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UNCERTAINTY IN THE SIMULTANEOUS CALIBRATION OF FOUR ROD SUSPENDED PRICE CURRENT METERS

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MANAGEMENT PERSPECTIVE

The importance of water quality monitoring has made it necessary to improve the accuracy of discharge measurements. One of the factors contributing to the error in a flow velocity measurement is the uncertainty in the current meter calibration itself. In Canada, calibration of current meters are obtained in the towing tank of the Hydraulics Laboratory (HL) at the National Water Research Institute (NWRI). Current meters can be calibrated one at a time or several meters simultaneously. The towing tank is wide enough to accommodate four current meters simultaneously and there are obvious operational and economic advantages to this towing configuration. Data from careful, repetitive tests showed that the accuracy of meter calibrations depends on the number of meters calibrated simultaneously for velocities less than one meter per second. The results provide important information for the development of data quality control standards and development of an updated calibration strategy by the Surveys and Information Systems Branch (SISB) for measurement of flow in rivers with solid ice cover.

SOMMAIRE À L'INTENTION DE LA DIRECTION

En raison de l'importance accordée à la surveillance de la qualité de l'eau, il a fallu rendre plus précises les mesures du débit. L'incertitude au niveau de l'étalonnage du courantomètre lui-même est un des facteurs d'erreur de la mesure du débit. Au Canada, l'étalonnage des courantomètres est effectué dans un canal à chariot mobile du laboratoire d'hydraulique de l'Institut national de recherche sur les eaux (INRE). On peut étalonner les courantomètres individuellement ou plusieurs à la fois. Le canal à chariot mobile est suffisamment large pour recevoir quatre appareils à la fois et cette configuration du canal présente des avantages opérationnels et économiques évidents. Les données provenant d'essais répétés effectués avec soin ont montré que la précision de l'étalonnage des appareils dépend du nombre d'appareils étalonnés en même temps dans le cas de vitesses inférieures à un mètre par seconde. Les résultats nous fournissent des informations importantes pour l'élaboration de normes sur le contrôle de la qualité des données et l'élaboration d'une meilleure stratégie d'étalonnage par la Direction des relevés et des systèmes d'information pour la mesure du débit dans des rivières entièrement recouvertes de glace.

ABSTRACT

Five Price winter meters were calibrated together with other, similar current meters in a towing tank, four at a time, repeated ten times, for a total of fifty calibrations. Analysis showed that, accuracy of the calibration of the rod suspended meters depends on the number of meters calibrated simultaneously. Comparison with the same meters calibrated one at a time showed that uncertainties are significantly greater for meters calibrated four at time for velocities less than 0.7 m/s with presently used calibration procedures. Results suggest that longer settling times are required before each run at velocities less than 0.7 m/s when four meters are calibrated at the same time. Tests to investigate settling time requirements have been recommended.

RÉSUMÉ

Dans un canal à chariot mobile, cinq courantomètres d'hiver de marque Price ont été étalonnés avec d'autres appareils similaires, dix fois chacun, pour un total de cinquante étalonnages. Les appareils étaient placés par groupe de quatre. L'analyse a montré que la précision de l'étalonnage des appareils suspendus à une tige dépend du nombre d'appareils étalonnés en même temps. Une comparaison portant sur les mêmes courantomètres étalonnés individuellement a montré que les incertitudes étaient significativement plus importantes pour les appareils étalonnés par groupe de quatre lorsque la vitesse était inférieure à 0,7 m par seconde avec la méthode employée à l'heure actuelle. Les résultats semblent indiquer que, dans le cas de l'étalonnage d'un groupe de quatre appareils, il faut attendre plus longtemps entre chaque essai lorsque la vitesse est inférieure à 0,7 m par seconde. On a recommandé l'exécution d'essais portant sur les temps d'attente.

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1. INTRODUCTION

The importance of water quality monitoring has made it necessary to improve the accuracy of discharge measurements. The determination of river discharge requires the measurement of the flow velocity. During the winter, for flows under ice cover, these velocities are often measured with rod suspended Price current meters. These meters are calibrated in the towing tank of the Hydraulics Laboratory (HL) at the National Water Research Institute (NWRI). The current meter calibrations are normally expressed by some form of equation from which calibration tables are prepared for use in the field. One of the factors contributing to the error in a flow velocity measurement is the uncertainty in the current meter calibration itself (Smoot and Carter 1968).

Current meters can be calibrated one at a time or simultaneously by suspending two, three or four meters at a time. The number of meters that can be calibrated in this way depends on the width of the towing tank to ensure freedom from mutual interaction of adjacent meters. The towing tank of the HL has a width of 5 metres and this has been considered to be sufficient to calibrate four meters simultaneously. To determine the uncertainty, at the 95% confidence level, arising from this method, five Price winter meters were selected from a group calibrated, four at a time, repeated ten times, for a total of fifty calibrations. The results are compared with the uncertainties at the 95% confidence level associated with calibrating the same meters one at a time as reported by Engel and Wiebe (1992).

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2. PRELIMINARY CONSIDERATIONS

2.1 Calibration Equation

The present practice of the United States Geological Survey (USGS) is to fit two linear equations to the calibration data, one for velocities less than 0.3 m/s and one for velocities greater than 0.3 m/s. In Canada, the present practice is to use a single linear equation over the full velocity range. These methods do not take into account the non-linear behaviour of the current meters which is most pronounced at the low velocities. A single, continuous calibration equation, which combines linear and non-linear, components of the meter response, was developed by Engel (1989 b) and is given as

$$V = AN + Be^{-kN} \tag{1}$$

where V = the velocity, N = the rate of rotation of the meter rotor in rev/s and A, B and k are coefficients to be determined by calibration in a towing tank.

Physically, A represents an effective pitch of the rotor of a frictionless meter and is defined as the distance through which the meter must be towed to achieve one complete revolution of the rotor. The coefficient A, can be expressed as

$$A = \frac{D}{\pi}\left[\frac{K+1}{K-1}\right] \tag{2}$$

where D = the effective rotor diameter, π = 3.14..., and $K = \frac{C_{D1}}{C_{D2}}$, C_{D1} = the drag coefficient of the conical elements of the rotor on the stoss side and C_{D2} = the drag coefficient of the conical elements of the rotor on the lee side. Equation (2) shows that the performance of the meter depends on the shape and orientation of the geometric elements and the size of the rotor. For a given meter type, the rotor geometry is the same with minor variances due to fabrication tolerances. Therefore, one should expect very little variation in A from one meter to another.

