MIXOGRAPH INSTRUMENTATION FOR MOVING BOWL AND FIXED BOWL COMPARISONS OF WHEAT FLOUR PERFORMANCE

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Mixographs are commonly used in the baking industry and research laboratories to determine optimum water absorption capacity, mixing time and other quality characteristics of wheat flour. The mixograph consists of a bowl into which portions of flour and water are added. A set of four moving pins inter-mesh with three stationary pins within the bowl and rotate in a prescribed path to produce the mixing action. The bowl is attached to a platform which is free to pivot except for mechanical friction and restraint provided by a small coiled spring. The conventional recording mixograph produces a curvilinear recording of the amplitudes of the pivoting platform as mixing and time proceed. The curvilinear recording is then examined by an expert for both quantitative and qualitative information relating to flour quality. The developmental history of the mixograph was summarized by Shogren (1989). For a more complete description and operating procedures for a 10g mixograph, see Finney and Shogren (1972) and approved methods of the AACC (1988).

Voisey, Miller and Kloek (1966) reported investigations relating to the use of electronic recording devices in lieu of mechanical recording methods. Friction and dampening in mechanically recorded signals were of concern. Their electronic recording methods utilized a fixed bowl configuration. Subsequently, several other researchers have investigated electronic instrumentation methods which included fixed and moving bowl configurations and digital data acquisition of platform amplitude, force, torque or power. Recent investigations by Rubenthaler (1986), Navickis (1989) and Walker (1989) emphasize the need for standardized instrumentation procedures.

One issue regarding standardized procedures is the interpretation of mixograms from fixed vs moving bowl configurations. Other issues relate to calibration and frequency of digital data acquisition. This paper describes the initial stages of a mixograph simulation study, the instrumentation of a mixograph for digitized acquisition of mixograms for both moving and fixed bowl configurations, calibration procedures and a comparison of moving and fixed bowl mixograms.

SIMULATION ANALYSIS

The 10g mixograph uses a planetary gear set to propel four moving pins. Gear centers and pin spacing on each planetary gear are given in Fig. 1. The number of teeth on the stationary and planetary gears was 12 and 16 respectively. This ratio dictates the number of input shaft rotations required for each moving pin to traverse identical patterns. During four input shaft revolutions, the path shown in Fig. 2 is traversed by each moving

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pin starting at some point on the path and returning to that point. The starting point may be defined at any position within the four revolutions, but the 'home' position is commonly defined by a manufacturer's template which is provided to establish proper pin and gear alignment when assembling the planetary gear set. The pins are shown at the template home position in Fig. 1.

To begin the simulation study, equations defining the path of each moving pin in terms of input shaft rotation were developed. With the pins positioned at the 'home' position, the planetary gears were given a left (L) and right (R) designation as shown in Fig. 1. The pins on each planetary were designated as A or B. An X-Y coordinate system was defined at the input shaft(also bowl) center line. For pin A on the left (L) planetary gear, the following X-Y position equations were developed:

$$X_{LA} = R_5 COS((1 + GR)\theta_0 + \theta_1 + \pi) + R_6 COS(\theta_0 + \pi) \quad (1)$$
$$Y_{LA} = R_5 SIN((1 + GR)\theta_0 + \theta_1 + \pi) + R_6 SIN(\theta_0 + \pi) \quad (2)$$

where X_{LA}= X-coordinate of pin A on left planetary, mm
Y_{LA}= Y-coordinate of pin A on left planetary, mm
θ_0 = input shaft rotation angle, rad
θ_1 = planetary rotation angle at $\theta_0 = 0$, equal to 0.3927 rad
R_5 = radius of planetary pin center, mm
R_6 = radius of planetary gear center, mm
and GR = ratio of stationary to planetary gear teeth = 12/16.

Equations (1) and (2) were used to prepare Fig. 2. The hypothesis was made that simulations of torque cycles for pins moving in a uniform viscous liquid would be helpful. To determine drag force, pin velocity in terms of input shaft angular velocity is needed. Differentiation of Eq.'s (1) and (2) and conversion of $d\theta$ to $d\theta/dt$ provided the X and Y velocities of pin A on the left planetary as follows:

$$V_{XLA} = [-R_5(1 + GR)SIN((1 + GR)\theta_0 + \theta_1 + \pi) - R_6 SIN(\theta_0 + \pi)][\omega] \quad (3)$$
$$V_{YLA} = [+R_5(1 + GR)COS((1 + GR)\theta_0 + \theta_1 + \pi) + R_6 COS(\theta_0 + \pi)][\omega] \quad (4)$$

where V_{XLA}= X component of velocity of pin A on left planetary, mm/s
V_{YLA}= Y component of velocity of pin A on left planetary, mm/s
and ω = angular velocity of input shaft, nominally -9.215 rad/s.

