2.7377	2.7505	2.7248	2
15	3.0054	2.9372	2.9408	2.9336	2

V_C = average velocity of towing carriage

V_A = average velocity obtained with flowmeter

n = number of velocity samples to compute V

V_{AMAX} = maximum velocity obtained with flowmeter

V_{AMIN} = minimum velocity obtained with flowmeter

TABLE 3

Data Summary for Calibration No. 3

Test	V_C m/s	V_A m/s	V_{AMAX} m/s	V_{AMIN} m/s	n
1	0.2006	0.2018	0.2051	0.1981	36
2	0.4006	0.3942	0.3983	0.3907	17
3	0.6007	0.5873	0.5922	0.5807	13
4	0.7987	0.7818	0.7878	0.7716	8
5	1.0020	0.9797	0.9846	0.9740	7
6	1.2092	1.1881	1.1941	1.1794	5
7	1.4044	1.3719	1.3775	1.3645	5
8	1.6035	1.5642	1.5706	1.5564	4
9	1.8047	1.7608	1.7750	1.7530	3
10	2.0047	1.9600	1.9702	1.9512	3
11	2.2058	2.1530	2.1510	2.1476	3
12	2.4053	2.3478	2.3581	2.3365	3
13	2.6053	2.5362	2.5486	2.5299	3
14	2.8062	2.7294	2.7306	2.7281	2
15	3.0057	2.9107	2.9277	2.8937	2

V_C = average velocity of towing carriage

V_A = average velocity obtained with flowmeter

n = number of velocity samples to compute V

V_{AMAX} = maximum velocity obtained with flowmeter

V_{AMIN} = minimum velocity obtained with flowmeter

TABLE 4

Data Summary for Calibration No. 4

Test	V_C m/s	V_A m/s	V_{AMAX} m/s	V_{AMIN} m/s	n
1	0.2009	0.1983	0.2045	0.1880	37
2	0.4010	0.3957	0.4000	0.3879	19
3	0.6016	0.5907	0.5947	0.5827	11
4	0.8038	0.7826	0.7872	0.7780	8
5	1.0059	0.9790	0.9872	0.9744	7
6	1.2063	1.1729	1.775	1.1683	6
7	1.4067	1.3724	1.3751	1.3683	5
8	1.6039	1.5637	1.5676	1.5571	4
9	1.8075	1.7746	1.7795	1.7668	4
10	2.0094	1.9513	1.9614	1.9470	4
11	2.2124	2.1581	2.1659	2.1493	3
12	2.4106	2.3466	2.3597	2.3256	3
13	2.6117	2.5362	2.5481	2.5219	3
14	2.8070	2.7296	2.7390	2.7200	3
15	3.0046	2.9419	2.9454	2.9384	2

V_C = average velocity of towing carriage

V_A = average velocity obtained with flowmeter

n = number of velocity samples to compute V

V_{AMAX} = maximum velocity obtained with flowmeter

V_{AMIN} = minimum velocity obtained with flowmeter

TABLE 5

Data Summary for Calibration No. 5

Test	V_C m/s	V_A m/s	V_{AMAX} m/s	V_{AMIN} m/s	n
1	0.2011	0.1998	0.2134	0.1910	35
2	0.4004	0.3957	0.3986	0.3926	19
3	0.6011	0.5899	0.5941	0.5866	13
4	0.8065	0.7879	0.7952	0.7830	8
5	1.0034	0.9798	0.9903	0.9742	7
6	1.2037	1.1744	1.1791	1.1702	6
7	1.3996	1.3665	1.3766	1.3553	5
8	1.6035	1.5688	1.5720	1.5623	4
9	1.8068	1.7625	1.7694	1.7595	4
10	2.0064	1.9591	1.9749	1.9402	4
11	2.2080	2.1627	2.1682	2.1519	3
12	2.4082	2.3480	2.3637	2.3219	3
13	2.6079	2.5402	2.5461	2.5310	3
14	2.8091	2.7368	2.7457	2.7278	2
15	3.0099	2.9356	2.9486	2.9226	2

V_C = average velocity of towing carriage

V_A = average velocity obtained with flowmeter

n = number of velocity samples to compute V

V_{AMAX} = maximum velocity obtained with flowmeter

V_{AMIN} = minimum velocity obtained with flowmeter

TABLE 6

Data Summary for Meter Repeatability

Test	V_C m/s	V_A m/s	V_{AMAX} m/s	V_{AMIN} m/s	n
1	0.2009	0.2009	0.2040	0.1943	14
2	0.2006	0.2022	0.2096	0.1954	35
3	0.2006	0.2018	0.2051	0.1981	36
4	0.2009	0.1983	0.2045	0.1880	37
5	0.2011	0.1998	0.2134	0.1910	35
6	0.2009	0.2031	0.2122	0.1976	36
7	0.2009	0.2043	0.2145	0.1964	30
8	0.2012	0.2002	0.2080	0.1927	36
9	0.2008	0.1966	0.2052	0.1904	39
10	0.2008	0.2018	0.2115	0.1942	38

V_C = average velocity of towing carriage

V_A = average velocity obtained with flowmeter

n = number of velocity samples to compute V

V_{AMAX} = maximum velocity obtained with flowmeter

V_{AMIN} = minimum velocity obtained with flowmeter

TABLE 7

Data Summary for Meter Repeatability

Test	V_C m/s	V_A m/s	V_{AMAX} m/s	V_{AMIN} m/s	n
1	0.5998	0.5890	0.5939	0.5824	9
2	0.6011	0.5829	0.5912	0.5755	12
3	0.6007	0.5873	0.5922	0.5807	13
4	0.6016	0.5907	0.5947	0.5827	11
5	0.6011	0.5899	0.5941	0.5866	13
6	0.6009	0.5916	0.5968	0.5869	13
7	0.6010	0.5918	0.5984	0.5884	13
8	0.6008	0.5888	0.5938	0.5848	13
9	0.6001	0.5868	0.5899	0.5818	13
10	0.6015	0.5903	0.5932	0.5878	13

