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Comparison of Calculated and Experimentally Determined Punch Displacement on a Rotary Tablet Press Using both Manesty and IPT Punches

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Abstract—An indirect method of calculating punch displacement on a rotary tablet press from measurements of the change in punch force with the turret position was in good agreement with direct measurements of punch displacement made using a linear variable displacement transducer (LVDT)-slip ring system. The direct measurements were made during the compaction of three direct compression agents using Manesty punches. However, the agreement between calculated and experimentally determined punch displacements was unsatisfactory when IPT punches were used. The IPT punches have a much flatter punch head profile than the Manesty punches. Due to this difference, the analytic equation does not accurately describe the dynamics of the press under normal operating conditions. Terms in the analytic equation, determined originally under static conditions, were re-evaluated under dynamic conditions for both sets of tooling using the LVDT-slip ring system. Excellent agreement for both IPT and Manesty punches was found between punch displacement calculated using the revised analytic equation and direct experimental measurements. Punch displacements determined from punch head profile and machine geometry only, without taking machine deformations into account, were shown to differ widely from the calculated and experimental values.

Powder compaction into tablets occurs over a very small distance within the confines of a die and it is essential to take machine deformations and deflections, including axial punch contraction, into account when calculating punch displacement. Punch displacements are required for the construction of force-displacement (F-D) curves and thence for estimates of work (Krycer et al 1982) and power of compaction (Armstrong et al 1983). Accurate estimates of punch displacement are also required for evaluating changes in volume, density and porosity during powder compaction. Oates & Mitchell (1989) described an analytic method for calculating punch displacement on a Manesty Betapress. The method required a series of preliminary measurements, under both static and dynamic conditions, to establish the dependence of machine deformation on vertically applied force. The true change in punch displacement during powder compaction was calculated from the force applied to the upper and lower punches as the punches pass between the pressure rolls.

The press was instrumented to measure upper and lower punch forces and interfaced with a personal computer via a fast A/D converter for data collection, storage and analysis. Computer programs were written to calculate the change in punch displacement with mean punch force and turret position and thence to construct F-D curves where F is the mean of the upper and lower punch forces and D is the distance between the opposing upper and lower punch faces. The system enabled parameters such as work and power of compaction to be determined together with the construction of Heckel plots and similar relationships between volume reduction of the powder bed with force during the compression cycle. It seemed desirable, however, to confirm the validity of the analytical method by direct measurements of punch displacement.

In the Manesty Betapress with compression cycle analysis system first described by Ridgway Watt & Rue (1979) and in the instrumented rotary press described by Walter & Augsburger (1986), actuator arms mounted on the punch heads of one set of tooling link each punch with the armature of a linear variable displacement transducer (LVDT). In the Manesty system, extra holes are machined in the turret adjacent to the punches in order to accommodate the LVDTs and balance holes are machined on the opposite side of the turret to restore dynamic balance. Thus the activator arms are kept as short as possible to minimize "bending errors" (Ridgway Watt & Rue 1979; Ridgway Watt 1983). It is impracticable to machine extra holes in the turret of an existing press, and the LVDTs must be mounted in adjacent punch positions. This necessitates longer actuator arms and the possibility of increased errors in measured displacements. Since the displacement measurements in this paper were intended only to test the validity of the analytical method, we opted for a temporary linkage between the punch barrel and the armature of the LVDT rather than actuator arms mounted permanently on the upper and lower punch heads. A similar method of mounting was described by Jones et al (1985) who linked an LVDT to the barrel of an upper punch and used radiotelemetry to retrieve the signal.

Materials and Methods

The linkage made of 0·5″ steel was mounted securely on the punch barrel (Fig. 1). The end of the armature of the LVDT (Sangamo DG2.5) was cemented to an adjustable platen in the linkage to prevent bouncing. Signals from the LVDT were transmitted to the computer via slip rings mounted on the revolving turret. The slip rings were also used to supply

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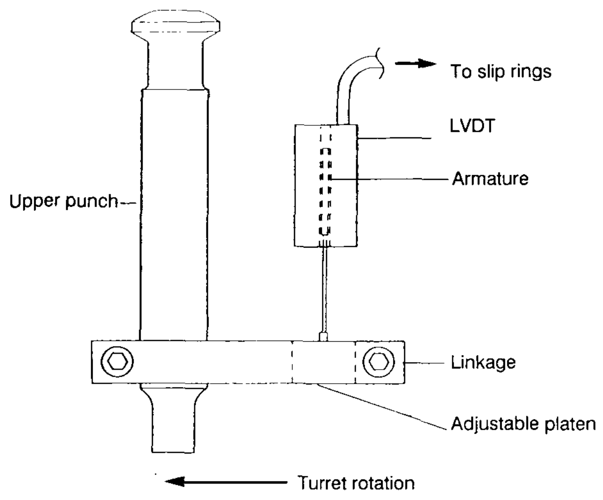

FIG. 1. Arrangement of linkage between upper punch and LVDT when mounted in the trailing position.