The drag force was assumed to be proportional to the resultant velocity squared. The component of drag force perpendicular to a radius from the bowl center to the X-Y pin coordinate was then determined. The torque imposed on the bowl was estimated as the product of the perpendicular component of drag times the radial moment arm defined by the X-Y pin coordinates. In this representation, the torque direction is velocity and quadrant sensitive. The following equations were used to simulate the torque contribution of pin A on the left planetary in a stationary uniform viscous liquid:

$$DF_{LA} = U_0 \; [V_{XLA}^2 + V_{YLA}^2] \quad (5)$$

$$\theta_2 = ATAN[V_{YLA} / V_{XLA}] \quad (6)$$

$$\theta_3 = ATAN[Y_{LA} / X_{LA}] \quad (7)$$

$$DF_{PLA} = DF_{LA} \; [SIN(\theta_2 - \theta_3)] \; [SGN(X_{LA})] \; [SGN(V_{XLA})] \quad (8)$$

$$T_{LA} = DF_{PLA} \; [X_{LA}^2 + Y_{LA}^2]^{0.5} \quad (9)$$

where DF_{LA}= drag force, N
U_0= proportionality constant, Ns^2/mm^2

θ_2 = resultant velocity angle, rad
θ_3 = X-Y coordinate angle, rad
DF_{PLA} = component of drag force perpendicular to bowl center radius, N
T_{LA} = torque contribution of pin A, left planetary, mNm

Similar position, velocity and torque equations were developed for the other three moving pins. The positive angular and torque direction is counter clockwise for these equations. Total torque imposed on the bowl is the summation of the torque contributions of each pin. For some values of R_6 and R_5, the torque contribution of a single pin is always negative while for other values, the contribution can be negative or positive depending on the pin position.

A computer program was written to simulate mixograph results based on the above position, velocity and torque equations. The computer program provides for graphic display and file output of all pin positions, velocities and torque values. The results were computed in step increments of input shaft rotation and for multiples of four input shaft revolutions. For the 10g mixograph geometry, the torque contribution of a single pin was almost always negative going positive only a small amount at the pin path loops near the center of the bowl (Fig. 3). Each pin projects three torque cycles in four input shaft revolutions. The sum of all pin torques (Fig. 3) was always negative having a larger average component and a smaller but more frequent cyclical variation. The average total torque did not occur at the 'home' position. The first occurrence of average total torque was at an input shaft position of -1.047 rad (-60 deg) from the 'home' position. Figure 3 was prepared from simulations for a stationary viscous liquid over an input shaft rotation angle of -1.047 to -26.180 rad (-60 to -1500 deg).

The second phase of the simulation analysis involves representation of the platform and bowl as an equivalent spring-mass system. The torque predictions from above represent the excitation input to an equivalent system. These simulations will provide insight regarding the differences between fixed and moving bowl responses. For the fixed bowl, the spring constant in the equivalent spring-mass system is several times that for the moving bowl. Frictional and dampening differences may be significant. Adjustment of the fixed bowl response to an equivalent moving bowl response or vice versa will more clearly identify fixed vs moving bowl differences. Initial stages of the second phase analysis are currently in progress.

If the torque cycles of Fig. 3 represent a system response, then the frequency and amplitude may be used to evaluate or determine digital recording requirements. The six sub-cycles of Fig. 3 suggest a minimum digital recording frequency which depends on the desired degree of resolution within the sub-cycle. To identify a sub-cycle, the minimum number of points within the cycle would be two which translates to a digital sampling frequency of 4.4 points per second for 88 rpm of the input shaft. If symmetrical cycles are involved, then for better resolution the number of points should be an even divisor of the basic sub-cycle period, 240 degrees of input shaft rotation. If angular velocity of the input shaft is not constant, a time based digital sampling frequency requires knowledge of the velocity variation to synchronize data collection with pin position. If the drag force proportionality constant varies with position in the bowl, the sub-cycles are not symmetrical and knowledge of the pin position or input shaft position is essential. Digital data collection based on input shaft rotation would eliminate shaft speed variation uncertainties and also provide corresponding point by point pin positions.

The geometry of the mixograph, pin movement, and stationary bowl pins suggest that cycles other than those portrayed by the above torque analysis are present. Initial pursuit of this possibility was done by connecting the moving pins with line segments and observing the pin motion as simulated on a PC graphic screen. When pins A and B are connected to each other on each planetary, two types of motion relative to the stationary pins in the bowl can be observed. The motions may be described as a sliding (S) and chopping (C) action as the moving pins pass the stationary pins. These actions occur in sequence starting at -30 deg of input shaft rotation from the 'home' position and every -60 deg increment thereafter. In four input shaft revolutions, the sequence, 'CSSCCSSCCSSCCSSCCSSCCSSC', is double alternate for a total of twelve occurrences of each action type. Adjusting the 'home' position by -60 deg and superimposing these actions would continue to produce the sub-cycles defined previously except that the sub-cycles would alternately portray the effect of sliding and chopping. Similar cyclic action could be investigated by connecting pins A left and A right, pins A left and B right, etc. These actions need further exploration and definition.

