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Chipper / Shredder: The Pull-In Hypothesis

By Ralph L. Barnett * and Dennis B. Brickman **

ABSTRACT

On rare occasions, a portion of an uncut fiber will exit the discharge chute of a consumer hammer mill type chipper/shredder and remain at rest with its inboard portion in the neighborhood of the rotating elements. Disturbing the fiber may cause it to commit to the rotating flails and be pulled instantaneously back into the machine. A number of investigators have postulated that an operator who grasps a fiber that subsequently experiences this pull-in phenomenon cannot release it fast enough to avoid being dragged into the flails. This hypothesis is discredited by both analytical and experimental analyses.

INTRODUCTION

A typical chipper/shredder of the hammer mill type is shown in Fig. 1a where its discharge chute is oriented in a horizontal direction at the bottom of the machine. A pull-in phenomenon is associated with the chipper/shredder when uncut fibers emerge from the discharge chute. Attempts by operators to grasp such fibers may cause them to shift into a position where the rotating hammer mill elements latch onto the fibers and instantly pull them back into the machine at a speed corresponding to the peripheral speed of the hammer mill. Under this condition, the fibers are literally dragged out of the operator's hand so rapidly that no movement of the arm is perceived until after the fiber exits the hand. The drag exerted on the hand by the moving fiber delivers an impulse which causes subsequent swing or pendulum motion of the upper and lower arm in the direction of the discharge chute.

There are many scenarios involving agricultural machinery where operators attempt to clear clogged machinery by pulling on cornstalks and the like. When the clogs finally clear, these fibrous products are pulled into the machine at relatively low speeds compared to the hand speed constant of 63 in./sec. Problems of this type are analyzed from a safety point of view by invoking notions of reaction time that include calculations of the elapsed time necessary to perceive a danger, to cognitively process a countermeasure strategy, and to execute the escape program decided upon. For example, if we assume the time from perception of movement of a cornstalk to hand release is 0.75 seconds, one determines how far the stalk can be pulled into the machine in 0.75 seconds. This critical distance defines the gripping zone which leads to pull-in and, conversely, the gripping zone which leads to safe release. On the basis of such classical models, it seems natural to propose a hypothesis that a hand may be pulled into a chipper/shredder if one grasps a fiber which is dangling from the discharge chute. Such a hypothesis is even more plausible in the face of observations of fibers being pulled back into the machine's hammer mill at great speed and with great force. Unfortunately, we have a case where intuition is a good servant, but a bad master. Testing of this hypothesis reveals that it is false. Unlike the example of unclogging the corn picker, the pull-in time associated with a chipper/shredder is approximately 0.01 seconds. This gives rise to completely different phenomena than those encountered in the slower moving applications. Indeed, the fibers are wrenched or dragged out of an operator's hand in a time interval which is much smaller than a person's reaction time.

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No Charge

Can an operator's hand remain clasped to a fiber which is pulled into the discharge chute of a chipper/shredder? The primary purpose of this paper is to answer this question and two independent approaches have been adopted. The first of these involves a series of experiments which simulate a pull-in excursion using an anthropomorphic dummy. The second approach involves the formulation of a mathematical model for predicting the behavior of an operator's arm during drag-in. The model leads to a straightforward relationship among the arm response, grip strength, machine speed, exposed fiber length, and the length, weight and dynamic characteristics of the arm.

The discharge chute is constructed with a hinged door that is locked in position over the top of the chute. The safety role of the door is explored with respect to the swing-in hazard. In addition, it is shown that the door prevents the hand from entering the discharge chute under a fanciful worst case scenario where a very strong fiber is actually tied to the operator's arm.

TEST PROGRAM

Test Setup

Figure 1a shows a side elevation of the test setup that was used to study the pull-in phenomenon. The chipper/shredder rotating hammer mill elements illustrated in Fig. 1b can entwine fibrous material that may escape the flails when exiting the machine. The particular chipper/shredder studied operated at 3600 rpm, weighed 236 lb and had its flails removed to preclude premature cutting of the fibers. A 73 in. tall anthropomorphic dummy weighing 206 lb with a locked elbow is poised in front of the discharge chute with its right arm acting as a compound pendulum. The discharge chute door is held open in a raised position in contrast to the chipper/shredder manufacturer's instructions. The arm is oriented so that it grasps a fiber which is horizontally disposed to reenter the discharge chute. The fiber length depicted extends 2 ft in back of the leading edge of the dummy's hand. In the illustration shown in Fig. 1a, a simple clamping device provides a friction grip on a clothesline with a tensile strength of 754 lb. During the development of the test protocol, static clamping forces between 5 lb and 100 lb were applied to either a clothesline or a stick inserted in the dummy's hand. As indicated in Fig. 1a, the rope used for pull-in was threaded through the chipper/shredder in an initial position which would not commit to the rotating elements. Shifting of the rope caused immediate entanglement which snatched the stick or rope out of the dummy's hand so rapidly that the movement could not be captured on videotape. Furthermore, the exit frame captured by the videotape shows no movement of the hand or arm. Subsequent swinging of the arm is caused by an impulse applied to the hand by the moving rope or stick.