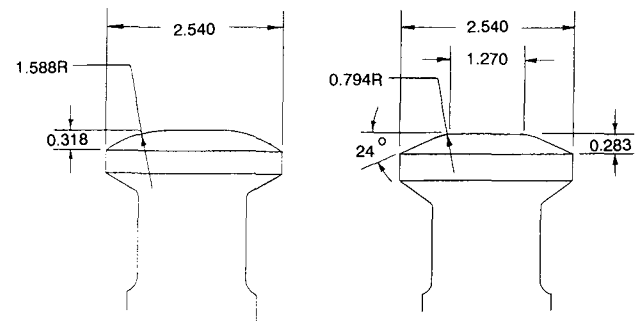

FIG. 2. Design of Manesty and IPT punch heads; dimensions in cm.

the LVDT with power. For accurate measurements of displacement, the linkage must remain parallel to the die table throughout the compression cycle. Preliminary measurements indicated that deviations occurred from the required parallel alignment as a result of angular deflection of the punches from the vertical position when they pass between the pressure rolls. In an attempt to compensate for this, measurements were first made with the linkage mounted on the upper punch in the trailing position as shown in Fig. 1, and then in the leading position. To measure the displacement of the lower punch, the experiments were repeated with the linkage mounted on the lower punch in both trailing and leading positions. It was necessary to add an extension to the armature of the LVDT in order to record the lower punch displacement. The LVDT was kept in the same position for all experiments and the punches were moved to the trailing and leading positions as required. Each determination of D therefore involved four separate experiments to measure punch displacement.

The three direct compression agents, Avicel PH 102, Emcompress and spray-dried lactose, used for these experiments were mixed with 0·5% w/w magnesium stearate and compressed on a Manesty Betapress using one set of 1·270 cm flat faced Manesty punches as described previously (Oates & Mitchell 1989). Sufficient material was weighed into the die cavity to give the required peak pressure and the press was operated at a turret revolution time of 1·00 s. Emcompress and spray dried lactose were compressed to approximately 80 and 160 MPa whilst Avicel was compressed to 80 MPa only, since the volume of powder required to give the higher pressure exceeded the capacity of the die.

There appear to be two distinctly different punch heads in common use. These are illustrated in Fig. 2 and will be referred to as Manesty and IPT (Swartz 1969).* IPT punches conform to the standard specifications of the Industrial Pharmacy Technology Section of the Academy of Pharmaceutical Sciences, American Pharmaceutical Association.

For the analytical method to be generally applicable it should be independent of the geometry of the punch head. To test this, punch displacements calculated using the analytical method were compared with direct measurements of punch displacement made using IPT tooling in addition to the direct measurements made using the Manesty tooling.

* The Betapress can be supplied with either Manesty or IPT tooling and fitted with the appropriate cam tracks.

Results and Discussion

The distance between opposing punch faces, D, can be estimated analytically by analysing the geometry of the tablet press (Oates & Mitchell 1989). During compression when the punches are pressed against their respective pressure rolls, the machine is physically constrained and an expression for D is obtained:

$$D = D_M - D_P + D_{AA'} - D_{PUN} \qquad (1)$$

where:

D_M is the total deflection and deformation in the vertical direction experienced by the press including the contraction of the punches when a vertical force is applied;

D_P is the vertical distance from the axis of the upper pressure roll to a fixed reference point on the upper punch plus the distance from the axis of the lower pressure roll to a reference point on the lower punch;

$D_{AA'}$ is the vertical separation of the upper and lower pressure roll axes when no force is applied;

D_{PUN} is the vertical distance from the reference point on the upper punch to the upper punch face plus the distance from the reference point on the lower punch to the lower punch face.

When this equation was analysed previously (Oates & Mitchell 1989), it was differentiated with respect to the upper and lower punch forces, F_1 and F_2, respectively, and the fractional turret position, fr. These were considered the only independent variables acting on the press. Since the upper and lower punch forces are almost equal during compression it is convenient to use the mean of these forces F (i.e. $F = (F_1 + F_2)/2$) thereby reducing the number of independent variables to two. Differentiating equation 1 with respect to fr and F gives the expression:

$$dD = [(\partial D_M/\partial F) - (\partial D_P/\partial F)]dF + [(\partial D_M/\partial fr) - (\partial D_P/\partial fr)]dfr \qquad (2)$$

The methods used to obtain the terms in equation 2 were described by Oates & Mitchell (1989) but are summarized here to assist with the subsequent discussion:

$(\partial D_M/\partial F)$ was measured under static conditions using feeler gauges to vary the distance between the opposing punch faces and then measuring the resultant force when the pressure rolls and punches were vertically aligned. This term was found to be constant equalling $2{\cdot}4 \times 10^{-6}$ cm N^{-1} for forces greater than 2·3 kN;

$(\partial D_P/\partial F)$ was determined from measurements of force obtained by compressing a steel tablet under dynamic conditions;

$(\partial D_M/\partial fr)$ was determined by measuring the change in $(\partial D_M/\partial F)$ with fr. This term was found to be independent of turret position and therefore equal to zero;

$(\partial D_P/\partial fr)$ was measured under static conditions using feeler gauges between the opposing punch faces at different fractional turret positions and constant force to ensure constant machine deformation.