To further investigate pin movement, a computer program was developed to determine the distances (gaps) between the moving pins and the stationary pins in terms of input shaft rotation angle (θ_0) and platform rotation angle (ϕ_0). For any given bowl position, all twelve possible gap distances are identical during four input shaft revolutions except for a θ_0 phase shift. The sum of the twelve gap distances is not constant with input shaft rotation, but the sum of the gap distances squared is constant for any shaft rotation angle and any platform rotation angle. The sum of squares of the distances between four moving pins and any one stationary pin also is constant with input shaft and platform rotation. This relationship implies certain predictable responses if the resistive forces were proportional to the gap distances squared. The rate of change of gap distances with respect to θ_0 and ϕ_0 was also determined.

INSTRUMENTATION

A 10g mixograph was instrumented so that conventional use and operation was maintained. Sufficient instrumentation was included so that either fixed or moving bowl operation was easily accommodated on the same mixograph. Since the torque imposed on the bowl is pin position sensitive, data acquisition was synchronized with input shaft rotation. In the system assembled, time based data acquisition is also an option. To meet these objectives, the instrumentation included a rotary variable differential transformer (RVDT) mounted beneath the bowl platform, a load cell mounted at the spring bulk head, an input shaft encoder mounted above the drive pulley, a signal conditioning module, a multiplexer and analog to digital board (A/D) and an MS-DOS compatible personal computer. Figure 4 shows the organizational layout of the instrumentation.

The mixograph was provided by National Manufacturing Company, Lincoln, NE. The RVDT was model R300 from Schaevitz, the load cell was model GS-250 from Transducer Techniques, and the shaft encoder was model 81-06332 from Hohner. The signal conditioning module was assembled using components from several manufacturers. The multiplexer and A/D board was model DAS16 from Metrabyte Corp. The PC was an Everex Model 286/12 with 1 meg memory, a floppy drive, and a 40 meg hard drive. The shaft encoder was driven from the input shaft using four to one ratio anti-backlash gears and provided an external signal for data acquisition at four deg increments of input shaft rotation. The encoder also provided a 'home' position marker representing four revolutions of input shaft rotation. Modifications of the encoder signal conditioning circuit can provide data acquisition over a wide range of input shaft rotation increments.

Computer software for data acquisition was developed in Quick-BASIC using multiplexer and A/D routines provided by Metrabyte. During acquisition, all data were stored in resident memory as A/D count and transferred to disk upon completion of the sample or mixograph run. Other software was prepared to graphically display and plot the acquired mixograph results.

CALIBRATION

Two devices were fabricated to aid in-place calibration of the load cell and RVDT. The devices were a circular arc attachment which locks on the platform in place of the bowl and a pulley mounted on low friction bearings. Both devices were grooved and mounted so that a string or small filament could be used to suspend known weights and apply a known horizontal force or torque to the load cell or platform. The diameters of the circular arc attachment and pulley were 14.9 and 10.4 cm respectively.

With the mixograph instrumented as described, several calibrations are possible. Calibrations for force vs load cell output, chart position vs RVDT output, and platform angle of rotation vs RVDT output were determined and used to verify sensor linearity. With the devices described above, torque calibrations were made for the moving bowl (spring at slot #12) using the RVDT output and for the fixed bowl (positioned at chart center) using the load cell output. These calibrations are given in Fig.'s 5 and 6.

RESULTS

Figures 7 and 8 are graphic representations of digitized moving and fixed bowl mixograms, respectively. The flour used in the moving and fixed bowl test runs was a laboratory standard, hard red winter wheat flour (RSB80), typically 12.0 percent protein, and an absorption of 0.65 g/g. The mixograms are similar except for greater amplitudes and higher frequencies in the torque observed for the fixed bowl compared to moving bowl. Visual interpretation of the mixograms suggest mixing times of 4.7 and 4.0 min for the moving and fixed bowl mixograms respectively and based on an input shaft angular velocity of -9.215 rad/s (-88 rpm). The average torque represented by the mixograms from 0 to -3887 rad (7.0 min) was 161.5 mNm for the moving bowl and 169.5 mNm for the fixed bowl.