The coefficient B represents the threshold velocity of the meter. Theoretically, the threshold velocity is the maximum velocity for which the rotor will remain stationary. In other words, it is the flow velocity at which the rotor is on the verge of the beginning of rotation. Using dimensional analysis, it was shown by Engel (1989 b) that B can be expressed as

$$B = \frac{bT_o}{D^{\frac{3}{2}}\sqrt{\rho\gamma}} \tag{3}$$

where T_o = the resistance in the meter at the point of beginning of rotation which occurs at the threshold velocity (i.e. when $N = 0$), b = a coefficient, ρ = density of the fluid and γ = the unit weight of the fluid. One can expect that the threshold velocity increases as T_o increases. Clearly, for best performance, T_o should be kept as small as possible. In the case of the Price meter, the dependence of the threshold velocity on T_o has significant implications. The Price meter has "cat-whisker" electrical contact brushes which form part of the pulse signal circuit. The overall resistance torque T_o is strongly dependent on how snugly these contact brushes are set. It is therefore important that these adjustments and settings made at the time of meter calibration are maintained during use in the field. Equation (3) also shows that the threshold velocity is inversely proportional to the rotor diameter. Therefore, for a given static resistance T_o, the threshold velocity can be significantly decreased by increasing the rotor diameter. Finally, B changes as the fluid density changes. Fortunately, changes in density of the water, as a result of temperature changes are small and therefore, the density of the water does not affect the response of the meter rotor significantly for standard calibrations.

The exponent kN in equation (1) is dimensionless and therefore, k has the units of s/rev. Physically, k is a decay constant, the magnitude of which dictates the rate at which the non-linear component of equation (1) approaches zero as velocities increase. The rate of change in the non-linear component reflects the rate of change of the resistance in the meter. Since the threshold velocity is directly proportional to

T_o, then k should be directly related to B. Limited data from Engel and Wiebe (1992) show that B increases as k increases. Physically, one would expect that $B \to 0$ as $k \to 0$, implying that when $k = 0$ the meter operates as an ideal frictionless meter (i.e. linear throughout).

The difference between the linear equations presently used in Canada and by the USGS and equation (1) can be seen in Figure 1 for the calibration of a single winter meter from Engel (1989 b). The differences are significant in the non-linear portion of the calibration with the discrepancies increasing as velocities decrease. For measurements of stream flows under ice, where a large percentage of the flow regime consists of low flows, the differences shown in Figure 1 are important. Analysis by Engel and Wiebe (1992) have shown that uncertainties in calibrations with equation (1) can be very low, indicating that this relationship suitably defines the performance characteristics of the Price winter meters, especially the non-linear component at the lower velocities. Equation (1) is therefore used for all subsequent analysis in this report.

2.2 Calibration Uncertainty

The relative uncertainty for a given parameter can be expressed as the ratio of the standard deviation to the corresponding mean and as such becomes the coefficient of variation (Herschy, 1978). The coefficient of variation is a measure of the relative uncertainty in the mean value of the parameter it represents. In I.S.O. standards, the uncertainty is normally expressed at the 95% confidence level, which in the case of velocity has been expressed by Engel and Wiebe (1992) as

$$E_V = \frac{\pm 100 t_{0.975} C_V}{\sqrt{n-1}} \qquad (4)$$

where E_V= the relative uncertainty at the 95% confidence level in percent, $t_{0.975}$ = the confidence coefficient at the 95% confidence level from Student's t distribution for $(n-1)$ degrees of freedom (Spiegel, 1961) and C_V = the coefficient of variation for the velocity V.The same reasoning applies to A, B and k in equation (1) for which the relative uncertainties can be given as E_A, E_B and E_k. Uncertainties in hydrometry are generally expressed as percentages. This practice has been recommended by the International Standards Organization (ISO 5168) and experience in the field has proved this approach to be convenient both in statistical analysis of the data and in the use to which data are put (Herschy 1978).

The uncertainty in a calibration should depend on the towing tank geometry, the meter properties, number of meters, spacing between the meters, fluid properties, towing velocity, settling time between successive tows of the meters and the acceleration due to gravity. This can be expressed by the functional relationship

$$E_V = f(L, B, d, D, N_m, b, \rho, \nu, N, t, g) \tag{5}$$

where f denotes a function, L = the length of the towing tank, B = the width of the towing tank, d = the depth of the towing tank, D = the effective diameter of the meter rotor, N_m = the number of current meters, b = the spacing between adjacent current meters, ρ = the density of the water in the towing tank, ν = the kinematic viscosity of the water in the towing tank, N = the rate of rotation of the meter rotor, t = the settling time between successive tows of the current meters and g = the acceleration due to gravity. Using dimensional analysis, equation (5) can be expressed in dimensionless form as

$$E_V = f_1\left(\frac{L}{B}, \frac{B}{d}, \frac{D}{d}, N_m, \frac{b}{D}, \frac{g^{\frac{1}{2}}D^{\frac{3}{2}}}{\nu}, t\sqrt{\frac{g}{d}}, \sqrt{\frac{D}{g}}N\right) \tag{6}$$

where f_1 denotes a dimensionless function. For the HL towing tank, $\frac{L}{B}$ and $\frac{B}{d}$ are constant, the settling times t are in accordance with established practice, the water depth d is kept constant and for the winter meters the rotor diameter is constant. Therefore,the variables $\frac{L}{B}$, $\frac{B}{d}$, $t\sqrt{\frac{g}{d}}$ and $\frac{D}{d}$ may be omitted from equation (6). The variable $\frac{g^{\frac{1}{2}}D^{\frac{3}{2}}}{\nu}$ may also be omitted from further consideration because it was kept virtually constant as a result of negligible changes in the water temperature. In addition, it was shown by Engel (1976) that viscosity of the water does not affect the performance of the meter. Finally, for a given type of meter, the value of $\frac{b}{D}$ reflecting the spacing between adjacent meters, is dependent on the number of meters N_m and therefore one of these variables should be considered to be redundant. Retaining the variable $\frac{b}{D}$, the calibration uncertainty E_V may now be expressed in the reduced dimensionless form

$$E_V = f_2\Big(\sqrt{\frac{D}{g}}N, \frac{b}{D}\Big) \tag{7}$$

where f_2 denotes another dimensionless function. Equation (7) represents the basic relationship for the present investigation and is valid for the conditions specified. Two cases will be examined: (1) calibration of a single meter and (2) simultaneous calibration of four meters. In the first case, each meter is mounted coincident with the centre-line of the towing tank and therefore, there is no meter-meter interference. This is equivalent to the condition of $\frac{b}{B} \rightarrow \infty$. Tests for this case were conducted by Engel and Wiebe (1992) on five meters. In the second case, four meters are spaced equal distances apart across the width of the towing carriage. Tests on propeller type meters have shown effects of the tank wall to be negligible at a distance of about one propeller diameter from the wall (Charlton, 1978). No information was available for Price type meters. Presently, the centre lines of the suspension rods are placed at a distance of 1.07 m ($\frac{b}{D} = 14$) from the tank wall and about 0.95 m from each other ($\frac{b}{D} = 12.5$). Tests were conducted to compare the calibration uncertainties when meters are towed one at a time and four at a time.