Equation 2 can be integrated to give an expression for the punch displacement when the turret rotates between turret positions fr_A and fr_B:

$$D_{AB} = \int dD = \int_{F_A}^{F_B} (\partial D_M/\partial F)dF - \int_{fr_A}^{fr_B} (\partial D_P/\partial fr)dfr - \int_{F_A}^{F_B} (\partial D_P/\partial F)dF \quad (3)$$

where:

F_A and F_B are the forces experienced at turret positions fr_A and fr_B, respectively.

The work done by the machine when the turret rotates from fr_A to fr_B can be derived from equation 2:

$$W_{AB} = \int FdD = \int_{F_A}^{F_B} F(\partial D_M/\partial F)\, dF - \int_{fr_A}^{fr_B} F(\partial D_P/\partial fr)dfr - \int_{F_A}^{F_B} F(\partial D_P/\partial F)dF \quad (4)$$

When fr_A corresponds to the turret position at which compression begins and $fr_B = 0$, then W_{AB} is the work done in forming a tablet, W. This work, W, includes non-recoverable work associated with particle rearrangement, fracture, plastic deformation etc., and recoverable elastic work done to the compact during compression. Elastic work on recovery of the tablet during decompression has not been fully analysed as yet but is small relative to the elastic recovery of the machine.

The movement of the punches was measured directly using the LVDT-slip ring system. Fig. 3 shows the vertical change in upper punch position, D_U, and the lower punch position, D_L, relative to the top surface of the die table with respect to fr during the compression phase of the compression cycle of Emcompress determined using Manesty punches with the mechanical linkage in both leading and trailing positions. The initial rise in D_U is caused by the upward movement of the lower punch as it moves onto the lower pressure roll forcing the powder bed, together with the upper punch, upward until contact is made with the upper pressure roll. The distance between the curves of D_U and D_L is equal to D and includes all deformations in the press and punches.

To compare the experimentally measured values of D with the values calculated according to equation 3, the distance $(D - D_I)$ was plotted versus fr, where D_I is the initial depth of the powder in the die. Just before compression $D = D_I$ and hence $(D - D_I) = 0$. During compression $(D - D_I)$ becomes increasingly negative as the punch faces are forced towards each other reducing the thickness of the powder bed. Fig. 4a shows that the experimental and calculated values of $(D - D_I)$ for Avicel, Emcompress, and spray-dried lactose are in close agreement.

Punch displacements were also measured directly using the LVDT-slip ring system for the IPT tooling and compared with the values calculated using equation 3. Unlike the excellent agreement found between the experimental and calculated values of $(D - D_I)$ found using the Manesty punches, Fig. 4b shows that there were large discrepancies between the experimental and calculated values for each of the three direct compression agents. The calculated curves were steeper at the initial stages of compression and flatter as the punches approach $fr = 0$ than the experimental curves. Fig. 2 compares the design of the Manesty and IPT punch heads. Unlike the Manesty head, which has a semi-circular profile with only a small flat, the IPT head has an outside head angle of 24° with an abrupt transition to a 0·5″ diameter head flat. Examination of equation 3 suggests that $(\partial D_P/\partial fr)$

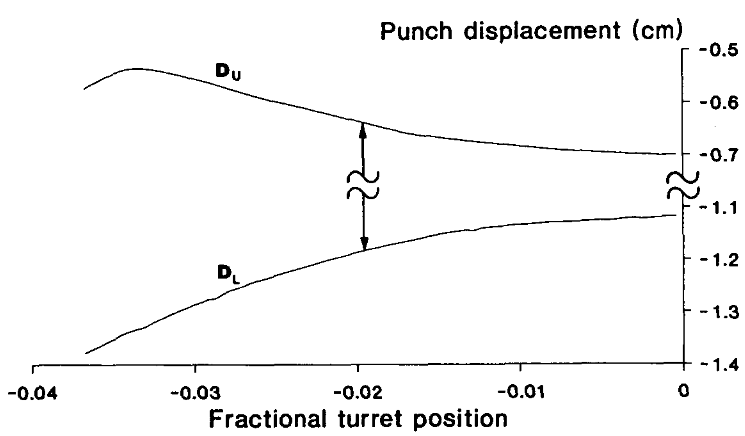

FIG. 3. Upper and lower punch displacements with fractional turret position during the compression phase of the compression cycle for Emcompress at a peak pressure of 160 MPa.