Figure 9 is a superimposed expansion of a selected region of the moving and fixed bowl mixograms. The region selected was from -2888 to -2888 - 8π rad of Fig.'s 7 and 8 using the 'home' position mark in superposition. The similarity in torque sub-cycles is evident in the moving and fixed bowl mixograms, however the moving bowl amplitudes appear to be dampened by the moving spring-mass system. In Fig. 9, the moving bowl cycles do not appear to be in phase with those of the fixed bowl. The phase difference is partly the result of measurements or responses of two different spring-mass systems. Moving vs fixed bowl comparisons are even more complex than the difficulties depicted in Fig. 9. Two different methods of instrumenting for fixed bowl measurements may also depict differences similar to those of Fig. 9.

SUMMARY AND CONCLUSIONS

The history and some issues concerning instrumentation of a 10g mixograph were briefly reviewed. Mathematical equations to express position, velocity and simulated torque contributions were developed for each of the four moving pins in terms of input shaft rotation. The position equations demonstrate that all pins traverse the same path during four revolutions of the input shaft and that four revolutions of the input shaft is a basic cycle in 10g mixograph data. Torque simulations for a stationary viscous liquid demonstrate that each moving pin has three torque cycles in four revolutions. When the torque contributions of all four moving pins are summed, six torque sub-cycles were observed in four revolutions of the input shaft. Distances and rates of change of the distances between the moving pins and the stationary bowl pins in terms of input shaft and platform rotation angles were investigated. A 24 point sliding and chopping sequence was noted in graphic displays of pin movement and other possible cycles were suggested for study. A description of the instrumentation used to maintain conventional mixograph operation and to obtain digitized mixograms for both moving and fixed bowl configurations was presented. Calibration procedures and calibrations for the sensors were presented. Typical digitized mixograms for moving and fixed bowl configurations were determined. Similarities and differences between the moving and fixed bowl mixograms were noted and were more evident when four revolution segments of each mixogram were superimposed with pin position synchronized. The differences were attributed to expected differences in equivalent spring-mass system responses. Development of the equations of motion for equivalent spring-mass systems is in progress.

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REFERENCES

1. American Association of Cereal Chemists. 1988. Approved methods of the AACC, physical dough tests, mixograph method, 54-40A, 5 p.

2. Finney, K.F. and M.D. Shogren. 1972. A ten-gram mixograph for determining and predicting functional properties of wheat flours. Bakers Digest 46(2):32-35, 38-42, and 77.

3. Navickis, L.L., R.O. Butterfield and T.C. Nelsen. 1989. A modified electronic torsion sensor for a 10-gram mixograph. Cereal Chem. 66(4):350-352.

4. Rubenthaler, G.L. and G.E. King. 1986. Computer characterization of mixograms and their relationship to baking performance. Fundamentals of dough rheology. H. Faridi and J. Faubion, editors. Department of Grain Science, Kansas State University. p 131-167.

5. Shogren, M.D. 1989. The mixograph: a history. Proc. Annual Meeting AACC, Washington, D.C., October 29. Abstr. No. 253.

6. Voisey, P.W., H. Miller and M. Kloek. 1966. An electronic recording dough mixer. Cereal Chem. 43:408-419.

7. Walker, C. E. 1989. Computerized representation of alveograms using fractional polynomials. Cereal Foods World 34(3):276-279.

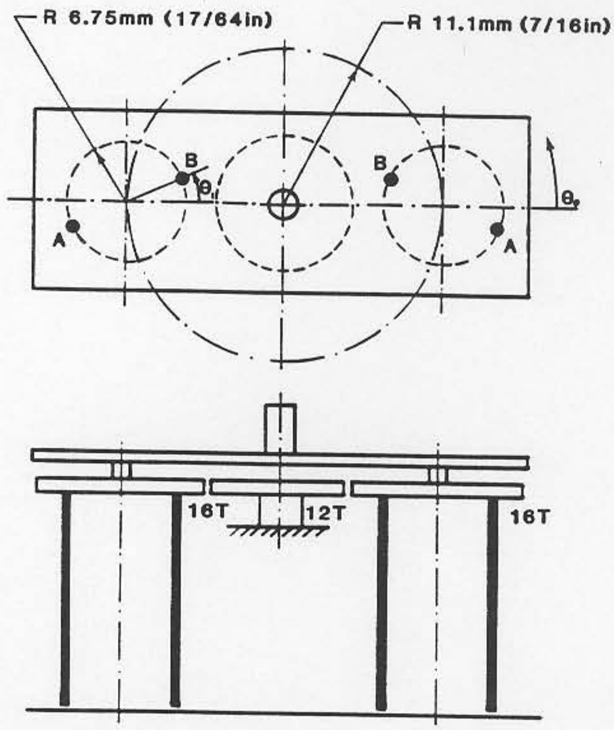

Fig. 1 Planetary gear radius, moving pin radius and angle designations for pin position, velocity and torque simulations.