3. EXPERIMENTAL METHOD AND PROCEDURE

3.1 Towing Tank

The towing tank 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 is below ground level. Normally the water depth is maintained at

2.7 metres. Concrete was chosen for its stability, vibration reduction and to minimize possible 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, 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 a), 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 recognized by the computer and are automatically aborted.

3.3 Meter Suspension

The calibration tests were conducted using five Price type winter meters, previously tested by Engel and Wiebe (1992), each fastened to a standard 20 mm diameter solid steel suspension rod. Initially, four of the five meters were secured to the rods, spaced 0.95 m apart, in accordance with present methods used by the National Calibration Service (NCS) at the HL for meters with rod suspensions. After tests were completed on these four meters, the fifth meter was mounted the same way together with four other meters of the same type to ensure the same test conditions. All meters were suspended 0.30 m below the water surface. This depth was chosen to avoid surface effects and to create a minimum of drag on the suspension rods, thereby reducing undesirable vibrations. In all cases, great care was taken that the meters were always aligned so that their longitudinal axis was parallel to the direction of travel of the towing carriage. Small deviations from true alignment, especially for velocities less than 0.30 m/s do not affect the meter (Engel and Dezeeuw 1978) and therefore any uncertainty due to meter alignment can be considered to be insignificant.

3.4 Test Procedure

A run of the towing carriage, with four meters mounted on the suspension rods at a particular towing velocity was defined as a test. To begin a set of tests, the meters were carefully aligned in their specified position at the back of the towing carriage. The meters were then towed at preselected velocities. Tests were conducted, beginning at velocities of 0.06 m/s up to a maximum of 3.0 m/s, for a total of 20 tests per calibration. After each set of 20 tests, the meters were thoroughly inspected before the next set of tests was begun. Each time the meters were towed, care was taken that steady state conditions prevailed when measurements were recorded. The lengths of the settling times between successive tests were in accordance with routine procedures used by the NCS. For each test, the towing speed, revolutions of the meter rotors and the measuring time were recorded. Water temperatures were not noted because temperature changes during the tests were small and do not affect the performance of the meters (Engel, 1976). A total of 8 meters were calibrated from which the five meters previously tested by Engel and Wiebe (1992) were selected. All meter were calibrated 10 times, resulting in a total of 50 calibrations for analysis.

4. DATA ANALYSIS

4.1 Least Squares Fit

An optimized fit of equation (1) to the calibration data is obtained by ensuring that the sum of the squared deviations between the observed values and their estimated values are as small as possible (Stanton, 1961). Mathematically, this is expressed as

$$S = \sum_{i=1}^{n} \left(V_{ci} - AN_i - Be^{-kN_i}\right)^2 \tag{8}$$

where S = the sum of the squared deviations, n = the total number of data pairs, i = the ith data pair in the range from 1 to n, V_c = the towing carriage velocity and all other variables are already defined. For the sake of simplicity the subscripts i are dropped and their presence is taken for granted. The sum S is a minimum for the conditions

$$\frac{\partial S}{\partial A} = \frac{\partial S}{\partial B} = \frac{\partial S}{\partial k} = 0 \tag{9}$$

Equation (9) results in a set of linear equations from which A and B can be expressed in terms of the third coefficient k. The values of A and B are given by

$$A = \frac{(\sum V_c e^{-kN}) - B(\sum V_c e^{-2kN})}{(\sum N e^{-kN})} \tag{10}$$

and

$$B = \frac{(\sum N V_c)(\sum N e^{-kN}) - (\sum N^2)(\sum e^{-kN})}{(\sum N e^{-kN})(\sum N e^{-kN}) - (\sum N^2)(\sum e^{-2kN})} \tag{11}$$

The solution of equations (10 and (11) requires a trial and error procedure. A value of k is initially assumed and values of A and B are computed. These initial values of A and B and the assumed value of k are then used to solve for the sum S in equation (8). Additional values of k are chosen and the process is repeated until the value of k which gives the minimum value of S has been found. Substitution of this optimum value of k into equations (10) and (11) ensures optimum values of A and B thereby providing the best fit of equation (1) to the calibration data.

4.2 The Effect of Simultaneous Calibrations on A, B and k

Mean values of A, B and k, and their corresponding uncertainties at the 95% confidence level are presented in the form of bar graphs in Figure 2 and Figure 3 respectively.

Comparison of the mean values of A in Figure 2 shows that this variable is affected only marginally by towing four meters at a time. Turbulence generated by the towed meters increases as the towing velocity increases. If the meters are spaced together close enough, that is if $\frac{b}{D}$ is small enough, to allow mutual interference between adjacent meters, this effect would increase as the towing velocity increases. The fact that the effect on A is so small, is an indication that mutual interference is not a big factor. This observation is confirmed by comparing the uncertainties E_A in Figure 3. In all cases, the uncertainties in A have increased when the meters were calibrated four at a time, suggesting some turbulence effects acting on the meter rotors. However, the absolute uncertainties are still very small and therefore, values of A for the same meter, from one calibration to another, can be expected to be sufficiently stable for standard current meter calibrations. This suggests that the meter spacing of 0.95 m ($\frac{b}{D} = 12.5$) between the meters may be considered to be the minimum allowable value. It is interesting to note that mean values of A for different meters are also very similar. As shown by equation (2), A reflects the rotor geometry and the consistency in its value for different meters is proof of the close tolerances in the fabrication of the rotor components.

In contrast to A, values of B vary considerably for both single and simultaneous calibrations and are substantially different for each meter. Theoretically, B represents the static friction T_o, as given by equation (3). However, the value obtained with a least squares fit, in accordance with equation (11), includes the variability as a result of residual currents in the towing tank and other factors which affect the rotation of the meter rotor. For each meter the uncertainty in the value of B is very high and for four out of five meters the uncertainty is greater when the meters are calibrated four at a time. The value of B is governed chiefly by the lower velocities, that is velocities less than about 0.7 m/s. At these velocities the turbulence generated by the towed meters is much less than that obtained at the medium to high velocities. Therefore, the variability in B cannot be attributed to mutual interference of adjacent meters since this has already been shown to be minimal at medium to high velocities. It is most likely, that the high values of E_B are due to residual currents existing in the towing tank at time that the meters are towed. These currents are the result of the disturbance created by towing the meters in the tank. The residual current activity decreases approximately with the square root of the settling time and increases with the blockage of the cross-sectional area of the water in the towing tank (Kamphuis 1971). This suggests that the larger uncertainty in the values of B for simultaneous calibrations are due to the greater disturbance created by the four meters as compared to those from a single meter. The larger disturbance requires a longer time to settle.