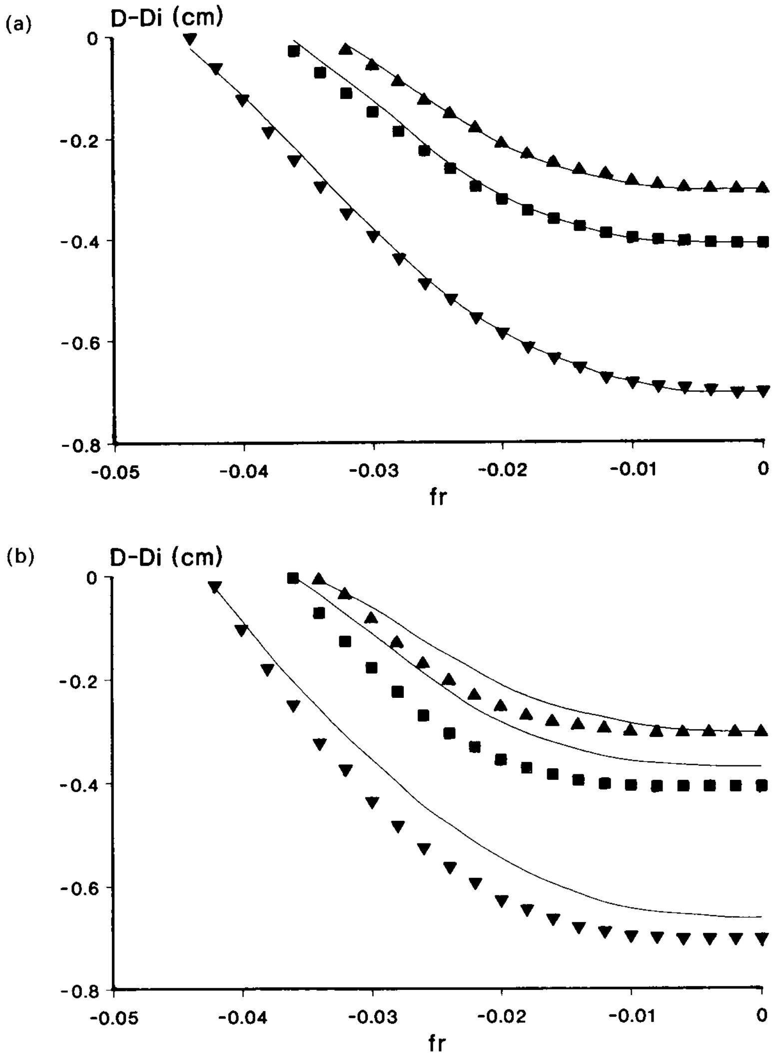

FIG. 4. Comparison of experimental and calculated values of the relative decrease in the thickness of the powder bed during compression versus fractional turret position. (a) Manesty punches, (b) IPT punches. Lines experimental; symbols calculated. ▼, Avicel (80 MPa); ■, Emcompress (160 MPa); ▲, spray-dried lactose (160 MPa).

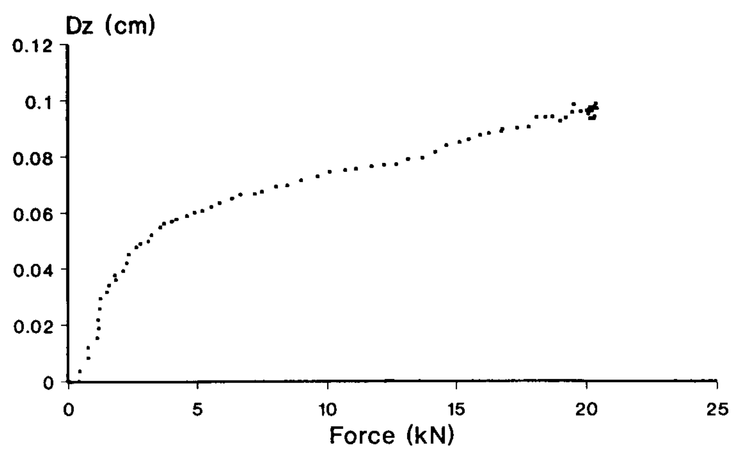

FIG. 5. Representative plot of machine deformation, including punch contraction, as a function of applied vertical force under dynamic conditions for spray-dried lactose.

determined under static conditions does not accurately describe the dynamics of the press under normal operating conditions when the IPT tooling is used. It appears that, during compression at normal running speeds, the deflections of the press do not react as expected to the sharp change in slope characteristic of the IPT heads. Since the press does not react the same under static and dynamic conditions, time must also be an independent variable. If equation 1 is differentiated by F, fr, and time t, the following equation is obtained:

$$\begin{aligned} dD = & [(\partial D_M/\partial F) - (\partial D_P/\partial F)]dF \\ & + [(\partial D_M/\partial fr) - (\partial D_P/\partial fr)]dfr \\ & + [(\partial D_M/\partial t) - (\partial D_P/\partial t)]dt \end{aligned} \quad (5)$$