V_C = average velocity of towing carriage

V_A = average velocity obtained with flowmeter

n = number of velocity samples to compute V

V_{AMAX} = maximum velocity obtained with flowmeter

V_{AMIN} = minimum velocity obtained with flowmeter

TABLE 8

Data Summary for Meter Repeatability

Test	V_C m/s	V_A m/s	V_{AMAX} m/s	V_{AMIN} m/s	n
1	0.9981	0.9790	0.9844	0.9754	5
2	1.0040	0.9835	0.9899	0.9790	7
3	1.0020	0.9797	0.9846	0.9740	7
4	1.0059	0.9790	0.9872	0.9744	7
5	1.0034	0.9798	0.9903	0.9742	7
6	1.0071	0.9868	0.9936	0.9815	7
7	1.0084	0.9869	0.9899	0.9830	7
8	1.0071	0.9856	0.9944	0.9791	7
9	1.0076	0.9842	0.9877	0.9808	7
10	1.0091	0.9828	0.9875	0.9786	7

V_C = average velocity of towing carriage

V_A = average velocity obtained with flowmeter

n = number of velocity samples to compute V

V_{AMAX} = maximum velocity obtained with flowmeter

V_{AMIN} = minimum velocity obtained with flowmeter

TABLE 9

Data Summary for Meter Repeatability

Test	V_C m/s	V_A m/s	V_{AMAX} m/s	V_{AMIN} m/s	n
1	1.6047	1.5677	1.5717	1.5641	3
2	1.6104	1.5703	1.5748	1.5633	4
3	1.6035	1.5642	1.5706	1.5564	4
4	1.6039	1.5637	1.5676	1.5571	4
5	1.6035	1.5688	1.5720	1.5623	4
6	1.6071	1.5626	1.5724	1.5495	5
7	1.6070	1.5635	1.5714	1.5568	5
8	1.6046	1.5653	1.5715	1.5604	5
9	1.6054	1.5719	1.5749	1.5664	5
10	1.6063	1.5704	1.5785	1.5685	5

V_C = average velocity of towing carriage

V_A = average velocity obtained with flowmeter

n = number of velocity samples to compute V

V_{AMAX} = maximum velocity obtained with flowmeter

V_{AMIN} = minimum velocity obtained with flowmeter

TABLE 10

Data Summary for Meter Repeatability

Test	V_C m/s	V_A m/s	V_{AMAX} m/s	V_{AMIN} m/s	n
1	1.9991	1.9545	1.9599	1.9717	3
2	2.0073	1.9537	1.9645	1.9452	3
3	2.0047	1.9600	1.9702	1.9512	3
4	2.0094	1.9513	1.9614	1.9470	4
5	2.0064	1.9591	1.9749	1.9402	4
6	2.0067	1.9571	1.9612	1.9508	4
7	2.0070	1.9541	1.9592	1.9512	4
8	2.0075	1.9665	1.9719	1.9621	4
9	2.0059	1.9727	1.9761	1.9693	2
10	2.0060	1.9526	1.9553	1.9486	3

V_C = average velocity of towing carriage

V_A = average velocity obtained with flowmeter

n = number of velocity samples to compute V

V_{AMAX} = maximum velocity obtained with flowmeter

V_{AMIN} = minimum velocity obtained with flowmeter

TABLE 11

Data Summary for Meter Repeatability

Test	V_C m/s	V_A m/s	V_{AMAX} m/s	V_{AMIN} m/s	n
1	2.6102	2.5348	2.5370	2.5326	2
2	2.6124	2.5505	2.5691	2.5362	3
3	2.6053	2.5362	2.5486	2.5299	3
4	2.6117	2.5362	2.5481	2.5219	3
5	2.6079	2.5402	2.5461	2.5310	3
6	2.6023	2.5493	2.5505	2.5480	2
7	2.6027	2.5345	2.5410	2.5279	2
8	2.6051	2.5484	2.5497	2.5470	2
9	2.6057	2.5486	2.5491	2.5480	2
10	2.6081	2.5460	2.5534	2.5386	2

V_C = average velocity of towing carriage

V_A = average velocity obtained with flowmeter

n = number of velocity samples to compute $\bar{V}$

V_{AMAX} = maximum velocity obtained with flowmeter

V_{AMIN} = minimum velocity obtained with flowmeter

TABLE 12

Data Summary for Meter Repeatability

Test	V_C m/s	V_A m/s	V_{AMAX} m/s	V_{AMIN} m/s	n
1	2.9975	2.9149	2.9160	2.9137	2
2	3.0054	2.9372	2.9408	2.9336	2
3	3.0057	2.9107	2.9277	2.8937	2
4	3.0046	2.9419	2.9454	2.9384	2
5	3.0099	2.9356	2.9486	2.9226	2
6	3.0061	2.9475	2.9557	2.9393	2
7	3.0077	2.9034	2.9056	2.9011	2
8	3.0087	2.9109	2.9204	2.9014	2
9	3.0095	2.9298	2.9353	2.9243	2
10	3.0118	2.9275	2.9373	2.9176	2

V_C = average velocity of towing carriage

V_A = average velocity obtained with flowmeter

n = number of velocity samples to compute V

V_{AMAX} = maximum velocity obtained with flowmeter

V_{AMIN} = minimum velocity obtained with flowmeter

TABLE 13

Linear Regression Coefficients

Calibration Number	m	a m/s	r
1	0.96981	0.0085	0.99999
2	0.97599	0.0000	0.99998
3	0.96995	0.0088	0.99998
4	0.97368	0.0023	0.99997
5	0.97370	0.0044	0.99999
Mean	0.97263	0.0048	
St. Dev.	0.00268	0.0039	