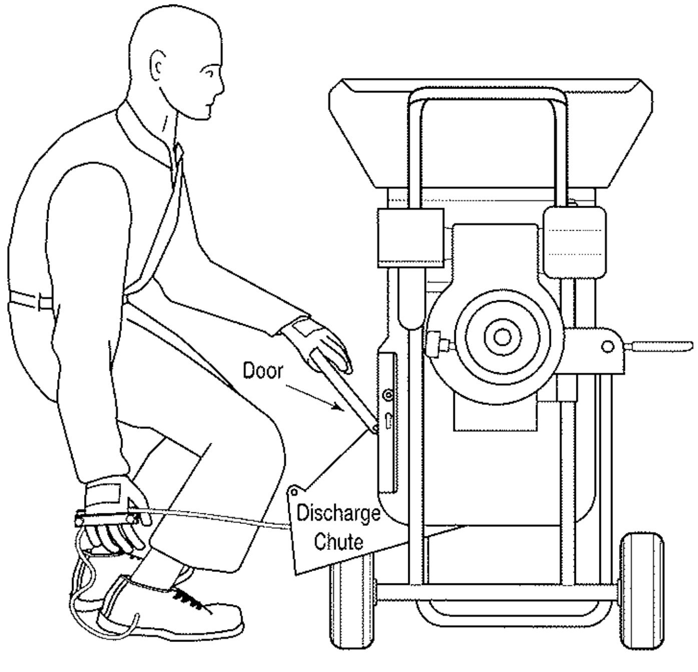


Fig. 1a: Side Elevation of Test Set-up

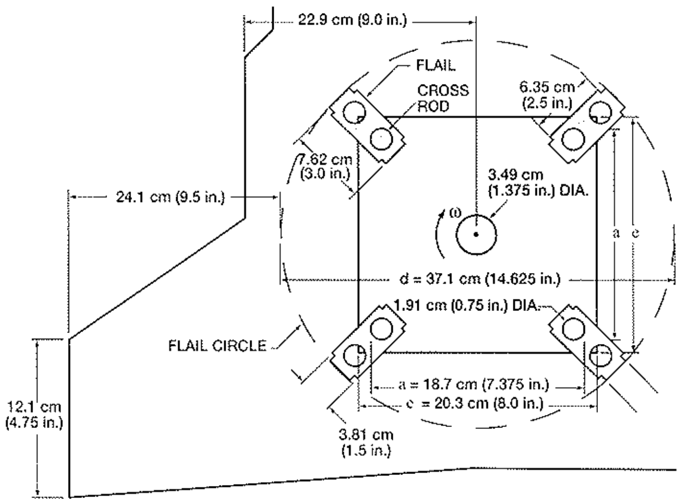


Fig. 1b: Internal Construction of Hammer Mill

Hand Grip Simulation

In an attempt to provide a constant force hand release to be used with either rope or wood strips, a number of conventional friction clamps were fabricated. Their performance proved to be inconsistent and led to drag forces of highly varying magnitude. These devices were replaced by the constant force spring illustrated in Fig. 2. The length of the spring was taken to be the same as the length of fiber protruding behind the leading edge of the dummy's hand. The spring forces varied in the six experiments conducted from 9.1 lb to 28.7 lb. In each case, the spring force was measured on the mandrel.

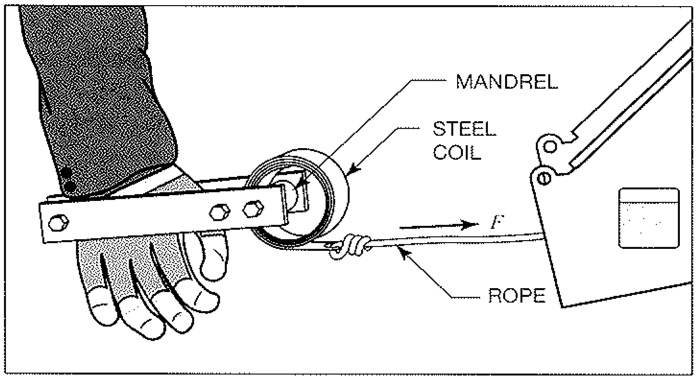
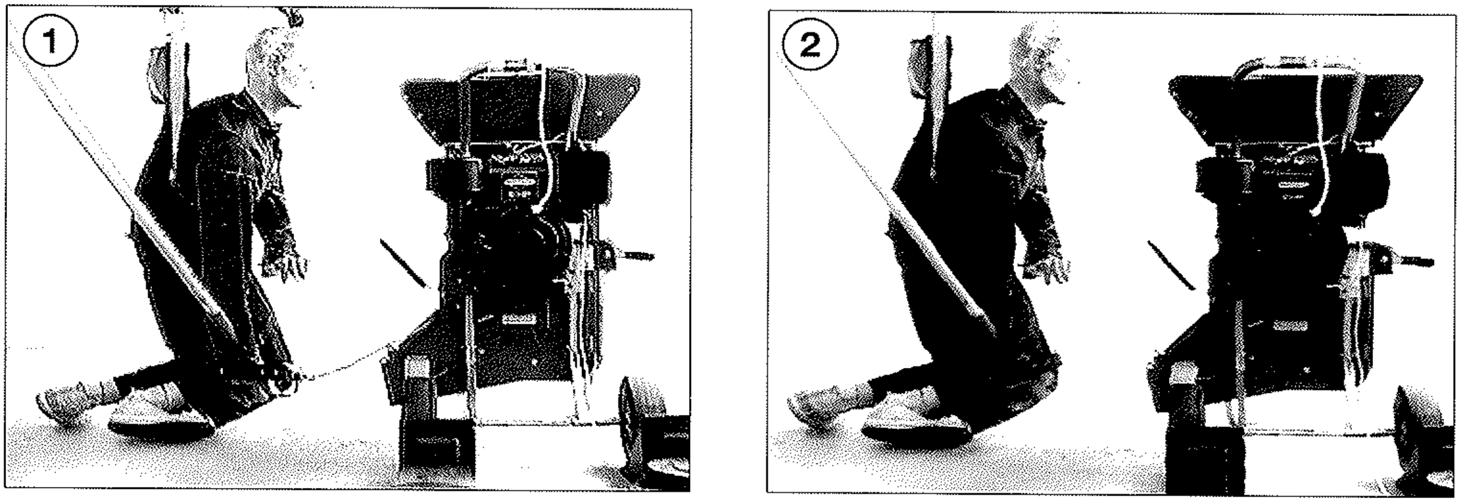