It is not possible to devise experiments which completely isolate each term in equation 5. This, however, is not necessary since certain terms are coupled and do not act independently. Terms $(\partial D_M/\partial F)$ and $(\partial D_M/\partial t)$ collectively describe the machine deflection under dynamic conditions. Since the machine deflection of interest always occurs while the machine is running, these terms may be combined to form a new term $(\partial D_M/\partial F)^*$, the machine deflection under dynamic conditions. Similarly, the terms $(\partial D_P/\partial fr)$ and $(\partial D_P/\partial t)$ form two new terms $(\partial D_P/\partial fr)^*$ and $(\partial D_P/\partial t)^*$. Term $(\partial D_P/\partial fr)^*$ is the change in distance between the opposing punch faces with respect to fr under dynamic conditions and term $(\partial D_P/\partial t)^*$ (which will be described later) is the acceleration of the punches during the initial stages of compression. As before, $(\partial D_M/\partial fr)$, the change in machine deflection with turret position equals zero and, as will be shown later, $(\partial D_P/\partial F)$ is negligible. Using the modified terms, equation 5 is rewritten:

$$dD = (\partial D_M/\partial F)^* dF - (\partial D_P/\partial fr)^* dfr - (\partial D_P/\partial t)^* dt \quad (6)$$

A revised expression for punch displacement can be estimated by integrating equation 6:

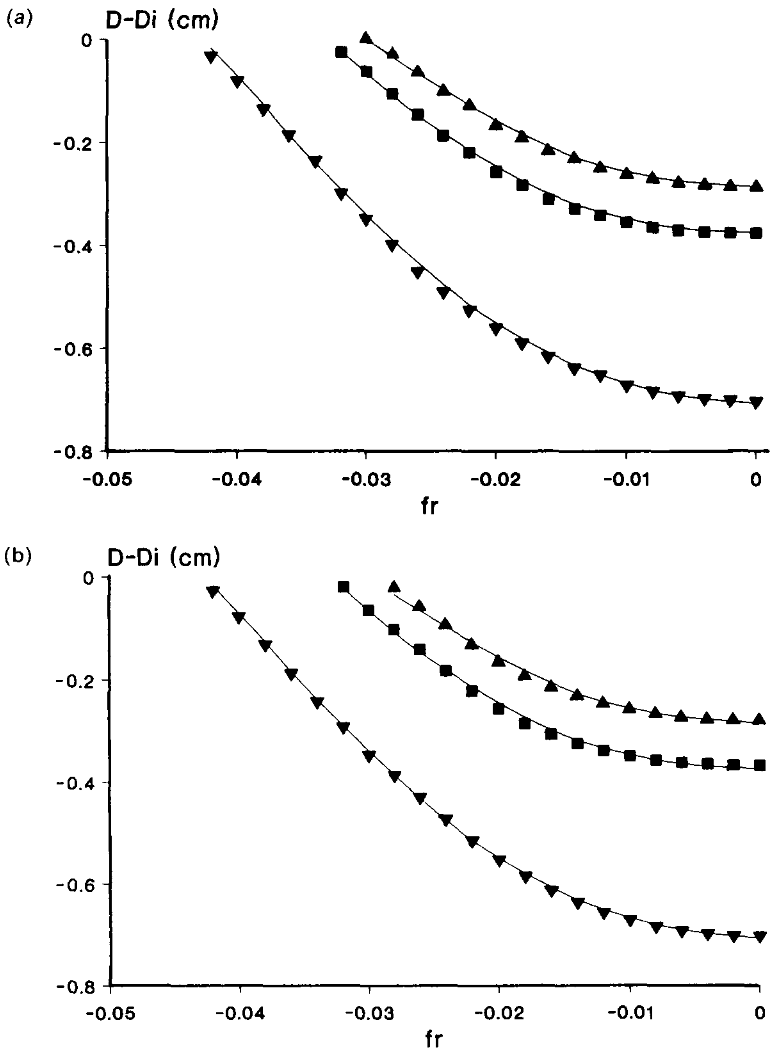

FIG. 6. Comparison of experimental values and values calculated according to equation 7 of the relative decrease in thickness of the powder bed during compression versus fractional turret position. (a) Manesty punches, (b) IPT punches. Lines experimental; symbols calculated: ▼, Avicel (80 MPa); ■, Emcompress (160 MPa); ▲, spray-dried lactose (160 MPa).

$$D_{AB} = \int dD = \int_{F_A}^{F_B} (\partial D_M/\partial F)^* dF - \int_{fr_A}^{fr_B} (\partial D_P/\partial fr)^* dfr - \int_{t_A}^{t_B} (\partial D_P/\partial t)^* dt \quad (7)$$