a = intercept
m = slope

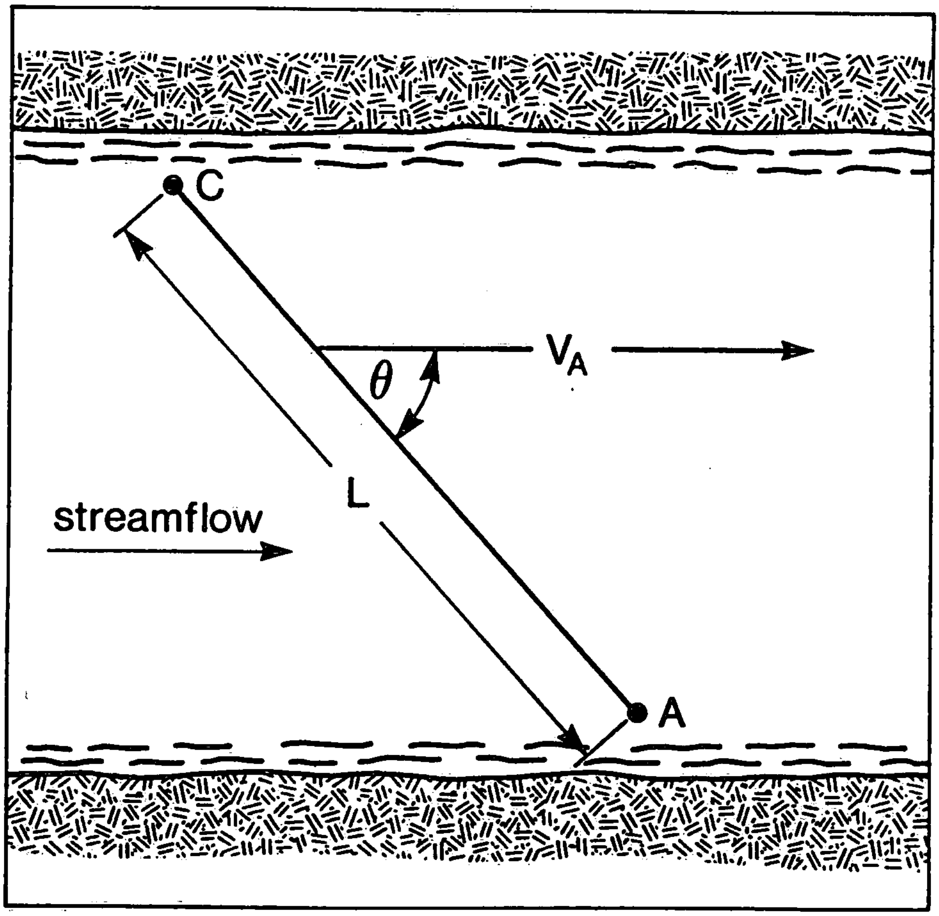

Figure 1 Definition diagram for acoustic flow meter operation

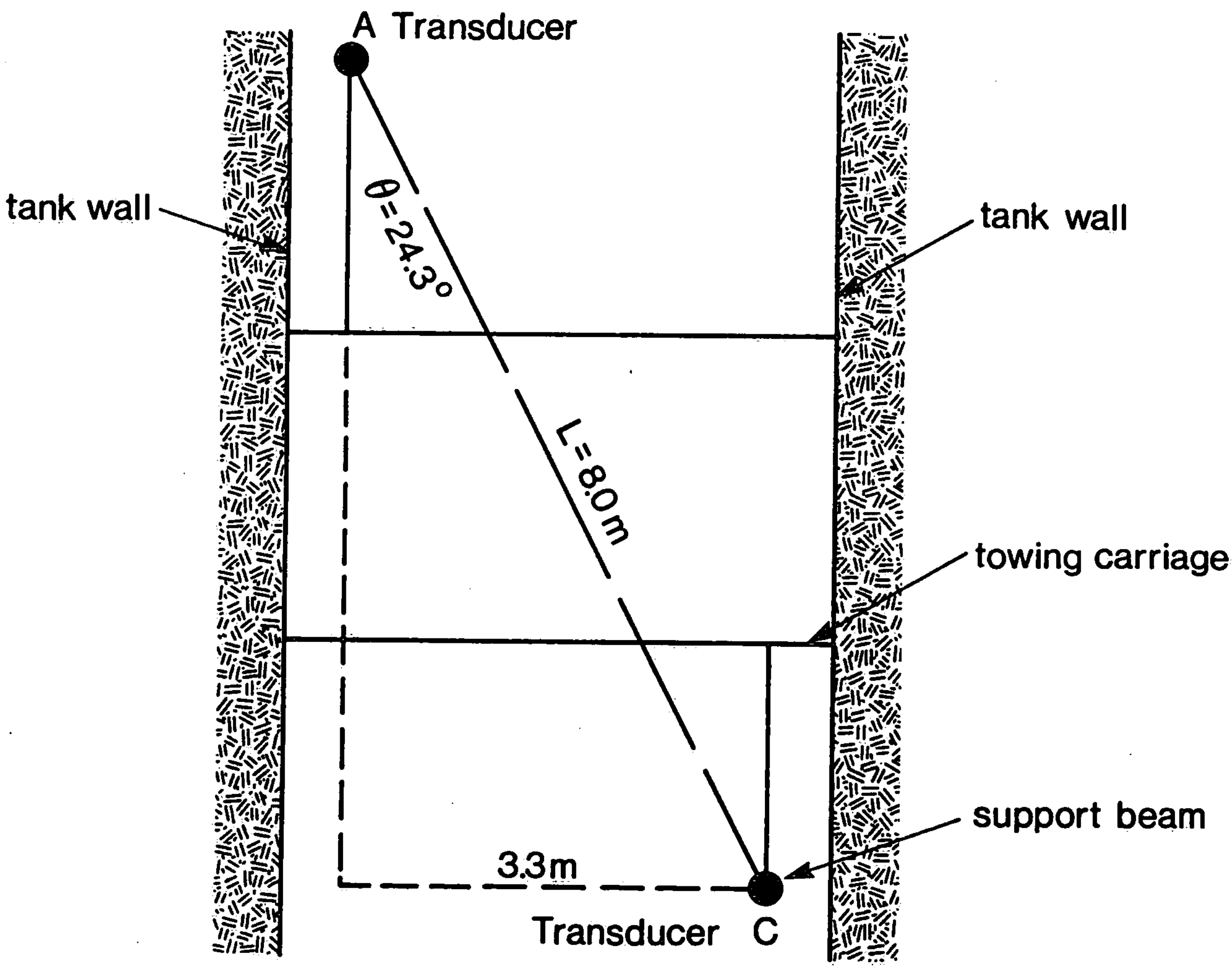