Fig. 2: Constant Force Stainless Steel Spring

Test Results

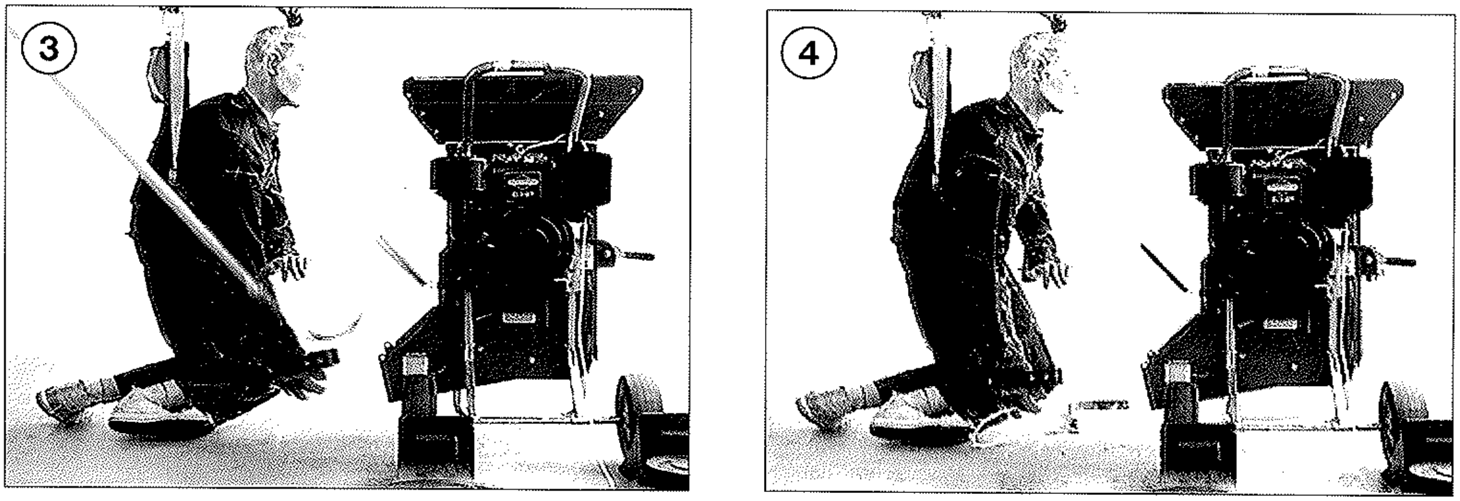
Six tests were performed using different strength springs with a length of either 1 ft or 2 ft. In all of the tests, the dummy's elbow was locked and the hammer mill rotated at 3600 rpm which produced a drag-in speed of v_p = 147.5 ft/sec (see Appendix A). In all six tests and in all protocol development tests, the arm was observed to remain vertically at rest until the rope, stick, or constant force spring exited the hand. Furthermore, it was observed that the shoulder location was almost unchanged during the experiment.

From frames 1 and 2, we conclude that the arm with the locked elbow remains vertical during the impulse. It is clear from frames 1 through 4 that the shoulder movement is very slight. The maximum swing taken from frame 3 is recorded as an experimental measurement in Table 1 together with the maximum amplitudes achieved in the other five tests. It should be noted that Table 1 also contains the analytical predictions of maximum arm swing where the experimental and predicted results are very close. The experimental results refute the hypothesis that an operator's hand remains clutched to a fiber that is drawn into the hammer mill.



1) Constant Force Spring on Mandrel

2) Constant Force Spring Withdrawn from Hand



3) Maximum Arm Swing Towards Discharge Chute

4) Arm Returns to Orginal Position

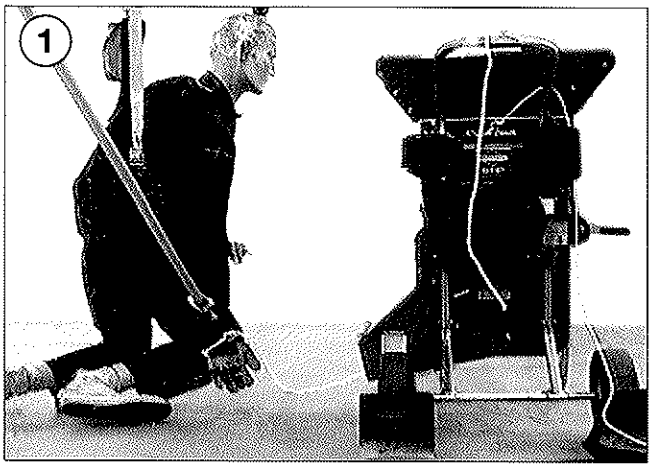
Fig. 3: Video Sequence of Pull-in Test

Figure 3 contains a video sequence of a typical pull-in test. The first frame is taken as the last frame where the constant force spring was in position on the mandrel. The following video frame taken 1/30 of a second later indicates that the entire 2 ft spring has been withdrawn from the hand and is completely inside the chipper/shredder. The third video frame taken 5/30 of a second after frame 2 captures the maximum swing of the arm. Frame 4 taken 20/30 of a second after frame 3 illustrates the arm returned to its original position.