In the present calibrations, for a given towing velocity, the same settling time was used for the single and four meter calibrations and therefore, one must expect that more residual current activity existed for the latter. This problem can be reduced by extending the settling time prior to test for velocities less than 0.7 m/s.

Finally, examination of Figures 2 and 3 shows that the trend in k is similar to that observed in B. This can be seen by the plot of B versus k in Figure 4. There is no apparent difference in the distribution of the plotted data for single and simultaneous calibrations and a single straight line on the log-log coordinates provides a satisfactory fit. The curve shows that B increases as k increases and that this should be in accordance with a relationship of the form

$$B = \alpha k^{\beta} \tag{12}$$

where α and β are experimental constants. The scatter in the plot is an indication of the uncertainty in determining both B and k. The uncertainty in k, shown in Figure 3, follows the same trend as that of B but is much larger, indicating that k is very sensitive to changes in the factors which affect the rotation of the meter rotor at low velocities. The uncertainty in k for simultaneous calibrations is again greater than that for single calibrations for four meters out of five. This is further confirmation that the calibration of four meters at the same time results in much more residual current activity, which in turn can only be reduced by reducing the number of meters or the settling time before each meter tow.

4.3 The Effect of Simultaneous Calibrations on E_V

Equation (7) shows that, for a given meter (i.e. given D), the calibration uncertainty should vary with N for a given value $\frac{b}{D}$. It was shown by Engel and Wiebe

(1992) that E_V can be expressed as a function of N by the relationship

$$E_V = \frac{\left\{A^2N^2E_A^2 + B^2e^{-2kN}\left[E_B^2 + k^2N^2E_k^2\right]\right\}^{\frac{1}{2}}}{AN + Be^{-kN}} \tag{13}$$

Using equation (13), values of E_V were computed for selected values of N for the case of $\frac{b}{D} \to \infty$ (i.e. single meter) and $\frac{b}{D} = 12.5$ (i.e. four meters at a time). The results are plotted in Figures 5, 6 and 7. The data for the two modes of calibration are presented in the form of bar graphs to obtain a direct comparison. The bar graphs clearly show, as expected, that the greatest uncertainty exists at the lowest velocities or lowest rate of rotor rotation N. As N increases, values of E_V decrease rapidly to less than 0.5% when $N = 1.0$ for both modes of meter suspension (i.e. single and 4 at a time). For values of $N > 1$, E_V decreases slowly as N increases to values much less than 0.5%.

The results also show that any significant differences in the calibration accuracy, due to single and simultaneous calibrations, are likely to occur for values of $N < 1$. In this range of N, values of E_V for four of the five meters are significantly higher for the simultaneous calibrations with the difference being greatest at the lowest value of N. In the case of meter No. 322, E_V is slightly lower for the multiple meter case. The reason for this is not known. The higher values of E_V are due to residual currents existing in the towing tank as a result of agitation created by the towing of the meters. Clearly, four meters towed simultaneously create more disturbance than one meter towed at the same velocity. As a result, residual currents set up by towing four meters will take a longer time to dissipate to a level where they no longer significantly affect the current meters. Therefore, if rod suspended Price meters are to calibrated four at a time with the present suspension configuration, longer settling times prior to each run will be required. The length of these settling times must be determined experimentally. Some reduction in uncertainty may be achieved by increasing the spacing between adjacent meters. Spacings up to 1.5 m ($\frac{b}{D} = 20$) are possible.

5. CONCLUSIONS

Using dimensional analysis, a functional relationship for the experimental evaluation of different modes of current meter calibrations was developed. Calibration test on five rod suspended Price winter meters, each calibrated ten times in combination with other meters in groups of four at a time, were conducted in the HL towing tank to provide the necessary data for determination of calibration uncertainties. The data were successfully used to compare uncertainties for meters calibrated four at a time and one at a time.

The data for each of the calibrations was successfully fitted, using least squares principles, with the following equation:

$$V = AN + Be^{-kN} \tag{1}$$

in which A, B and k are regression coefficients.

Analysis of the data showed that uncertainties, at the 95% confidence level, of A were very low and that values of A varied only slightly from meter to meter. Uncertainty in A were slightly greater when meters were calibrated four at a time when compared with uncertainties in the calibrations of the same meters taken one at a time. The maximum uncertainty in A for four meters towed at the same time was 0.15% for the five meters tested. This means that uncertainties in A do not affect calibration accuracy significantly.

Analysis of the data showed that uncertainty, at the 95% confidence level, in the values of B for the case of calibrating meters four at a time were larger than those for meters calibrated one at a time for four out of five meters. The uncertainties in determining B were much higher than those for determining A.

Analysis of the data showed that uncertainties in the values of k, at the 95% confidence level, in the case of calibrating meters four at a time were larger than those for meters calibrated one at a time for four out of five meters. The uncertainties in determining k were considerably higher than those for B.

Examination of mean values of B and k revealed a relationship between these two coefficients of the form $B = \alpha k^{\beta}$.

Results show that any significant differences in calibration accuracy for single and simultaneous calibrations will occur for velocities less than 0.7 m/s. In this range uncertainties, at the 95% confidence level, in the calibrations are significantly higher when meters are towed four at a time. These uncertainties are mainly due to residual currents existing in the towing tank as a result of agitation created by the towing of the meters.

Residual currents set up by towing four meters simultaneously take longer to dissipate than those set up by towing only one meter at the same velocity. Therefore, if four meters are to be calibrated simultaneously with the presently used suspension spacings, longer settling times are required prior to each tow at velocities of less than 0.7 m/s. Some improvement may be obtained by increasing the spacing between adjacent meters from 0.95 m to 1.5 m.

It is recommended that a study be conducted to determine the minimum settling time required for towing four meters simultaneously at velocities less than 0.7 m/s. when the meter rod suspensions are spaced 1.5 m apart.