Figure 2 Schematic layout of transducers for present tests

Figure 3 Fairings on meter support

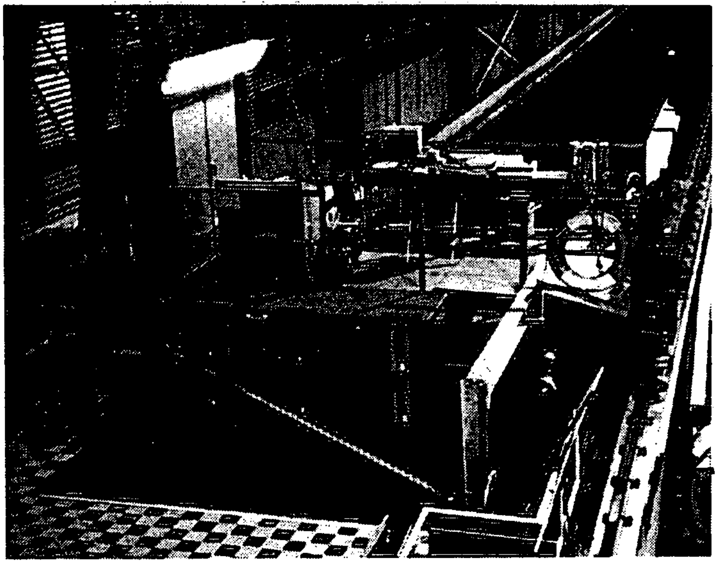

Figure 4 Towing carriage and suspension of rear transducer

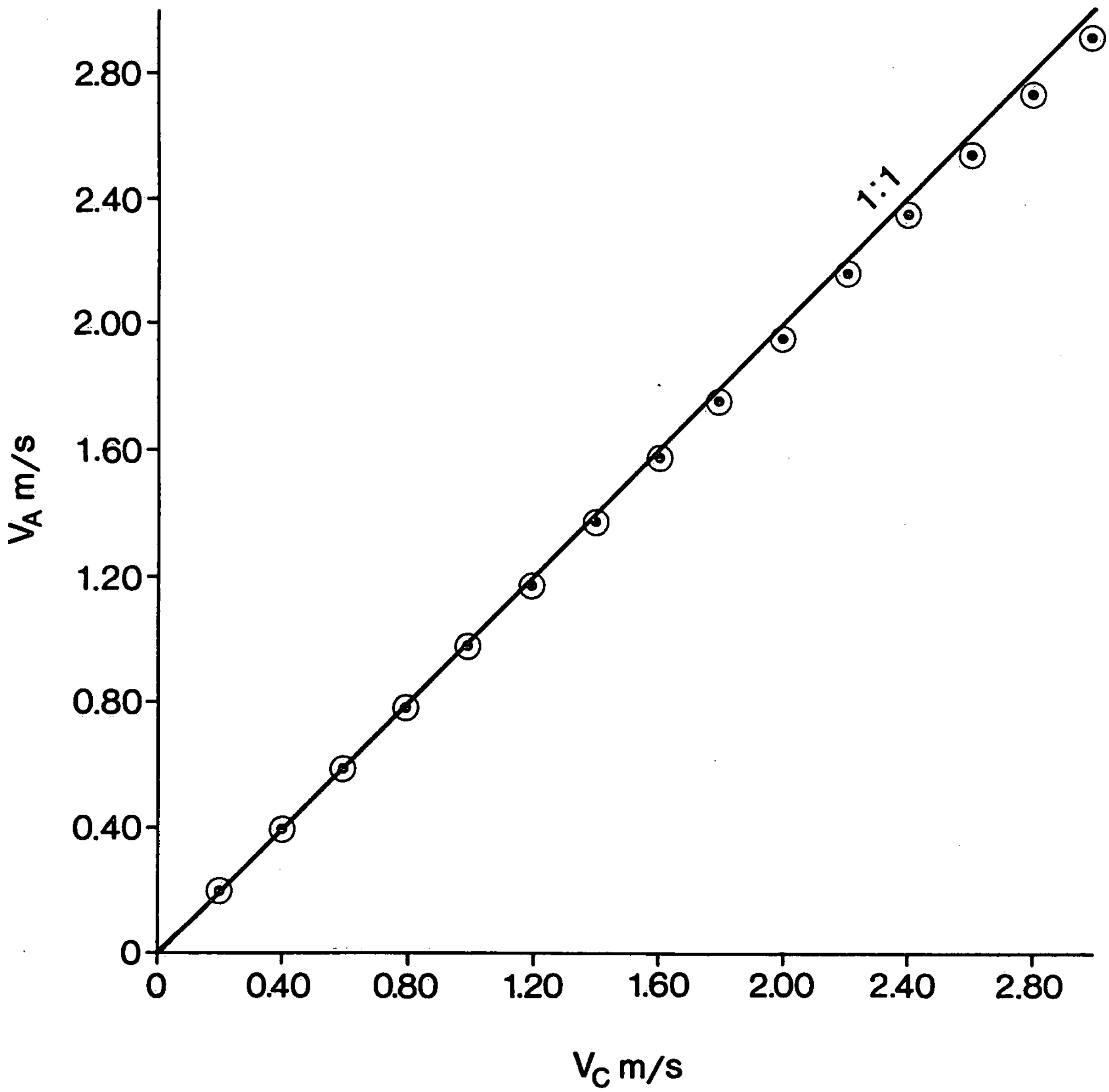