The work done when the turret rotates between positions frA and frB is calculated from equation 8:

$$W_{AB} = \int F dD = \int_{F_A}^{F_B} F(\partial D_M/\partial F)^* dF - \int_{fr_A}^{fr_B} F(\partial D_P/\partial fr)^* dfr - \int_{t_A}^{t_B} F(\partial D_P/\partial t)^* dt \quad (8)$$

In order to determine $(\partial D_P/\partial fr)^*$ for both the Manesty and IPT tooling, the die cavity was filled with Shell Macoma Oil No. 72 and the punch displacements were recorded at normal operating speeds using the LVDT-slip ring system. Measurements were made with the linkage in both leading and trailing positions as before. During compression, the oil was squeezed through the gap between the punches and the die wall such that the upper and lower punches were kept in contact with their respective pressure rolls throughout compression. The maximum force measured during this determination was less than 1 kN (7·9 MPa).

A curve fitting program was used to obtain a smooth curve for the displacement of each punch head with respect to fraction at this minimal force and the resulting curve was differentiated to obtain $(\partial D_P/\partial fr)^*$. This term now becomes the distance between the opposing punch faces under dynamic conditions determined using small vertical forces where machine deformation and deflections are negligible. Although the values of $(D - D_I)$ calculated using $(\partial D_P/\partial fr)^*$ showed better agreement with the direct measurements, slight discrepancies were still apparent during the initial stages of compression. To determine the source of this discrepancy, other possible sources of machine deflection were considered.

The distance D_{AB} is the vertical distance between the opposing punch faces when all machine deflections, deformations and punch contractions are taken into account. The integration of $(\partial D_P/\partial fr)^*$ is the distance between the opposing punch faces when the vertical force is negligible. Adding these integrals gives D_Z as defined by equation 9:

$$\int_{fr_A}^{fr_B} dD + \int_{fr_A}^{fr_B} (\partial D_P/\partial fr)^* dfr = D_Z \quad (9)$$

Where D_Z is all machine deflections etc. which occur during compression under dynamic conditions.

The dependency of D_Z on force is illustrated by the representative plot, Fig. 5, which shows a marked change in D_Z during the initial stage of compression followed by a linear region with a slope of $2{\cdot}4 \times 10^{-6}$ cm N^{-1}. This slope

Table 1. Work of tablet formation for Manesty punches[a].

Analysis	Material	Maximum pressure (MPa)	Mass (g)	W/m (Nm g^{-1})	Error[b] (%)
A	Emcompress	79	0·885	9·2	
	Emcompress	159	1·002	15·3	
	S. D. Lactose	84	0·640	12·1	
	S. D. Lactose	161	0·722	23·0	
	Avicel	83	0·646	30·8	
B	Emcompress	79	0·885	8·7	−5
	Emcompress	159	1·002	12·6	−18
	S. D. Lactose	84	0·640	11·5	−5
	S. D. Lactose	161	0·722	20·3	−12
	Avicel	83	0·646	28·2	−8
C	Emcompress	79	0·885	9·2	0
	Emcompress	159	1·002	13·5	−12
	S. D. Lactose	84	0·640	11·7	−3
	S. D. Lactose	161	0·722	21·5	−7
	Avicel	83	0·646	29·0	−6
D	Emcompress	79	0·885	8·8	−4
	Emcompress	159	1·002	14·5	−5
	S. D. Lactose	84	0·640	11·3	−7
	S. D. Lactose	161	0·722	21·7	−6
	Avicel	83	0·646	29·7	−4
E	Emcompress	79	0·885	5·5	−40
	Emcompress	159	1·002	9·8	−36
	S. D. Lactose	84	0·640	7·0	−42
	S. D. Lactose	161	0·722	14·4	−37
	Avicel	83	0·646	20·8	−32

[a] Turret revolution time 1·00 s.
[b] Relative to A.
A From direct measurements of punch displacement.
B From equation 4.
C From equation 8.
D From direct measurements of punch displacement with linkage in trailing position only.
E From punch displacement calculated using machine and punch head geometry.

represents the force dependent vertical deflection of the machine during compaction under dynamic conditions, $(\partial D_M/\partial F)^*$ in equation 6. In calculating D_Z, it is necessary to correct the direct measurements of punch displacement for the force dependent axial punch contraction using the modulus of elasticity for steel. This correction will vary according to the distance between the punch face and the top surface of the punch-LVDT linkage. In order to minimize this correction, the linkage was mounted as close to the punch face as possible (Fig. 1). This slope agrees with the slope determined previously under static conditions (i.e. $(\partial D_M/\partial F)$ in equation 2 and curve 1 of Fig. 2, Oates & Mitchell 1989).

Fig. 5 suggests, when the punch heads first contact the pressure rolls at the start of compression, that the force exerted moves the pressure rolls on their bearings to increase the distance between the punch faces by about 0·05 cm in about 0·01 s.