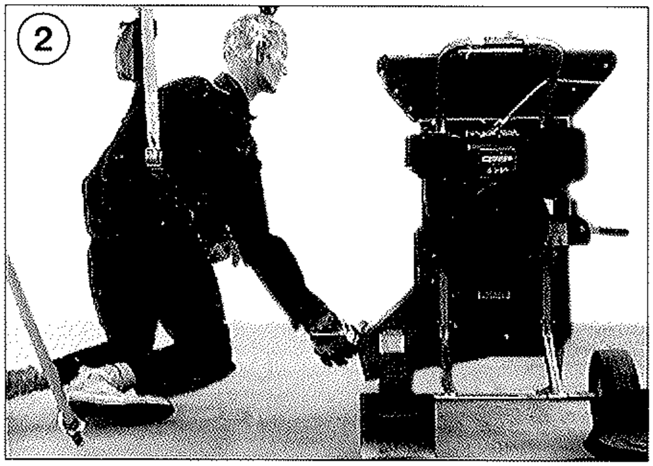
ATTACHMENT TESTS

As an extreme case, a scenario is explored where an extremely strong fiber is attached to an operator's hand by tying the fiber about the wrist. This is an interference joint and not a friction grip. A knotted clothesline with a measured tensile strength of 754 lb was used in a testing program which adopted the previously described protocol. Two tests were performed using the anthropomorphic dummy with a fixed elbow. In each test, the hand was rapidly drawn against the leading edge of the discharge chute door which was pinned in its normal operating position. In both cases, the clothesline was instantly fractured.

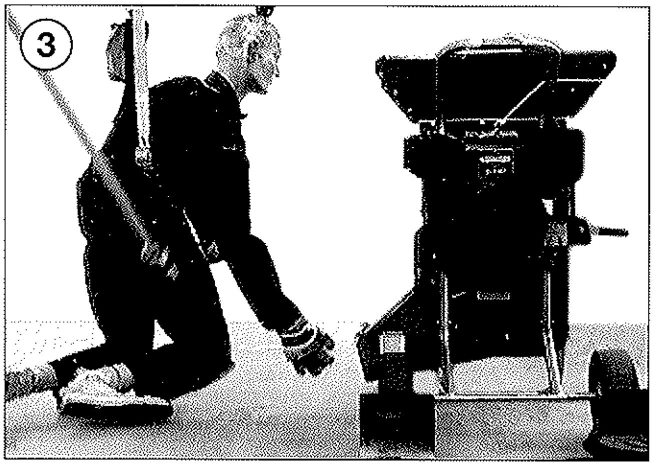
Figure 4 illustrates a series of videotape frames which portray one of the attachment tests. The first frame shows the arm an instant before movement occurs. The second video frame taken 1/30 of a second later indicates the moment of collision between the arm and the leading edge of the locked discharge chute door. The third frame taken 2/30 of a second after frame 2 illustrates the frayed end of the fractured clothesline which has been discharged from the hammer mill. It should be noted that the flails are absent during these tests. Clearly, a statically applied force of 754 lb would inextricably drag an operator into the discharge chute and into the hammer mill. Under dynamic conditions, the combined resistance of inertial forces in the arm and interference reactions from the lip of the discharge chute door have overwhelmed the tenacity of the clothesline.