Figure 5 Measured velocity vs carriage velocity No. 1

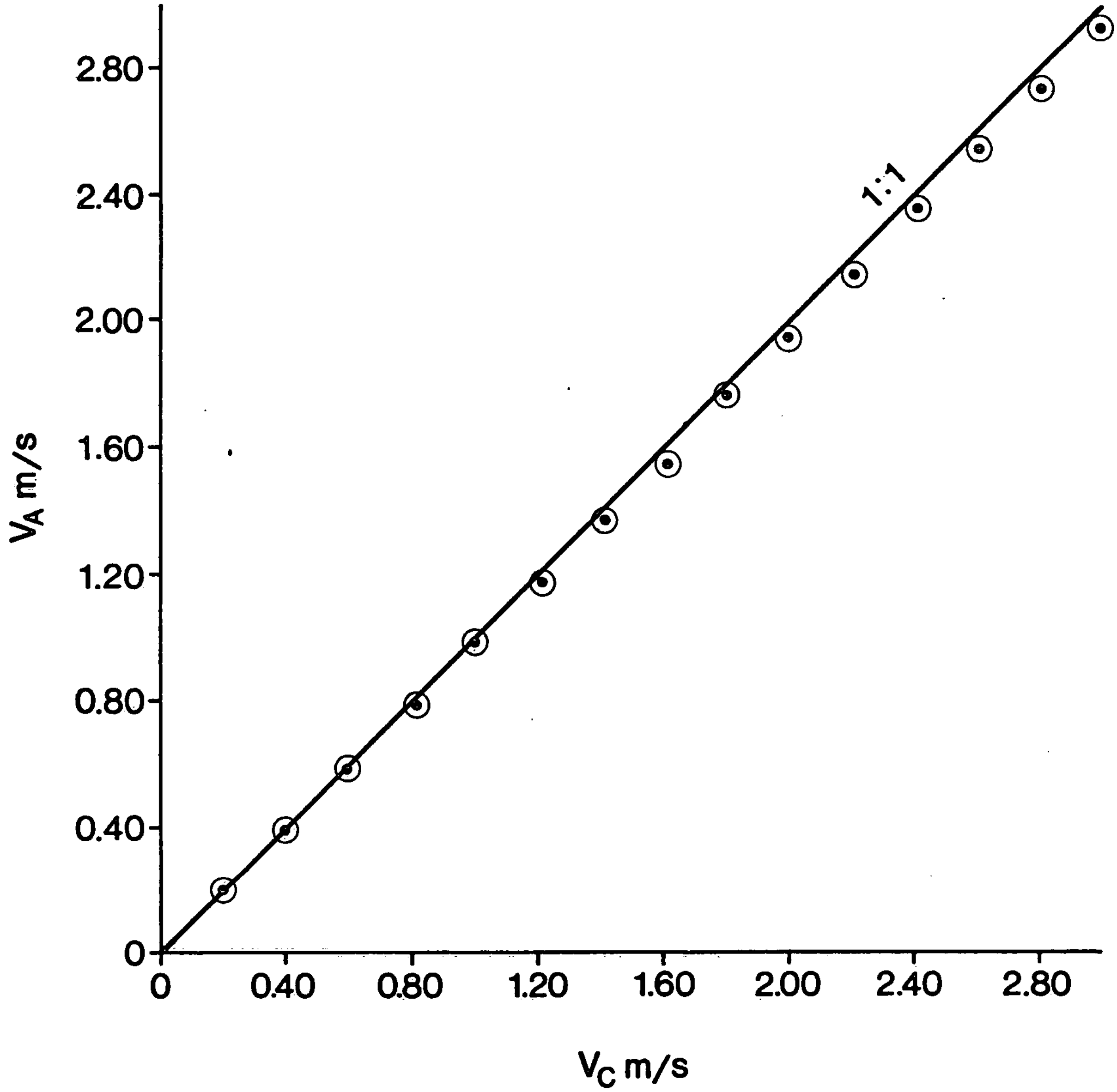

Figure 6 Measured velocity vs carriage velocity No. 2

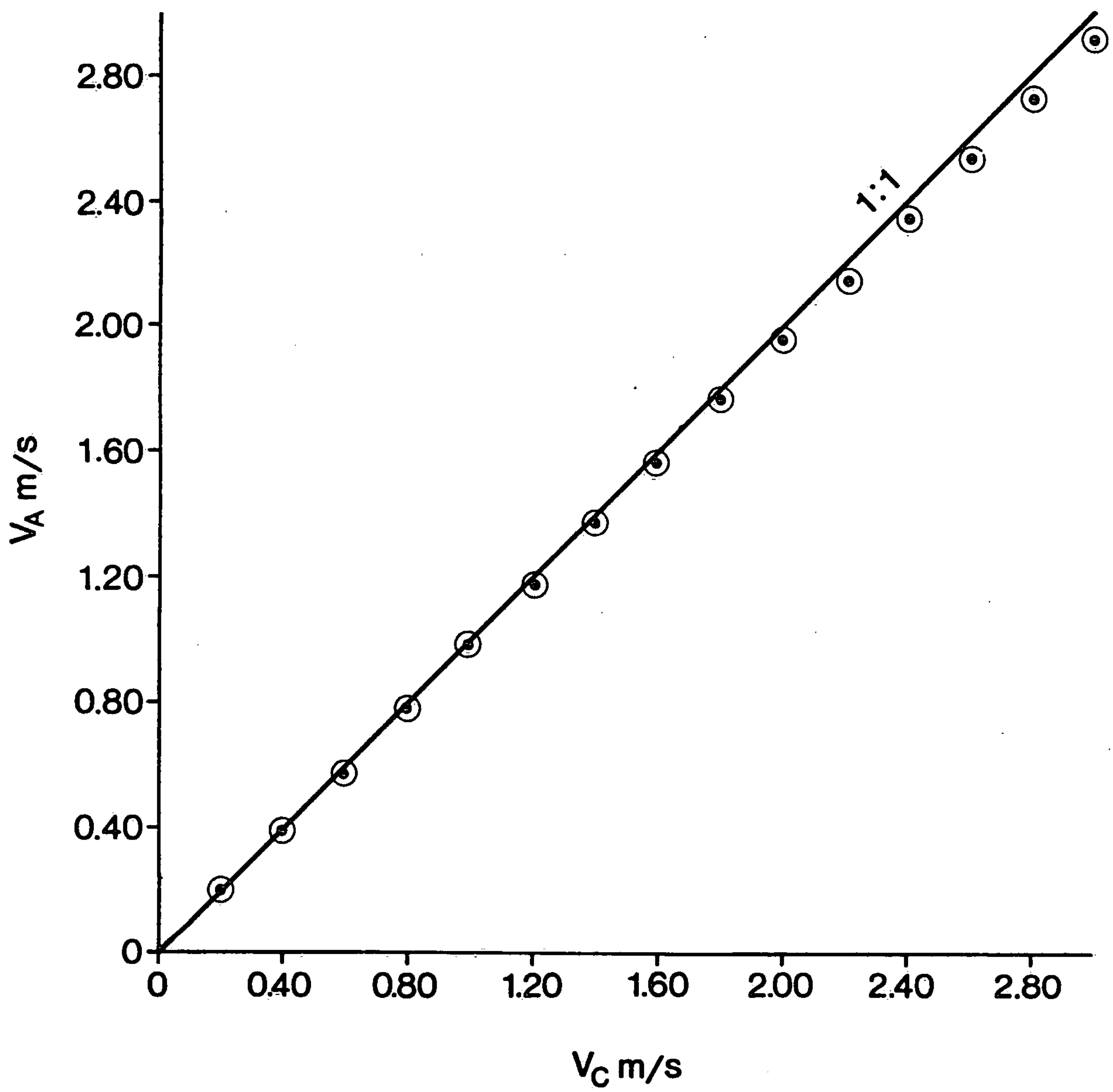