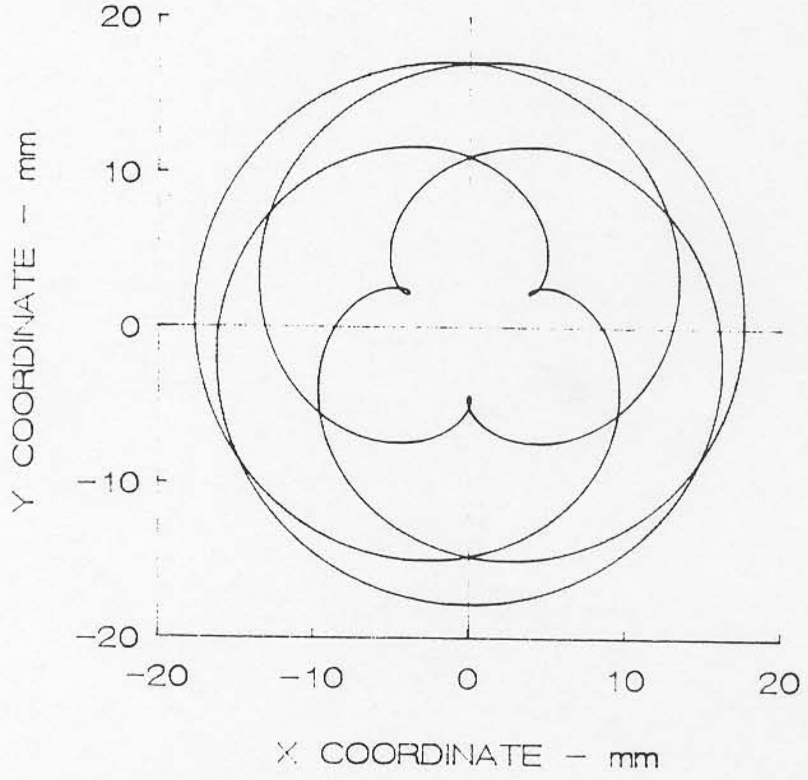

Fig. 2 Path traversed by all moving pins in four revolutions of the input shaft.

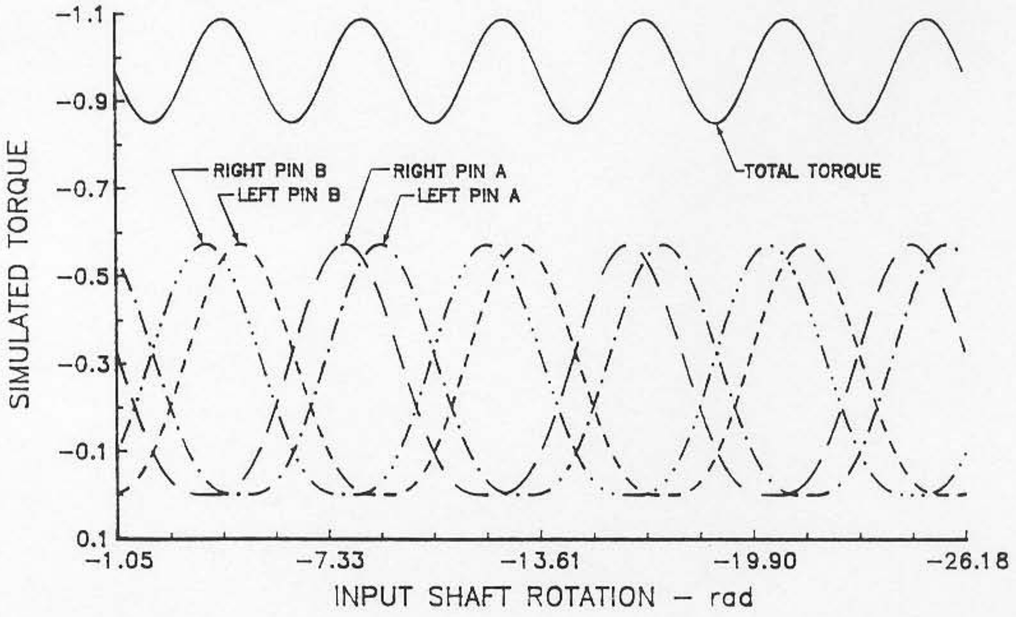

Fig. 3 Simulated relative torque in a stationary viscous liquid during four revolutions of the input shaft for each moving pin and their algebraic summation.