1) Rope Tied to Wrist



2) Arm Contacts Locked Discharge Chute Door



3) Arm Returns After Rope Fractures

Fig. 4: Video Sequence of Attachment Test

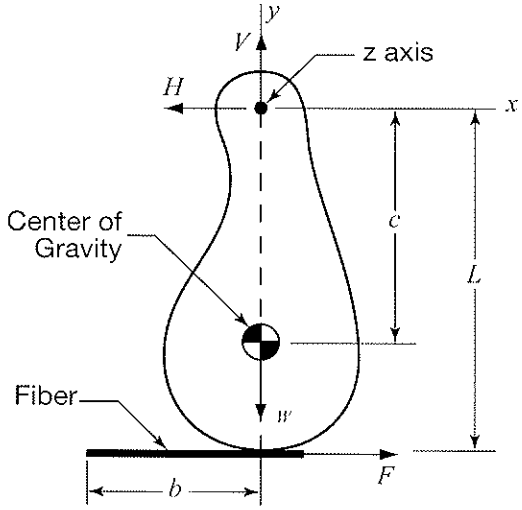


Fig. 5a: Free Body Diagram

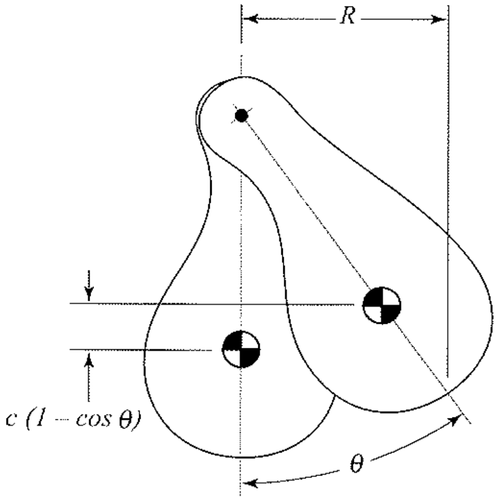


Fig. 5b: Maximum Pendulum Oscillation

COMPOUND PENDULUM

When an operator faces in a direction perpendicular to the discharge chute of a chipper/shredder and bends over to pull on an extending stationary fiber, his dangling arm resembles a compound pendulum pivoting about his shoulder and out to his side. If he grasps a fiber which is subsequently dragged from his hand at great speed, his arm takes on the aspect of a ballistic pendulum, i.e., a compound pendulum subjected to an impulsive load. Such a pendulum is shown in Fig. 5a and Fig. 5b. Appendix A exploits this mathematical model to produce the following relationship between the sideways swing θ of an arm with a triangular weight distribution and the system parameters:

$$\theta = \cos^{-1}\left[1 - \frac{9F^2b^2g}{W^2v_p^2L}\right] \tag{A-9}$$

where *F* is the drag resistance developed by gripping the fiber, *b* is the length of fiber trailing behind the leading edge of the operator's hand, *W* is the arm weight, v_p is the pull-in speed of the fiber by the hammer mill, *L* is the arm length and g is the gravitational acceleration, 32.2 ft/sec². Using a typical set of parameters from the test program, *F* = 27.4 lb, *b* = 2 ft, *W* = 12 lb, v_p = 147.5 ft/sec. and *L* = 2.083 ft, the swing angle becomes,

$$\theta = \cos^{-1}\left[1 - \frac{9(27.4)^2(2)^2(32.2)}{12^2(147.5)^2(2.083)}\right] = 29.93^\circ$$

This result and the corresponding calculations for the five other test events appear in Table 1 where the values of θ are quite close to those obtained experimentally.

Equation (A-9) may be used to calculate the forward reach *R* of the operator's hand:

$$R = L\sin\theta \tag{A-10}$$

or,

$$R = \frac{3Fb}{Wv_p}\sqrt{2gL}\left[1 - \frac{9}{2}\frac{F^2b^2g}{W^2v_p^2L}\right]^{1/2} \tag{A-12}$$

The values of *R* associated with the six tests in the test program section are tabulated in Table 1.

Table I: Measured v. Calculated Arm Swing

Hand Drag Force: *F* *(lb)*	Trailing Length of Fiber: *b* *(ft)*	Measured Arm Swing: *θ*	Calculated Arm Swing: *θ*	Calculated Reach: *R* *(in.)*
9.9	1	6°	5.35°	2.33
12.9	1	7°	6.97°	3.03
28.7	1	17°	15.54°	6.70
9.1	2	10°	9.84°	4.27
14.4	2	15°	15.60°	6.72
27.4	2	30°	29.93°	12.47

Using Equations (A-9) and (A-10), it is very convenient to establish the minimum drag force *F* (or grip strength) required to contact the flails of the test chipper/shredder; thus,

$$F = \frac{Wv_p}{3b}\sqrt{\frac{L\left[1-\cos\left(\sin^{-1}R/L\right)\right]}{g}} \tag{1}$$

The flail circle has a diameter *d* = 14.625 in. and its leading edge is about 9.5 in. from the entrance of the discharge chute. The flails will pull in a fiber at a speed $v_p = \pi d$ (RPM), i.e., v_p = 229.7 ft/sec. If a fiber is grasped just outside of the discharge chute, *R* = 9.5 in., and it extends one foot outboard, *b* = 1 ft, the threshold force becomes,

$$F = \frac{12(229.7)}{3(1)}\sqrt{\frac{2.083\left[1-\cos\left(\sin^{-1}9.5/25\right)\right]}{32.2}} = 64.0\ lb$$

This is an order of magnitude greater than the drag force generated to pull on an unresisting stationary fiber with one's fingers. It should be noted that a grip force *G* acting on two sides of a fiber leads to a drag force F = 2Gμ where μ is the coefficient of friction at the fiber-finger interface. Using μ = 0.5, the drag and grip forces are equal.

The largest possible reach, *R* = *L*, occurs when θ = 90°. The corresponding drag force is found from Eq. (1) to be F = 233.7 lb when *b* = 1 ft, *W* = 12 lb, v_p = 229.7 ft/sec, and *L* = 25 in.

When an operator faces the discharge chute, his or her arm forms a double pendulum. At one extreme the lower arm swings and the upper arm remains stationary. At another, the elbow joint is fixed and the entire arm swings as a rigid body. During the impulse phase, the upper and lower arms remain practically motionless, where the lower arm includes the forearm and the hand. Afterwards, the upper and lower arms may achieve different angles. The upper arm is always more massive and it supports the lower arm. Its maximum swing angle would be expected to be smaller than the lower arm swing.

Table 2: Response of Arm and Lower Arm
(b = 1 ft; v_p = 229.7 ft/sec.)