The difference in the relative positions of the upper and lower rolls on their bearings due to gravity makes this initial shift more pronounced in the upper roll assembly which is initially accelerated upwards on contact with the head of the upper punch until the play is taken up. On the basis of this analysis, term $(\partial D_P/\partial fr)$ can be subdivided into two parts: $(\partial D_P/\partial fr)^*$, the change in punch displacement with respect to turret position under dynamic conditions and minimal constant force, and $(\partial D_P/\partial t)^*$, the effect on punch displacement of shifts in the pressure rolls on their bearings during the initial stages of compression.

This initial displacement was originally incorporated in the F versus fr curves (Fig. 4, Oates & Mitchell 1989) and interpreted by the term $(\partial D_P/\partial F)$ in equations 2 and 5. The effect of $(\partial D_P/\partial F)$ is to decrease the predicted distance travelled by the punches as they approach $fr = 0$. When equation 5 is re-evaluated, taking this initial displacement into account, the magnitude of $(\partial D_P/\partial F)$ is greatly reduced.

Fig. 6 shows excellent agreement between plots of $(D - D_I)$ versus fr for both types of tooling calculated using the re-evaluated equation and the direct measurements using the LVDT-slip ring system. Table 1 shows that values of the work of tablet formation normalized for the powder mass, W/m, calculated for the Manesty punches using the revised analysis, equation 8, are in closer agreement with the values calculated from the direct measurements of punch displacement than are the values calculated using equation 4. On average, W/m, calculated using equation 4 is about 10% less than W/m calculated from the direct measurements, while W/m calculated using equation 8 is about 5% less.

The improvement in agreement between the values of W/m calculated from equation 8 and the values from direct measurement is even more evident for the IPT punches. Equation 4 seriously underestimates W/m compared with equation 8 which gives values of W/m much closer to the values calculated from the direct measurements. Thus, as

Table 2. Work of tablet formation for IPT punches[a].

Analysis	Material	Maximum pressure (MPa)	Mass (g)	W/m (Nm g^{-1})	Error[b] (%)
A	Emcompress	80	0·885	8·9	
	Emcompress	159	1·002	14·3	
	S. D. Lactose	83	0·638	11·3	
	S. D. Lactose	162	0·726	20·0	
	Avicel	83	0·650	30·4	
B	Emcompress	80	0·885	6·6	−26
	Emcompress	159	1·002	9·7	−32
	S. D. Lactose	83	0·638	8·1	−28
	S. D. Lactose	162	0·726	11·7	−42
	Avicel	83	0·650	27·2	−10
C	Emcompress	80	0·885	9·4	5
	Emcompress	159	1·002	14·0	−2
	S. D. Lactose	83	0·638	12·5	11
	S. D. Lactose	162	0·726	18·5	−8
	Avicel	83	0·650	30·4	0
D	Emcompress	80	0·885	7·7	−14
	Emcompress	159	1·002	11·5	−19
	S. D. Lactose	83	0·638	8·9	−21
	S. D. Lactose	162	0·726	15·8	−21
	Avicel	83	0·650	28·0	−8
E	Emcompress	80	0·885	4·6	−48
	Emcompress	159	1·002	7·8	−45
	S. D. Lactose	83	0·638	5·7	−50
	S. D. Lactose	162	0·726	9·9	−51
	Avicel	83	0·650	20·7	−32

[a] Turret revolution time 1·00 s.
[b] Relative to A.
A From direct measurements.
B From equation 4.
C From equation 8.
D From direct measurements of punch displacement with linkage in trailing position only.
E From punch displacement calculated using machine and punch head geometry.

shown in Table 2 for spray-dried lactose compressed at 162 MPa, W/m calculated from the original analysis of punch displacement is 42% less than that calculated from direct measurements, while equation 8 gave a value of 8% less. Equation 3 underestimated the change of punch displacement as fr approaches zero. Since any displacement in this region occurs under maximum force, errors in W are exaggerated particularly for the IPT punches with their larger punch head flat (Fig. 2).

Compaction simulators are increasingly used in tableting research (Hunter 1983; Jones et al 1985; Bateman et al 1989; Celik & Marshall 1989). To quote Celik & Marshall (1989) "the ultimate aim of the simulator is to be able to mimic the precise compaction cycle of any press in real time. To do this it is necessary to provide the system with co-ordinates of punch position with respect to time". Punch displacement profiles can be calculated from machine and punch geometry for each press using the equations of Rippie & Danielson (1981) or Charlton & Newton (1984). However, these calculations do not take machine deformations and deflections into account, and as shown in Fig. 7 this will lead to large errors in estimates of punch displacement and hence other dependent parameters such as work of tablet formation (Tables 1, 2). Alternatively, each press can be instrumented to make direct measurements of punch displacement as suggested by Jones et al (1985). The most elegant solution would be for the terms in our analytical model to be determined for each particular rotary press and to include these terms in the compaction simulator's software so as to mimic the punch displacement profile. LVDTs are the devices most commonly used to measure punch displacement. The sources of error in using LVDTs on the rotary press have been described by Ridgway Watt (1988). Any linkage between the punches and the LVDT is subject to twisting as the punches tilt in their guide holes when they travel between the pressure rolls. This can lead to measurement errors in the punch displacement profiles and hence in the calculation of W. Tables 1 and 2 show values of W/m calculated from displacement measured with the linkage mounted in the trailing position only. For the Manesty