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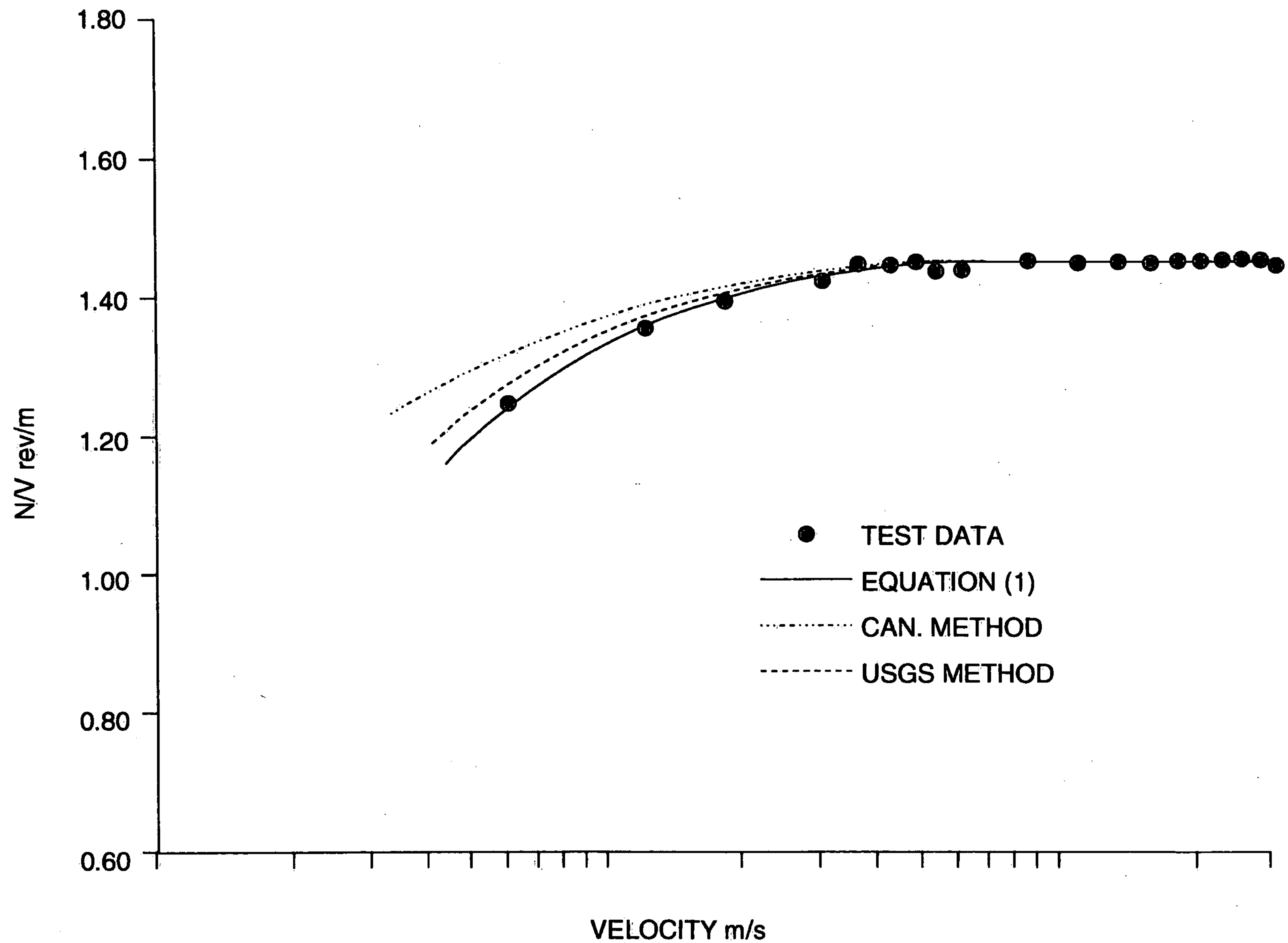

FIGURE 1. COMPARISON OF CALIBRATION EQUATIONS. (ENGEL 1989b)