Figure 7 Measured velocity vs carriage velocity No. 3

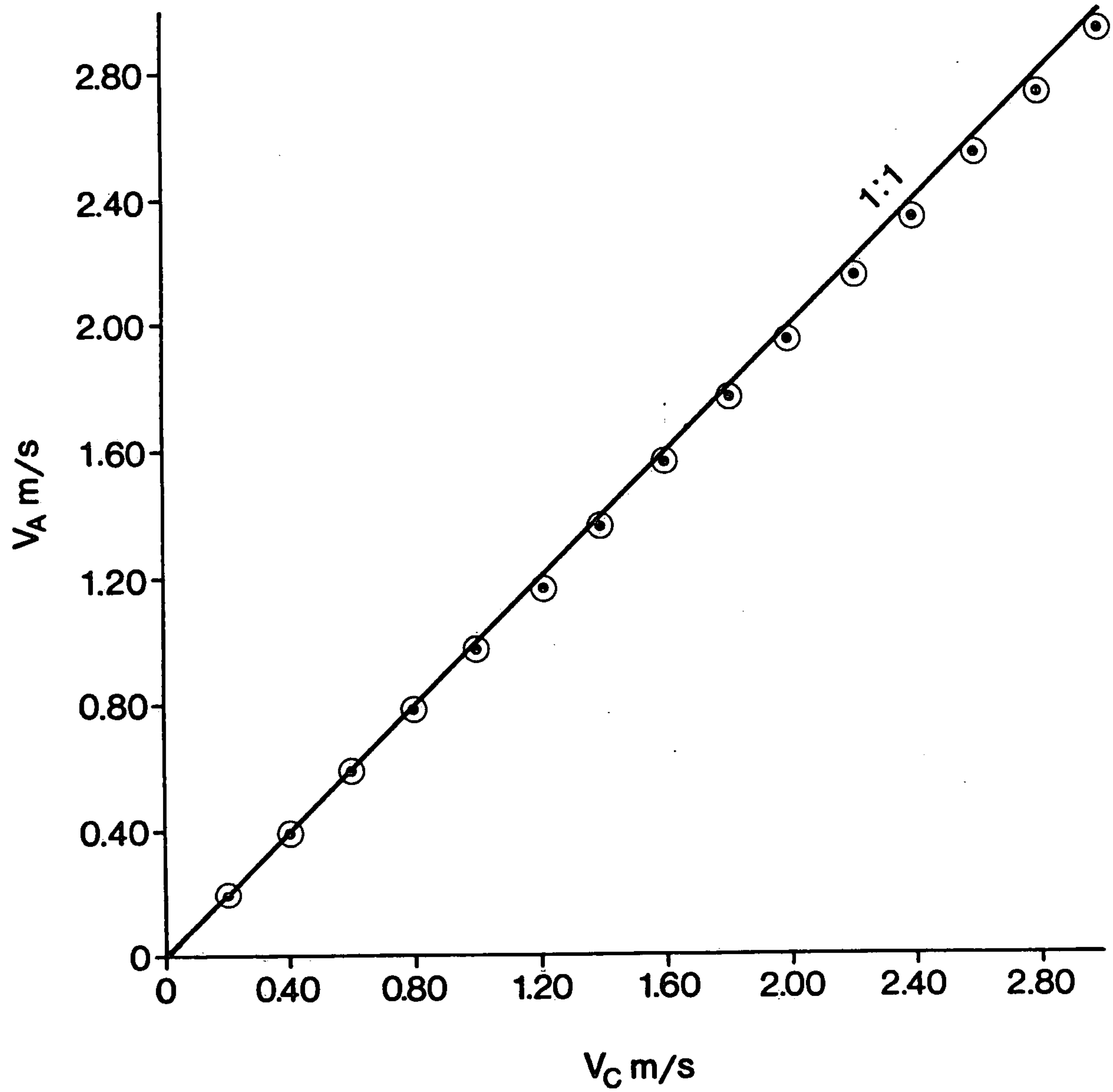

Figure 8 Measured velocity vs carriage velocity No. 4

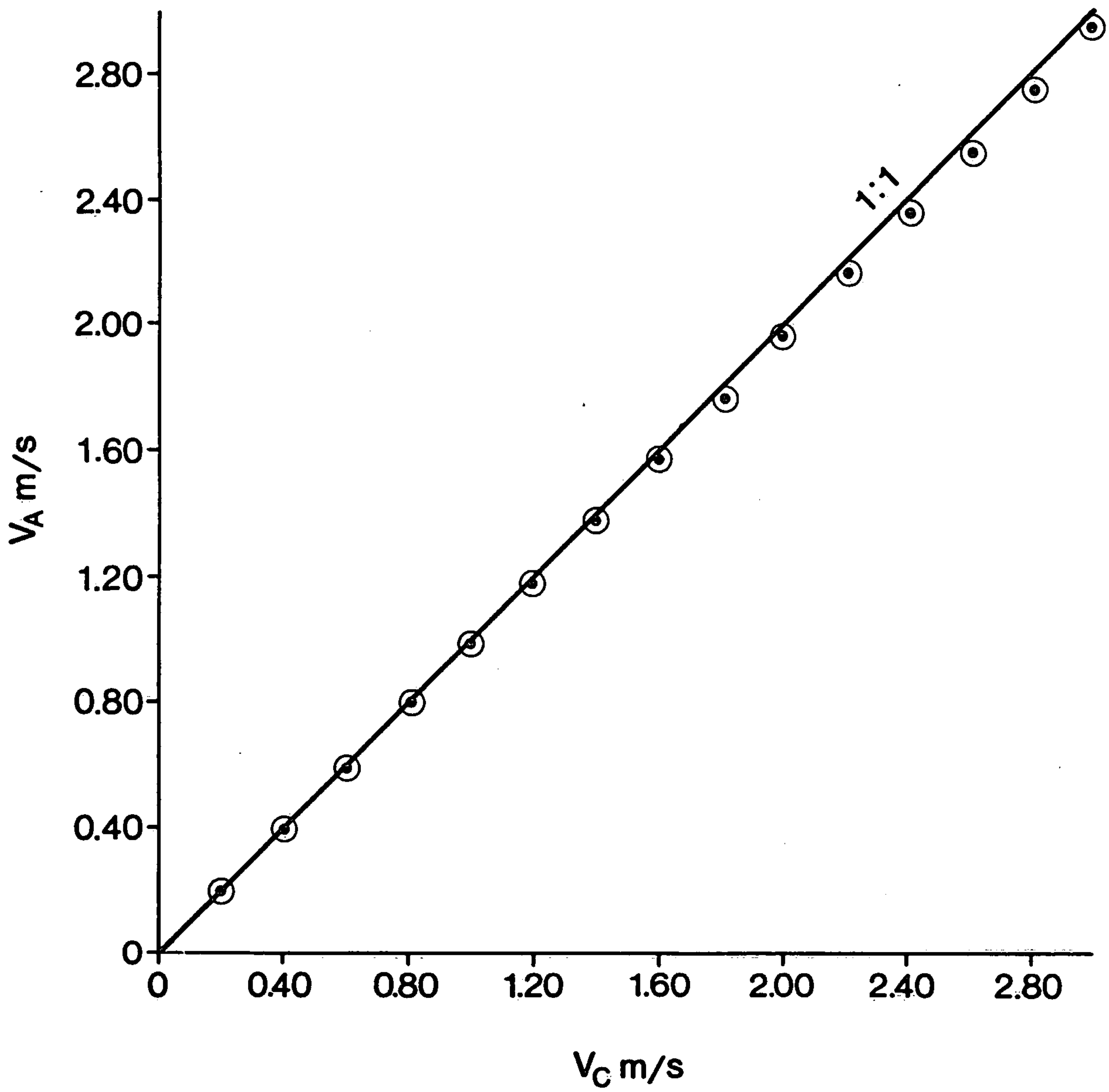