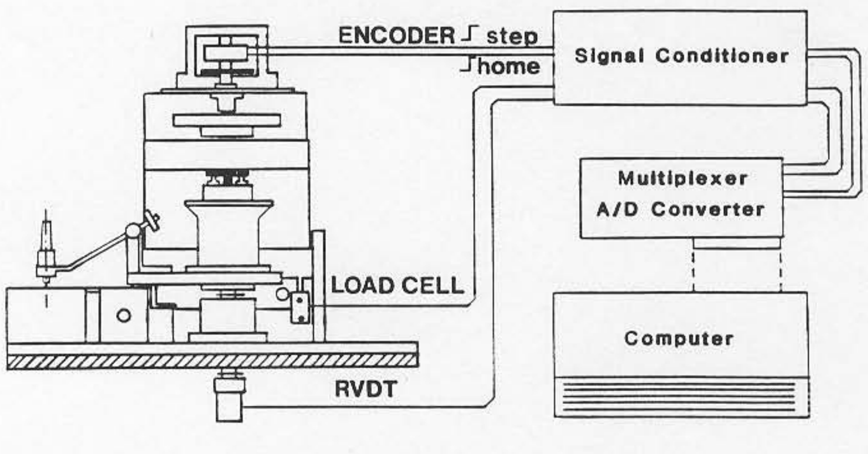

Fig. 4 Block diagram of sensor installations, signal conditioning and digital data acquisition procedures.

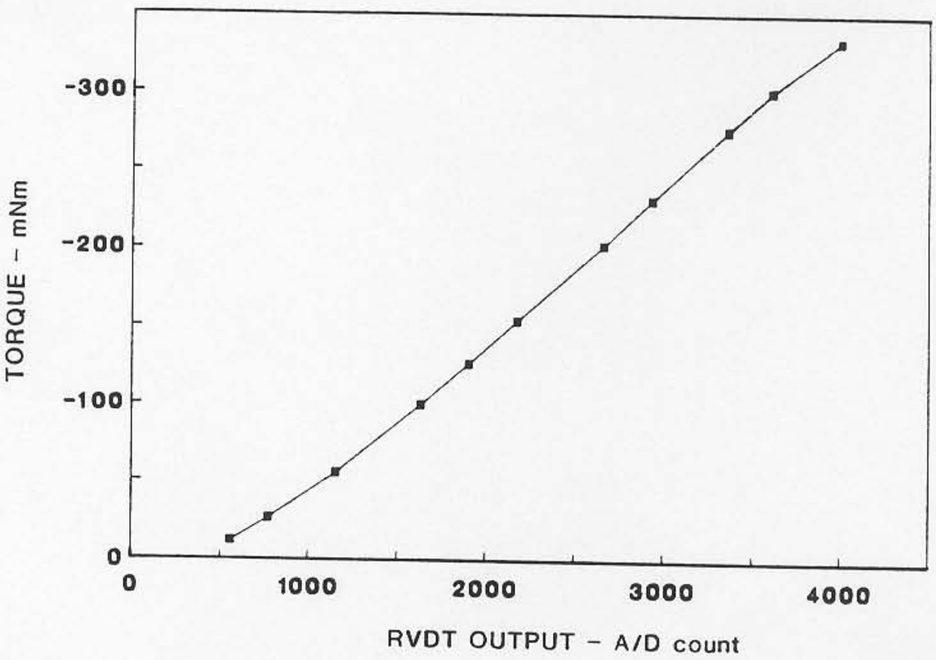

Fig. 5 Moving bowl calibration (RVDT) with spring in slot #12.