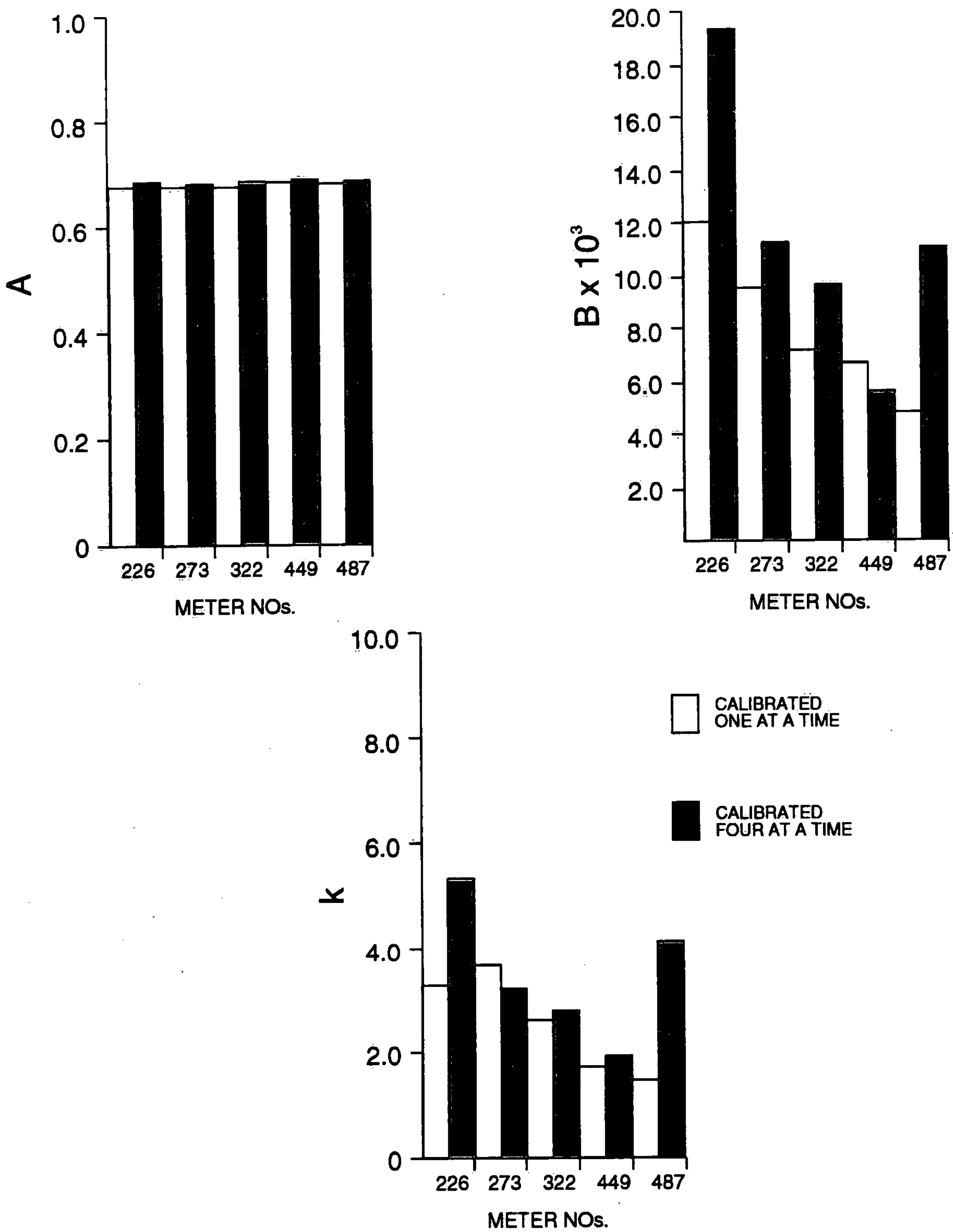

FIGURE 2. MEAN VALUES OF A,B, AND k

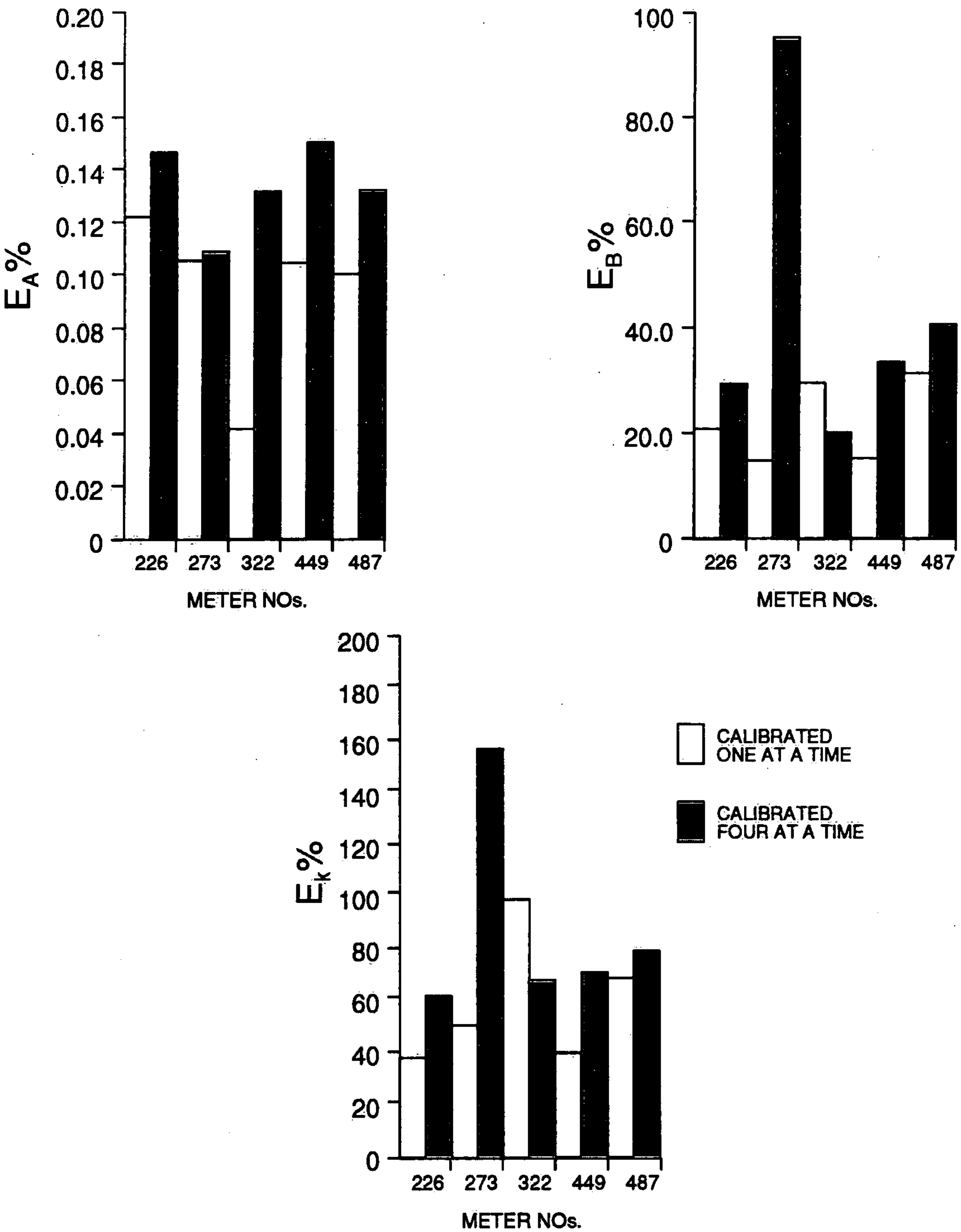

FIGURE 3. UNCERTAINTY IN A, B, AND k AT 95% CONFIDENCE LEVEL

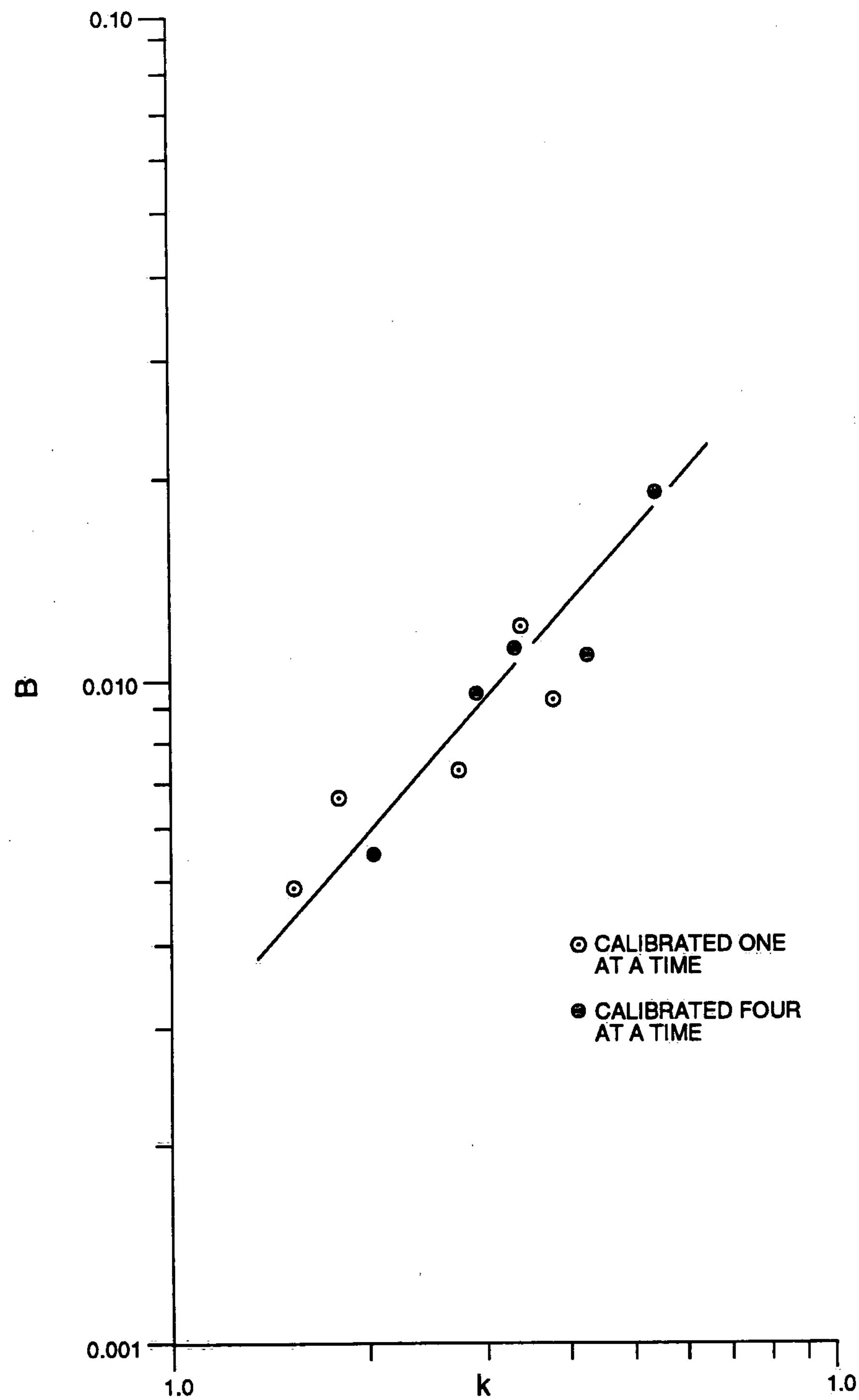