Figure 9 Measured velocity vs carriage velocity No. 5

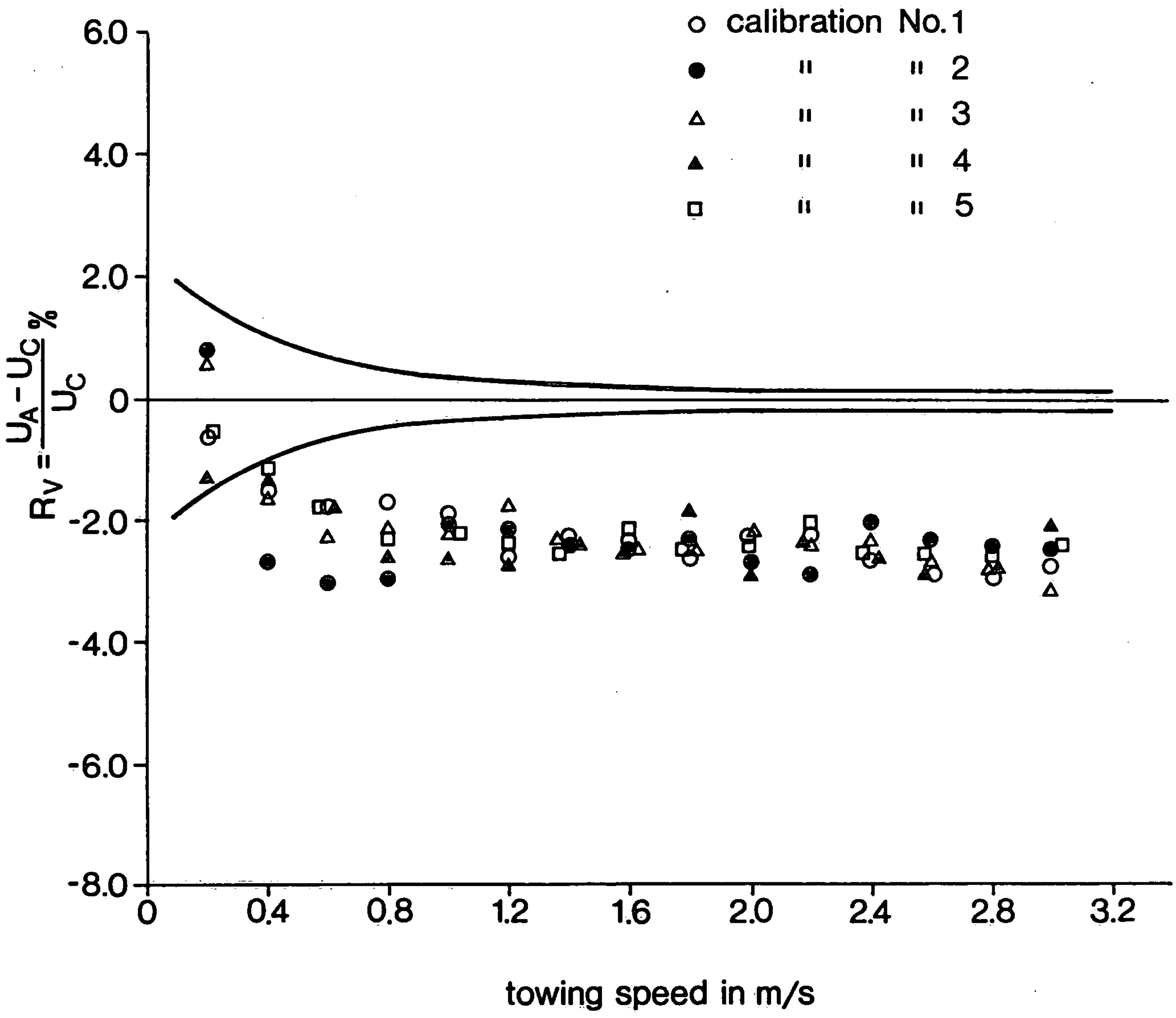

Figure 10 Residuals as a function of towing speed

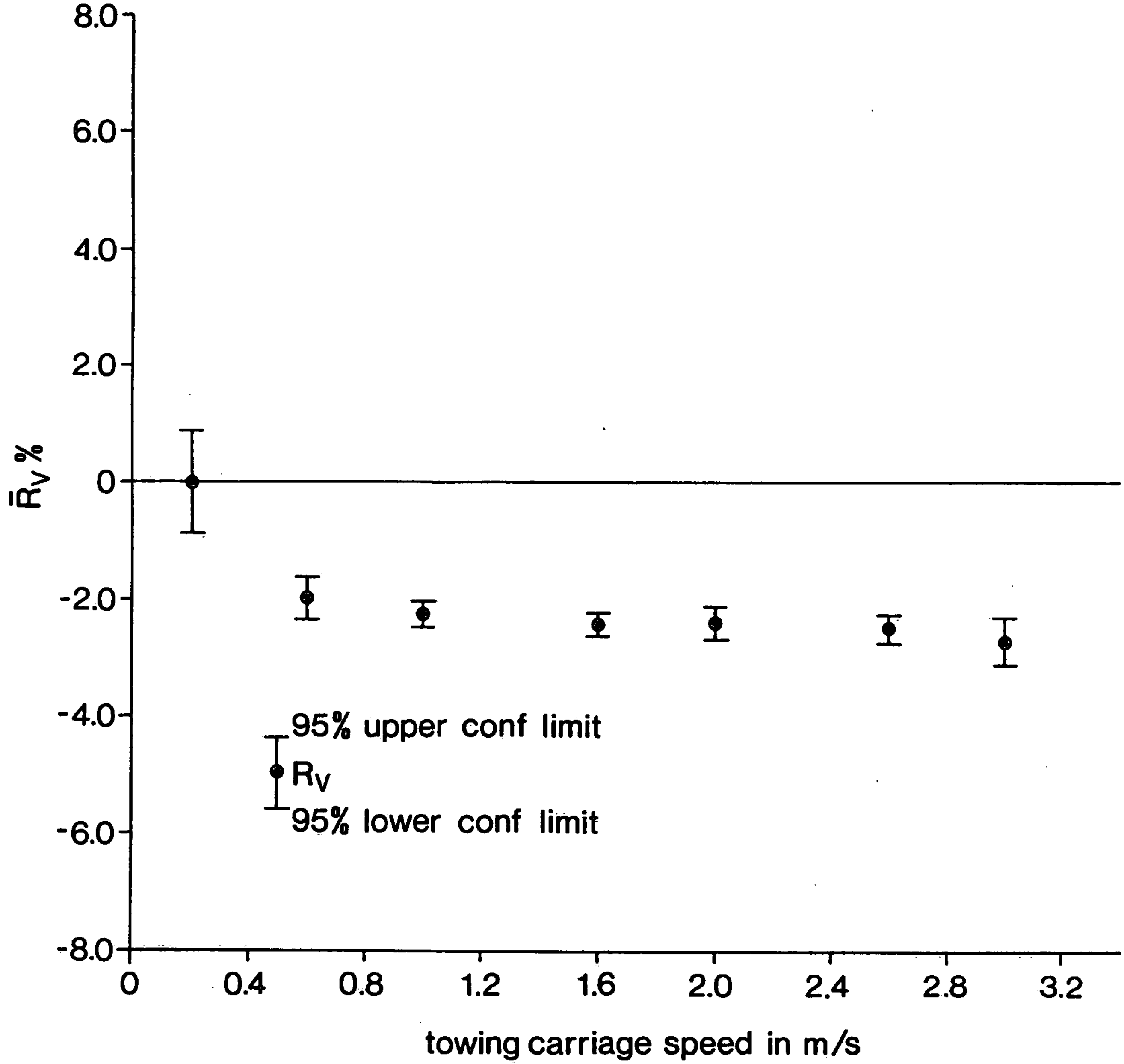