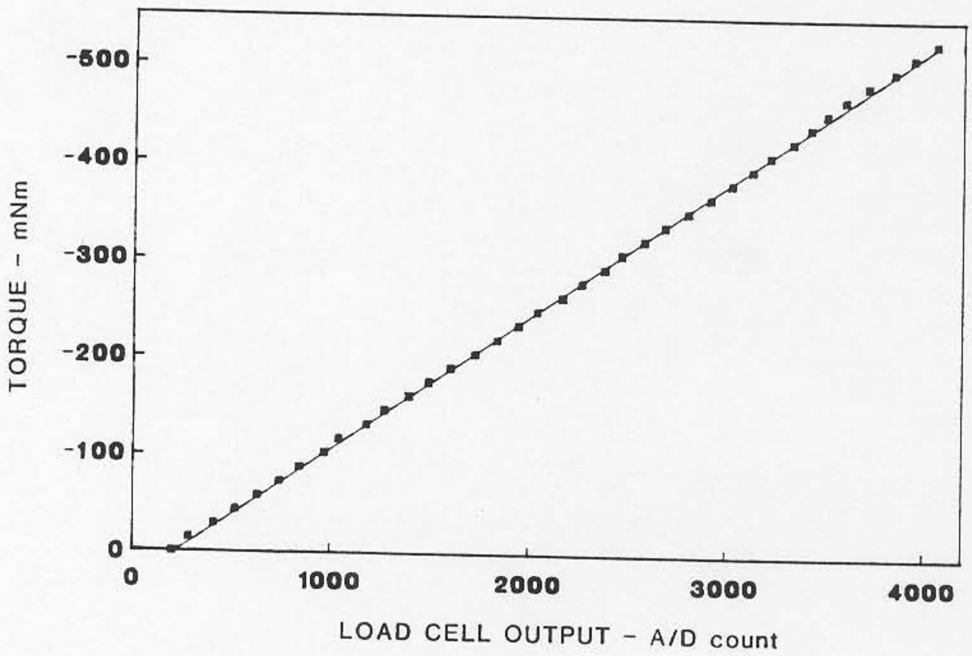

Fig. 6 Fixed bowl calibration (load cell).

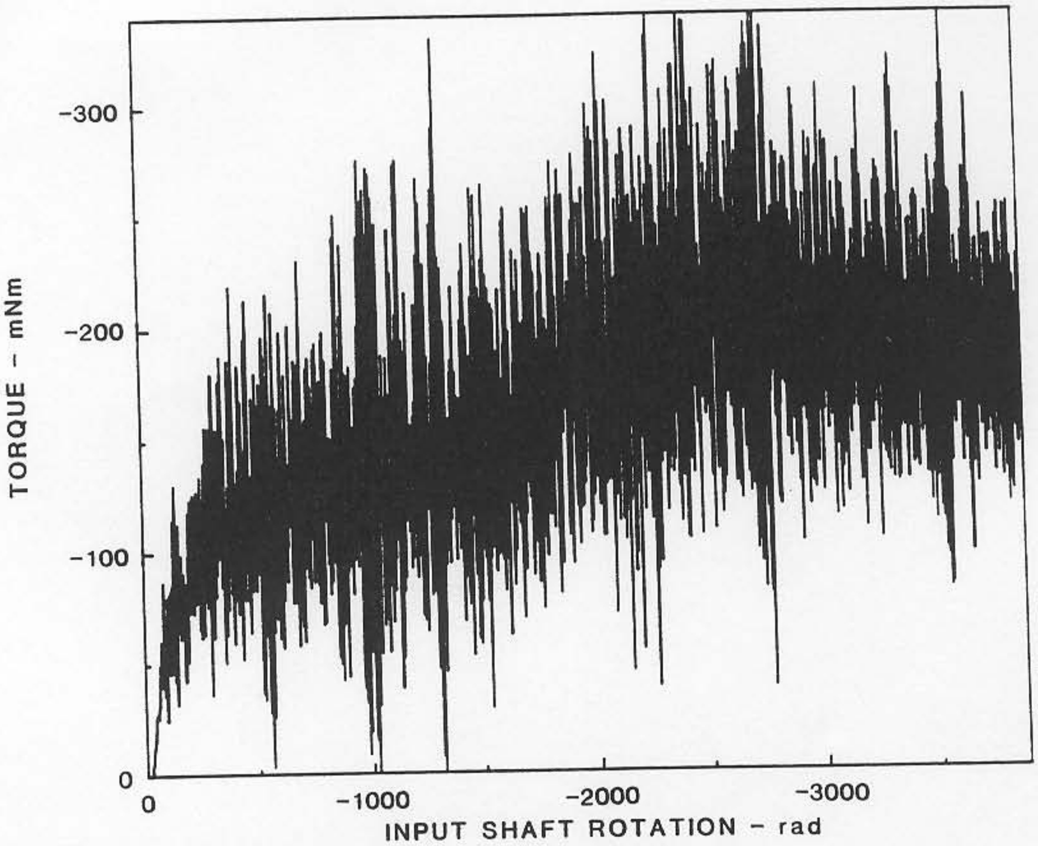

Fig. 7 Typical digitized moving bowl mixogram.