FIGURE 4. RELATIONSHIP BETWEEN B AND k

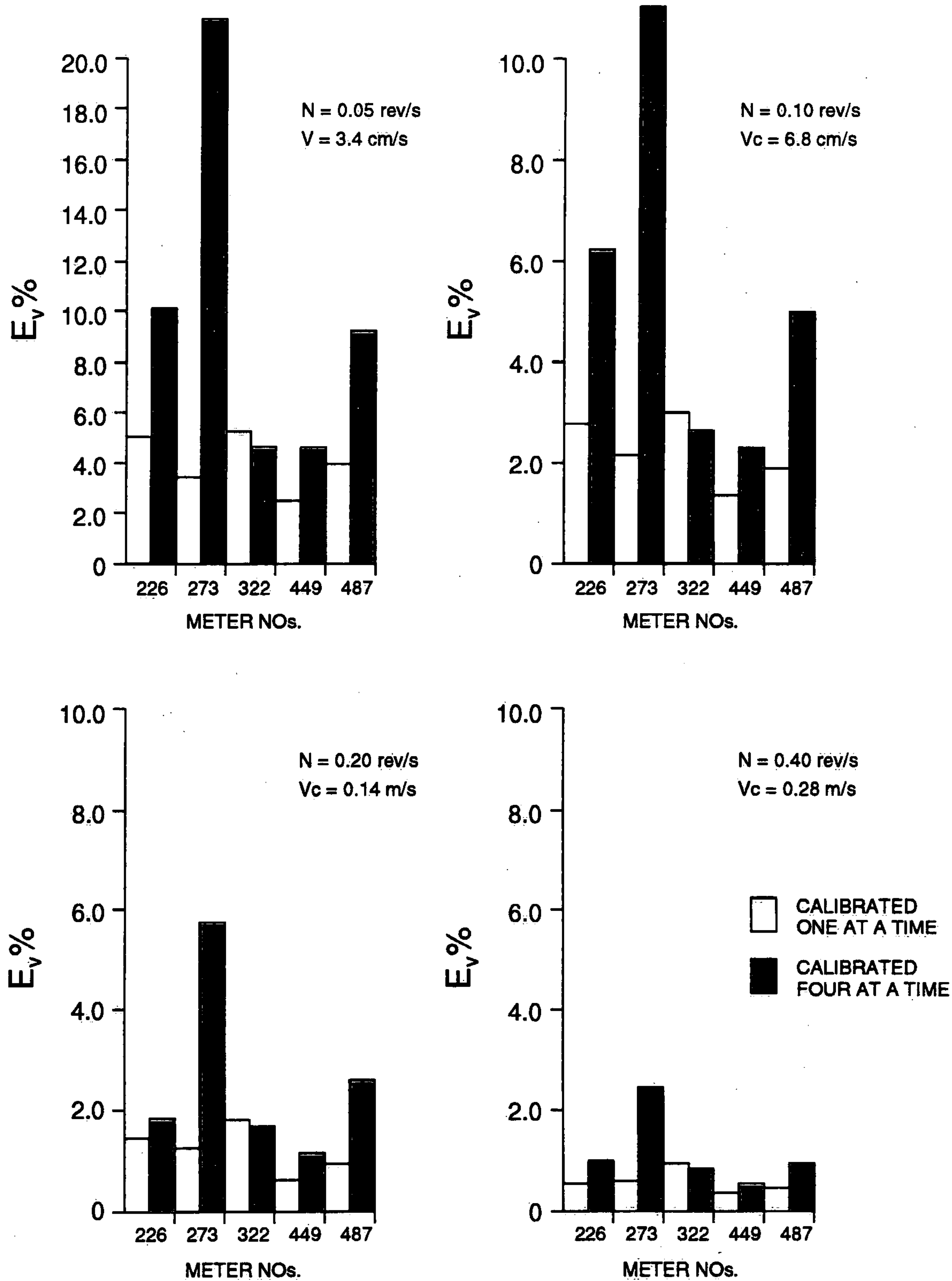

FIGURE 5. UNCERTAINTY E_V AT 95% CONFIDENCE LEVEL FOR $0.05 \leq N \leq 0.40$

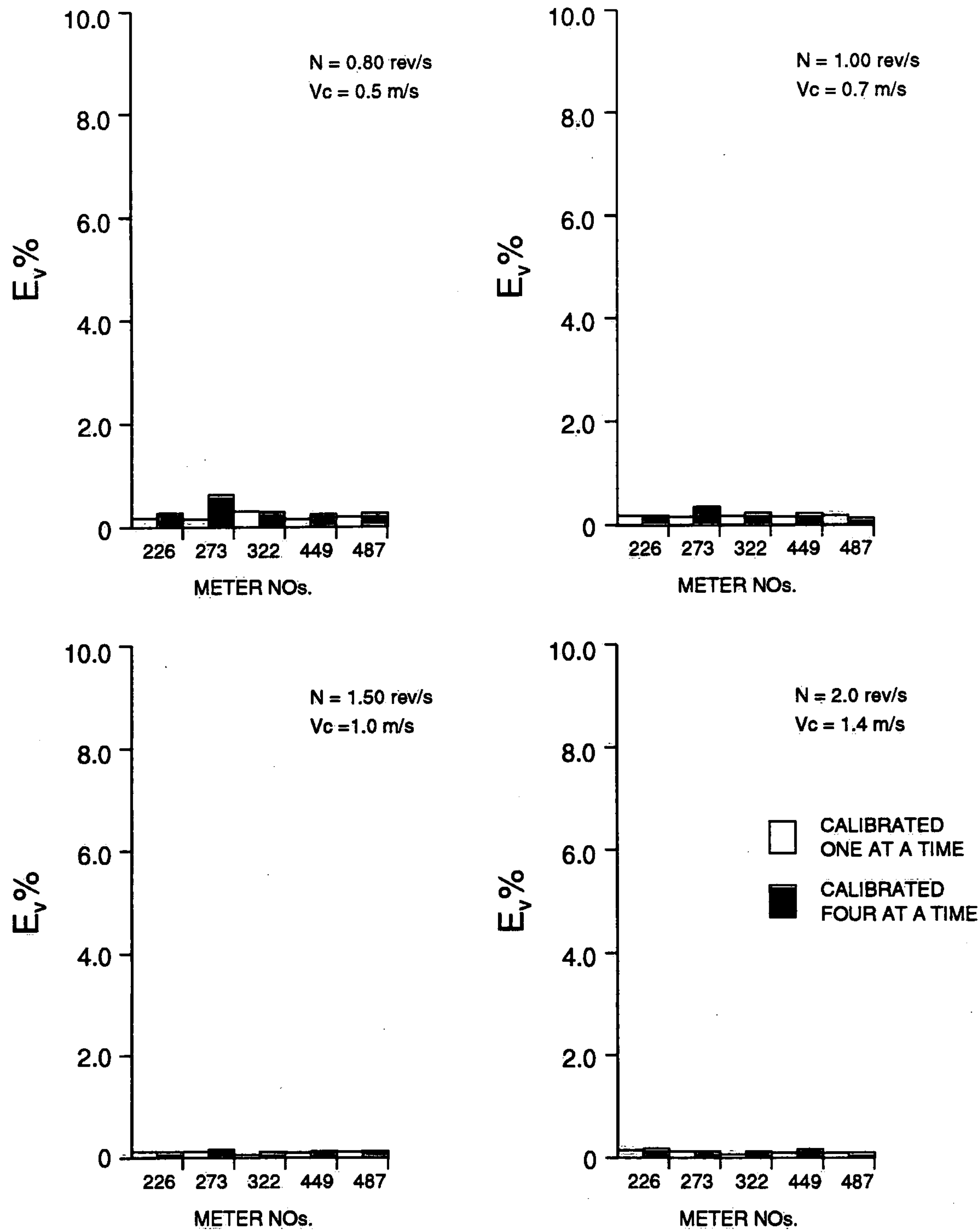