Drag Force: *F (lb)*	Arm		Lower Arm	
	(*W* = 12 lb; *L* = 25 in.)		(*W* = 3 lb; *L* = 12.5 in.)	
	Swing, *θ*	Reach (in.)	Swing, *θ*	Reach (in.)
5	1.73°	0.76	9.82°	2.13
10	3.47°	1.51	19.71°	4.22
15	5.20°	2.27	29.75°	6.20
20	6.94°	3.02	40.03°	8.04
24.5	———	———	49.58°	9.52
64	22.33°	9.50	———	———

A typical arm with a triangular weight distribution is compared in Table 2 to the same arm with an elbow joint in the middle. Observe that the lower arm acting alone achieves a significantly larger swing angle and reach. This observation is valid whenever the predicted range for the lower arm does not exceed the length of the lower arm. Under these circumstances, the actual reach of a real arm will be less than that predicted for the lower arm acting alone. Unfortunately, this conservative approach can only be used when the predicted R is less than the length of the lower arm. When the predicted θ is greater than 90°, the response predictions for the arm must be based on the proper formulation of a double pendulum model.

SAFETY PROFILE

The Consumer Product Safety Commission (CPSC) has accumulated a large body of accident narratives associated with consumer chipper/shredders (1). No pull-in accidents associated with the discharge chute have been recorded. The following safety characteristics of the chipper/shredder make it extremely unlikely that the pull-in phenomenon endangers the operator's hand:

1. Motivation: A fiber which is at rest and which dangles from the discharge chute poses no functional compromise to the chipper/shredder. Only a sense of neatness would motivate an operator to deal with this errant fiber.
2. Zero Mechanical State (lockout): Clearing a machine is a maintenance activity which is covered by a nationally known philosophy called zero mechanical state (ZMS) or lockout (2). This requires that before maintenance is attempted, the primary power be interrupted, all moving elements be at rest, reestablishment of primary power be precluded (detachment of spark plug wire), and that residual energy be isolated (also detachment of spark plug wire). In industrial applications, these procedures are mandated by the Occupational Safety and Health Administration (OSHA) (3). In consumer products, the manufacturer must rely upon information transfer and personal vigilance to apply the required maintenance philosophy. The information transfer is accomplished through on-product warnings and instructions and through warnings and instructions contained in the machine manual.
3. Common Sense: It has been shown that a locked discharge chute door eliminates the pull-in danger. Furthermore, it is obvious that a stationary machine cannot give rise to pull-in. For an operator's hand to be swung into or be pulled into the flails, it requires the discharge chute door (guard) to be unlatched which, for the test machine, requires the removal of a pin and the withdrawal of a locking rod. Furthermore, it is necessary that the machine be operating in either the powered or coast down modes. These states are indicated by audible, visual, and tactile feedback. It is common knowledge not to operate machinery with guards removed and not to touch dangerous moving machinery (4). Regarding the test chipper/shredder, numerous admonitions on the machine and in the manual reinforce these dictums of common sense.
4. Arm Swing: A response analysis of the lower arm indicates that fibers grasped just outside of the unlocked discharge chute require a gripping force of 24.5 lb or greater in order to cause contact with the hammer mill flails (b=1 ft). The grip strength required to extricate an unencumbered static vine from the discharge chute is de minimus which makes it difficult to envision a realistic pull-in scenario that would result in injury. It must be emphasized once again that the most extreme positions will still not produce flail contact when the discharge chute door is locked in place.
5. Occum's Razor: Once an operator has addressed a moving machine by unlocking the discharge chute door and holding it open with the intent to perform a cleanout operation, the simplest explanation for a resulting hand injury suggests that the operator directly contacted the invisible flails. This is an application of the reasoning associated with Occum's Razor. All other explanations of such accidents are complex.

CONCLUSIONS

1. The following hypothesis has been disproved by analytical and experimental means: "Operators are pulled into the discharge chute of a chipper/shredder because they cannot release reentering fibers in sufficient time."
2. The hammer mill withdraws fibers from an operator's hand before any motion of the operator's body can be perceived.
3. The ballistic pendulum provides an extremely accurate model for predicting the sideways response of an operator's arm during a pull-in scenario.
4. The forward double pendulum response of an operator's hand is less than that predicted for the lower arm alone. This bound is valid whenever the swing θ calculated for the lower arm does not exceed 90°.
5. If the discharge chute door of the chipper/shredder is locked closed, an operator who leans over to grasp an emerging fiber cannot be pulled into the discharge chute. The operator's arm cannot be swung into the flails and his arm cannot be drawn in by tying it to the most tenacious fibers.
6. An examination of CPSC chipper/shredder accident narratives does not reveal a single instance where the pull-in phenomenon has resulted in personal injury.
7. The task of pulling on a fiber introduces a moment resistance into the free swinging pendulum model assumed in our analysis. Consequently, the real sideways response angle of an operator's arm will be equal to or less than the predicted θ from Eq. (A-9).
8. No flails were used in the testing program because they usually cut the fibers before the impulse event is completed. This decreases the predicted impulse delivered to the arm. Once again, the real sideways response angle will be less than or equal to that predicted θ from Eq. (A-9).

APPENDIX A

Compound Pendulum under Impulsive Loading

Motion Analysis. Problems involving rotation of a rigid body about a fixed axis may be formulated using the principle of angular momentum in rotation (5), i.e., the rate of change of angular momentum of a rotating body with respect to its fixed axis of rotation is equal to the moment of all external forces acting on the body with respect to the same axis. Thus, referring to Fig. 5a,

$$\frac{d}{dt}\left(I_z\dot{\theta}\right)=M_z \qquad \text{(A-1)}$$

where,

I_z = $\int r^2 dm$...Moment of inertia with respect to z where r is a polar coordinate.