Figure 11 Variability in computed velocity at normal towing carriage speeds

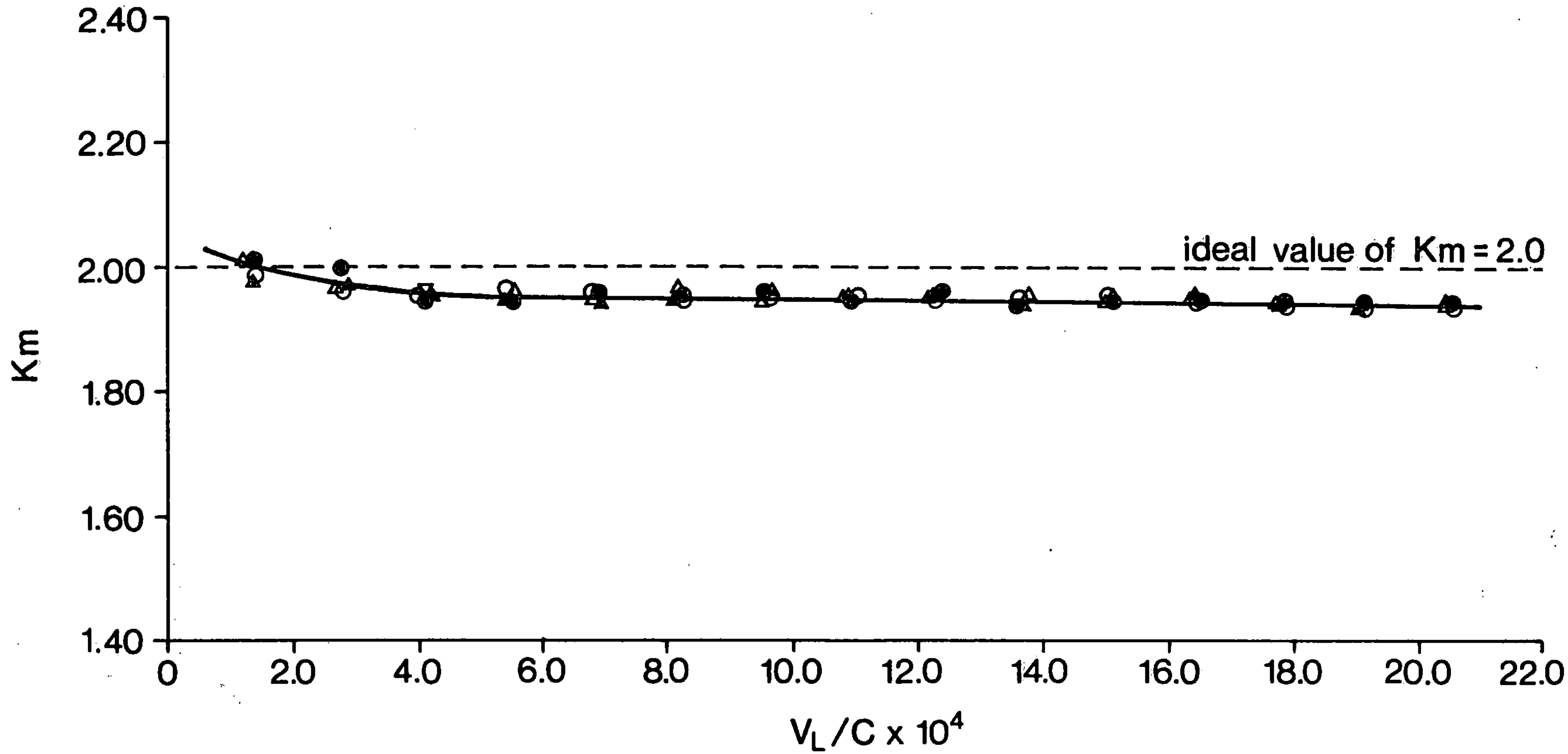

Figure 12 Behaviour of meter performance factor

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