FIGURE 6. UNCERTAINTY E_V AT 95% CONFIDENCE LEVEL FOR $0.80 \leq N \leq 2.0$

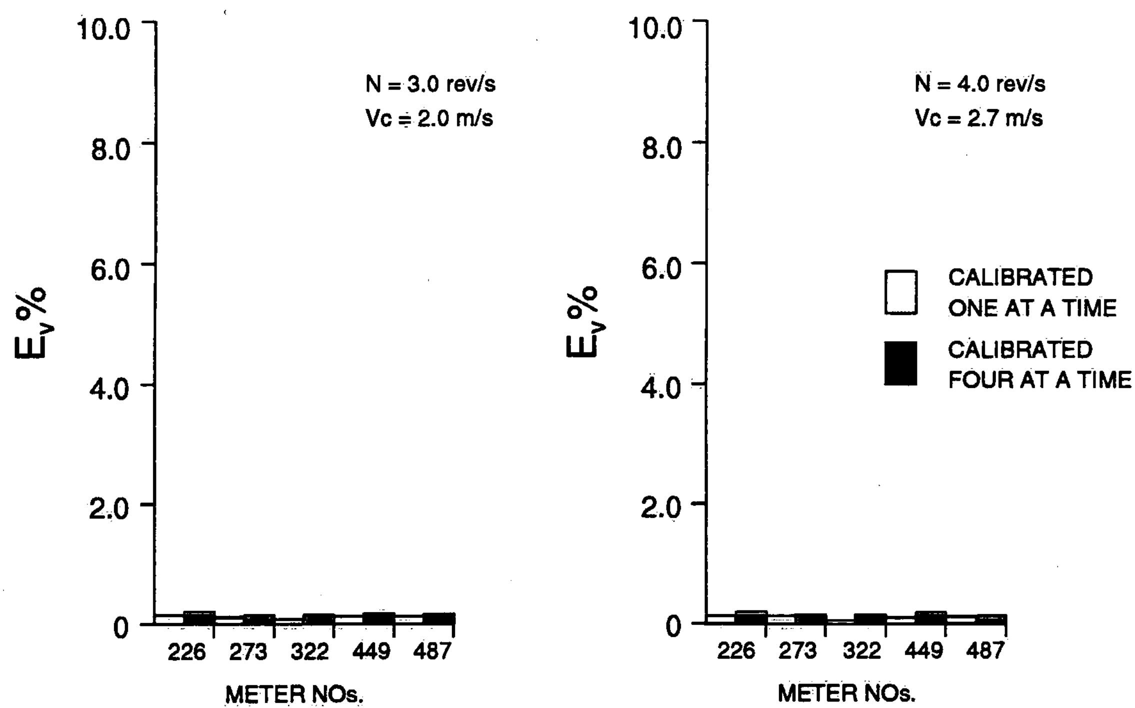

FIGURE 7. UNCERTAINTY E_V AT 95% CONFIDENCE LEVEL FOR $3.0 \leq N \leq 4.0$

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