$\dot{\theta}$ = angular velocity (see Fig. 5b)

M_z = resultant moment of external forces acting on the body.

Integrating this equation brings it into a convenient form for solving impulse and momentum problems; thus,

$$I_z\dot{\theta}_f - I_z\dot{\theta}_i = \int_{t_i}^{t_f} M_z dt \qquad \text{(A-2)}$$

where, t_i is the time of initiation of impulse event
t_f is the final time - termination of impulse event.

If a constant drag force F is applied horizontally to the end of a stationary pendulum for a short time interval $\Delta t = t_f - t_i$, Eq. (A-2) becomes:

$$I_z\dot{\theta}_f = LF\Delta t \qquad \text{(A-3)}$$

When a fiber of length b is pulled through a hand at a speed v_p, the event interval Δt is simply:

$$\Delta t = b/v_p \qquad \text{(A-4)}$$

Figure 1b shows a side elevation of a hammer mill where the four cross rods form a square array. The periphery of the array has a length of 4*a*. When the hammer mill rotates at an angular speed *w*, fibers wrapped around the array will be pulled into the machine at a speed $v_p = 4a\omega$ For the test chipper/shredder, ω = 3600 rpm and *a* = 7.375 in.; thus, v_p = 147.5 ft/sec.

Using Eq. (A-4), Eq. (A-3) defines the angular velocity of the compound pendulum $\dot{\theta}_f$:

$$\dot{\theta}_f = \frac{FbL}{v_p I_z} \qquad \text{(A-5)}$$

After the impulsive loading of the pendulum when it's still in its vertical orientation, its potential energy, P.E., is zero and its kinetic energy, K.E., is given by (6),

$$K.E. = \frac{1}{2} I_z\dot{\theta}_z^2 \qquad \text{(A-6)}$$

When the pendulum swings to its maximum amplitude as shown in Fig. 5b, it loses its motion and its associated kinetic energy. At this orientation the center of gravity has been elevated $c(1 - \cos\theta)$ acquiring a potential energy,

$$P.E. = Wc(1-\cos\theta) \qquad \text{(A-7)}$$

Conservation of energy requires that P.E. = K.E.; thus,

$$Wc(1-\cos\theta) = \frac{1}{2} I_z\dot{\theta}_f^2$$

or,

$$\theta = \cos^{-1}\left[1 - \frac{I_z\dot{\theta}_f^2}{2Wc}\right]$$

Substituting for $\dot{\theta}_f$ from Eq. (A-5), we obtain:

$$\theta = \cos^{-1}\left[1 - \frac{F^2b^2L^2}{2Wv_p^2cI_z}\right] \qquad \text{(A-8)}$$

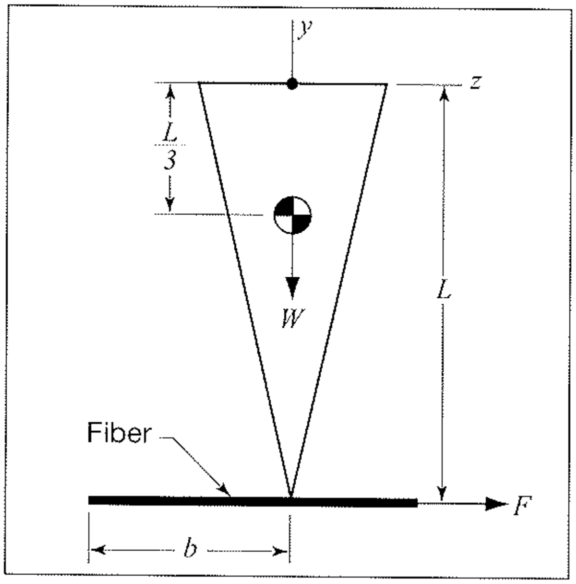


Fig. A-1: Model Arm or Lower Arm

For any particular shaped arm, the associated pendulum is characterized by *c*, *W* and I_z. Approximating the arm as a triangle as shown in Fig. A-1, $c = L/3$ and $I_z = WL^2/(6g)$.

For a triangular arm, Eq. (A-8) becomes,

$$\theta = \cos^{-1}\left[1 - \frac{9F^2b^2g}{W^2v_p^2L}\right] \qquad \text{(A-9)}$$

Figure 5b defines the maximum reach R achieved by the swinging pendulum. It may be expressed as,

$$R = L\sin\theta \qquad \text{(A-10)}$$

or, using the identity $\sin^2\theta + \cos^2\theta = 1$,

$$R = \frac{FbL^2}{v_p\sqrt{2WcI_z}}\left[2 - \frac{F^2b^2L^2}{v_p^2(2WcI_z)}\right]^{1/2} \qquad \text{(A-11)}$$

For an arm with a triangular weight distribution, Eq. (A-11) becomes,

$$R = \frac{3Fb}{Wv_p}\sqrt{2gL}\left[1 - \frac{9}{2}\frac{F^2b^2g}{W^2v_p^2L}\right]^{\frac{1}{2}} \qquad \text{(A-12)}$$