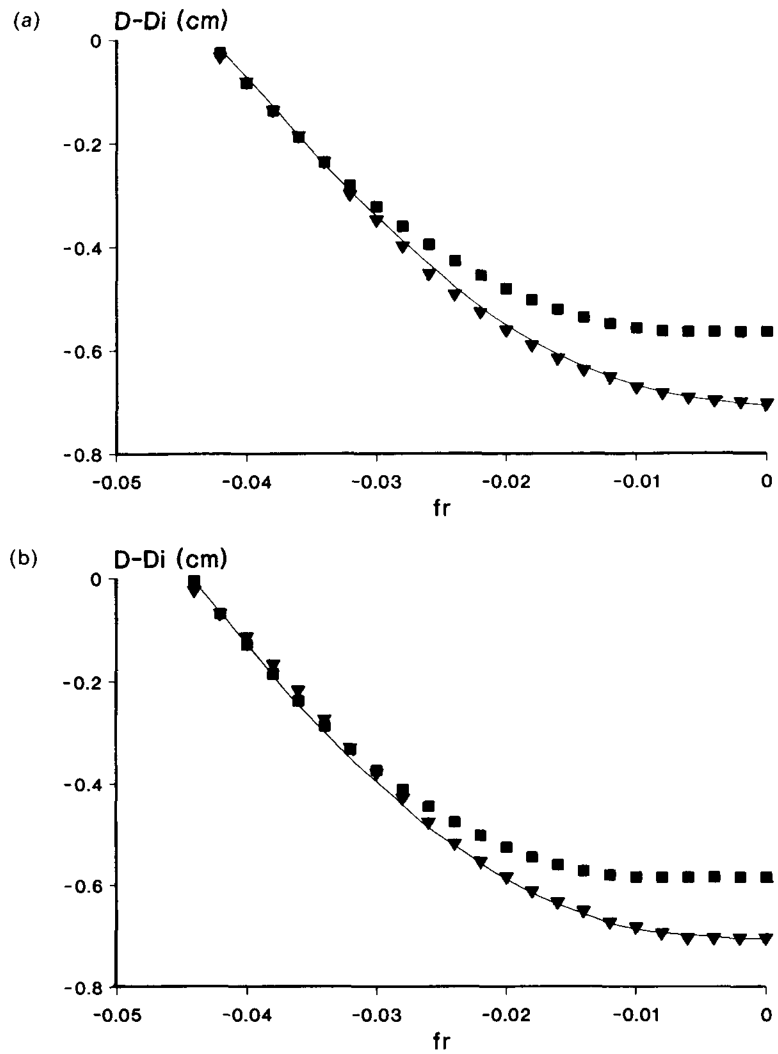

FIG. 7. Comparison of values calculated according to equation 7 and values calculated from punch head and machine geometry of the relative decrease in the thickness of Avicel during compression versus fractional turret position. (a) Manesty punches, (b) IPT punches. Lines experimental; symbols calculated: ▽, according to equation 7 □, from punch head profile and machine geometry.

punches, the difference between W/m calculated from punch displacement measurements made with the linkage in both leading and trailing positions and measurements made with linkages in the trailing position only is up to about 7%. With the IPT punches the corresponding difference is up to 21%. For accurate direct punch displacement measurements it is necessary to compensate for twisting by making measurements with the LVDT linkage mounted in both leading and trailing positions. This is clearly not a feasible procedure on an operational press particularly since, in the absence of a keyway to prevent punch rotation, guide posts were required to prevent the linkage from swinging out in response to the centrifugal forces created by the turret rotation and the rotation of the punch heads on the upper cam track.

For punch displacement profiles using equation 7, the LVDT-slip ring system is required first to measure punch displacement at zero force using a high viscosity oil and second, using various directly compressible powders, to verify that the measured punch displacements agree with the calculated punch displacement profile. The LVDT-slip ring system can then be removed and the punch displacement calculated from equation 7 using measurements of force and turret position only.

In principle the analytical method of calculating punch displacement and the experimental procedures used to determine the press characteristics should be applicable to any rotary press. The method is considerably less expensive than direct measurements using the Manesty Betapress with compression cycle analysis system and more convenient than having permanently mounted actuator arms linking punches to LVDTs on a custom modified machine.

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