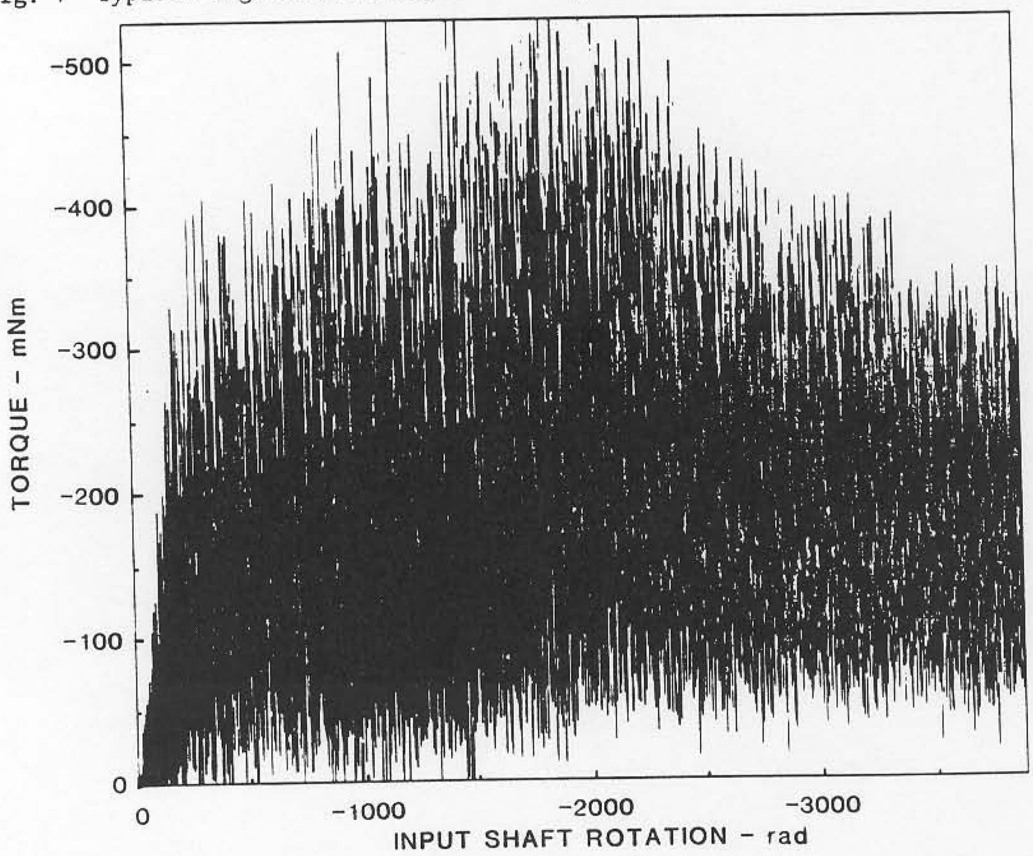

Fig. 8 Typical fixed bowl mixogram.

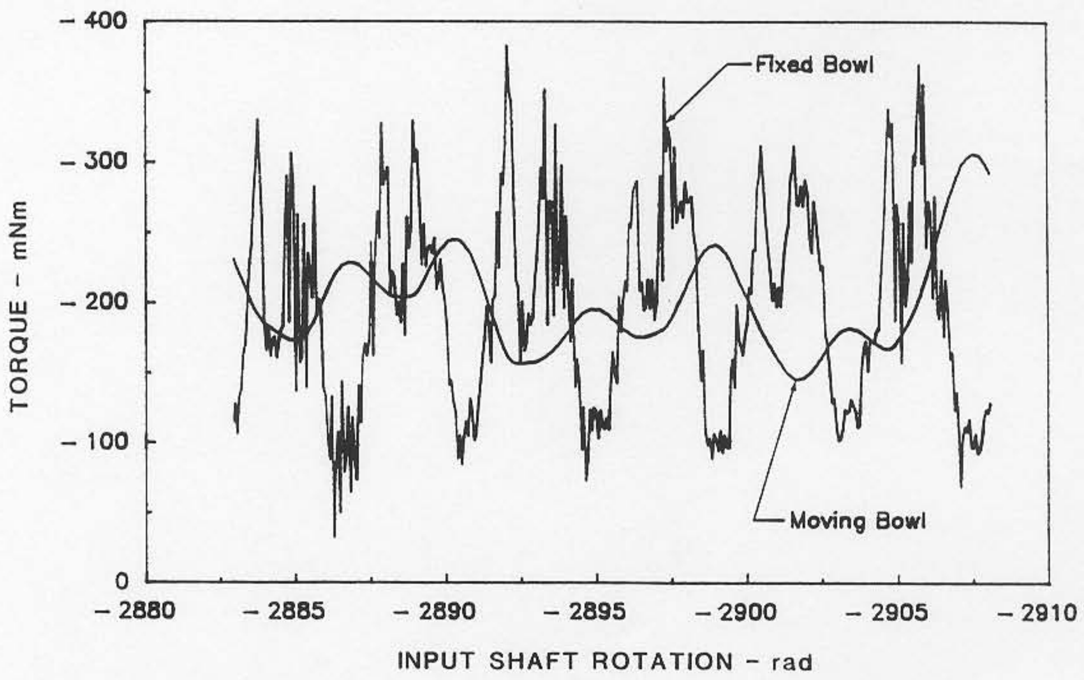

Fig. 9 Superimposed segments of the moving and fixed bowl mixograms with pin position synchronized.