In our response calculations of the ballistic pendulum, we have neglected any motion of the pendulum during the impulse interval Δt. This well known assumption is justified when the impulse interval is very small in comparison with the period of oscillation of the pendulum (7). The period is given by (8),

$$\tau = 2\pi\sqrt{\frac{I_z}{cW}} \qquad \text{(A-13)}$$

For a triangular weight distribution,

$$\tau = 2\pi\sqrt{\frac{L}{2g}} = 2\pi\sqrt{\frac{2.083}{2(32.2)}} = 1.13 \text{ sec}$$

where *L* = 25 in. Using Eq. (A-4) for the test hammer mill with v_p = 147.5 ft/sec and *b* = 2 ft, the impulse interval is Δt = 0.0136 sec. It becomes $\Delta t = 0.00871$ sec. when flails are used, i.e., $v_p = 229.7$ ft/sec. These values are halved when $b = 1$ ft. Consequently, Δt is usually less than 1% of the natural oscillation period and our "motion assumption" is justified. Indeed, the test program revealed no discernible movement of the anthropomorphic arm, shoulder, or elbow during the impulse phase.

The ballistic pendulum model assumes a stationary pivot point. During the impulse interval, Δt, the reactions shown in Fig. 5a are impulsive and are given by (9),

$$V = O \tag{A-14}$$

and

$$H = \frac{I_c - \frac{W}{g}c(L-c)}{I_c + \frac{W}{g}c^2}(\text{Impluse}) \tag{A-15}$$

The moment of inertia about the centroid of a triangle is $I_c = \frac{WL^2}{18g}$; thus,

$$H = \frac{\frac{WL^2}{18g} - \frac{W}{g}\left(\frac{L}{3}\right)\left(L - \frac{L}{3}\right)}{\frac{WL^2}{18g} + \frac{W}{g}\left(\frac{L}{3}\right)^2}(\text{Impulse})$$
$$= -(\text{Impulse})$$

This result implies that the shoulder or elbow will feel the same impulse as the hand in the rearward direction. Note that the torso and shoulder are ten times the mass of the arm and that the upper arm is three times as massive as the lower arm. Since the arm or lower arm remain stationary during an impulse $F\Delta t$, an equal and opposite acting impulse will not move the shoulder or elbow.

The video frames in Fig. A-2 illustrate the behavior of our anthropomorphic test dummy with a freely articulating elbow. Under the same test protocol used with the fixed elbow, the first frame shows the double pendulum arm immediately before the impulsive loading. In frame 2 taken 1/30 of a second later, the entire one foot long ($b = 1$ ft) constant force spring ($F = 29$ lb) has been pulled into the hammer mill. No movement of the dummy can be seen at this stage. The final illustration is frame 3 taken 8/30 of a second after frame 2 which shows the configuration of the upper and lower arms at maximum reach. A slight movement of the upper arm may be observed.

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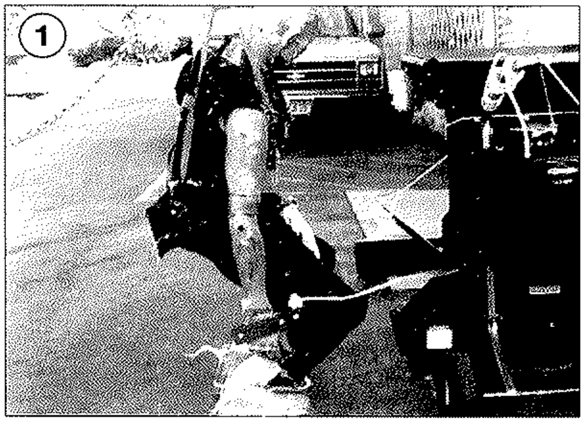
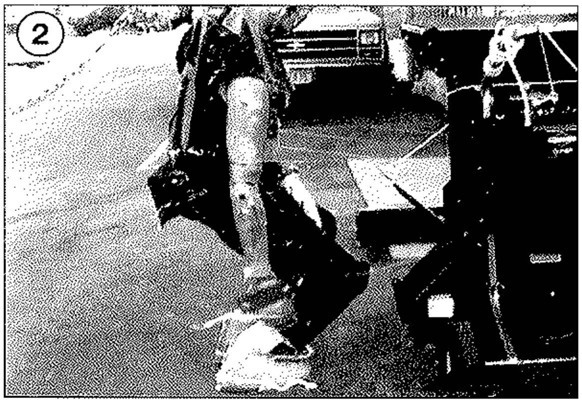
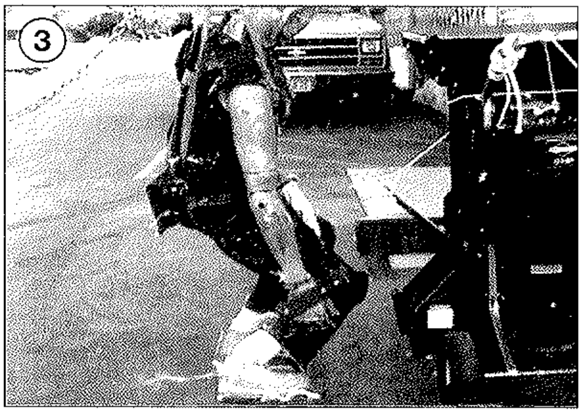


1) Constant Force Spring on Mandrel



2) Constant Force Spring Withdrawn from Hand



3) Maximum Arm Swing Towards Discharge Chute

Fig. A-2 : Test Dummy with Freely Articulating Elbow

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