PNEUMATIC-BALLISTIC IMPACT DEVICE

by G.S. Nusholtz, P.S. Kaiker, Z. Lou and S.C. Richter

Man is subjected to the risk of violent injuries all his life. Head trauma, 49 percent of which is caused by automobile accidents, merits serious consideration by researchers. Head injuries not only cause abnormalities in neural and bodily functions, but can lead to long-term neurological and behavioral problems. Damage to the heart and its vessels (notably the aorta) frequently leads to death. These thoracic injuries as well as abdominal injuries are second only to head injuries as the most frequent cause of death. Pelvic injuries, in particular fractures, may occur while walking, running, or even sitting. The extensive literature on human trauma addresses many of the mechanical and physiological processes that take place during blunt impact to the body. In order to gain knowledge for the prevention of trauma, experimental investigations in biomechanics use various subjects as human surrogates. Two such subjects are unembalmed human cadavers and animals.

In order to understand the subject's impact response, accelerometers, string-pot transducers, pressure transducers, and strain gages are attached to anatomical structures in order to document such things as kinematic responses (displacement of bones and organs, underlying tissues, and pressure). Studying the mechanisms of injury which occur during an automobile accident is vital to biomechanics research. In order to analyze these crashes and the resulting injuries, a controlled experimental environment is created in the laboratory. The primary objective is to deliver a calibrated amount of energy to an instrumented test subject. For this purpose, The University of Michigan Transportation Research Institute (UMTRI) has designed and constructed two highly specialized impact devices. Blunt impact to the human surrogate subject is delivered with one of two free-traveling impactors: the pneumatic-impact device and the pneumatic-ballistic pendulum-impact device.

PNEUMATIC-IMPACT DEVICE

The UMTRI pneumatic-impact device (Fig. 1) consists of an air reservoir, a ground and honed cylinder, and two carefully fitted pistons. The pressure is regulated by a series of hand valves and measured with a gage having an accuracy of ±0.25 percent. The driver piston is secured at the reservoir end of the cylinder by an electronically controlled locking mechanism. When the air reservoir is pressurized and the locking mechanism released, the driver piston is propelled by the compressed air along the cylinder until its bumper impacts the bumper on the striker piston, which is allowed to travel up to 25 cm. Excess kinetic energy is absorbed by a 3003 H14 seamless aluminum inversion tube, 6.35-cm in diameter with a 0.165-cm wall thickness. Impactor velocity is controlled by reservoir pressure and the ratio of the masses of the driver and striker pistons. The desired impactor stroke can be accurately controlled by the initial positioning of the striker piston with respect to the inversion tube. Both driver and striker pistons can vary in mass from 2-20 kg. The impactor-force transducer assembly consists of a Kistler 904A piezoelectric accelerometer-load washer with a Kistler 804A piezoelectric accelerometer mounted internally for inertial compensation.

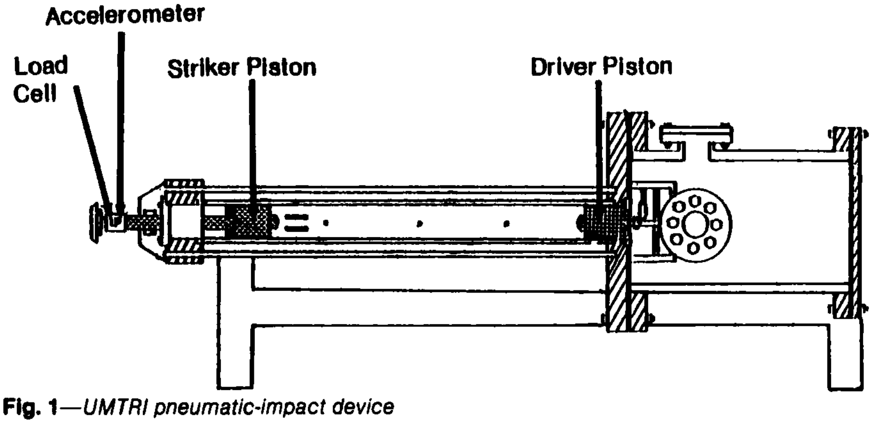

Fig. 1—*UMTRI pneumatic-impact device*

G.S. Nusholtz is Assistant Research Scientist, P.S. Kaiker is Research Associate II, Z. Lou is Research Assistant I and S.C. Richter is Research Associate I, The University of Michigan, Transportation Research Institute, Ann Arbor, MI.

PNEUMATIC-BALLISTIC PENDULUM

The UMTRI pneumatic-ballistic pendulum-impact device (Fig. 2) consists of a 10-kg aluminum I-beam which can accept additional mass up to 200 kg. The pendulum is mechanically coupled to the UMTRI pneumatic-impact device which is used as the energy source. A steel rod is attached to the driver piston and runs the length of the ground and honed cylinder. The rod is connected to the ballistic pendulum with a nylon cable (Fig. 3). Two bearings were introduced to guide the rod with a minimum of friction and prevent the driving rod from bending as a result of the inertial loading of the pendulum. The piston (Fig. 3) is propelled by compressed air through the cylinder from the air-reservoir chamber. This accelerates the ballistic pendulum, which becomes a free-traveling impactor.

The pendulum is a modification of the pneumatic-impact device. The reversible modifications include the exchange of the internal-striker piston for an external-ballistic piston and the connecting and supporting structures necessary to accelerate the external-ballistic pendulum. The piston is connected to the ballistic pendulum with a nylon cable.

With these two devices, impacts can be delivered covering a wide range of circumstances in order to simulate automobile, industrial, sports, aviation, and other environments. However, an operating problem exists in that the speed of the ballistic pendulum can exceed those normally obtained through gravitational acceleration. This means that the ballistic pendulum will not necessarily follow the arc dictated by the supporting cables. Therefore, the correct angle and the length of the nylon cable are critical to the proper operation of the pendulum. If the angle or length is inappropriate, then the ballistic pendulum will not follow the desired trajectory and may miss the impact target completely.

The pneumatic-ballistic pendulum impactor supports several different types of impact surfaces as well as several different masses and mass distributions. Once obtained, the moment and mass of the piston are used to calculate the angle and length of the nylon cable, as well as its mooring

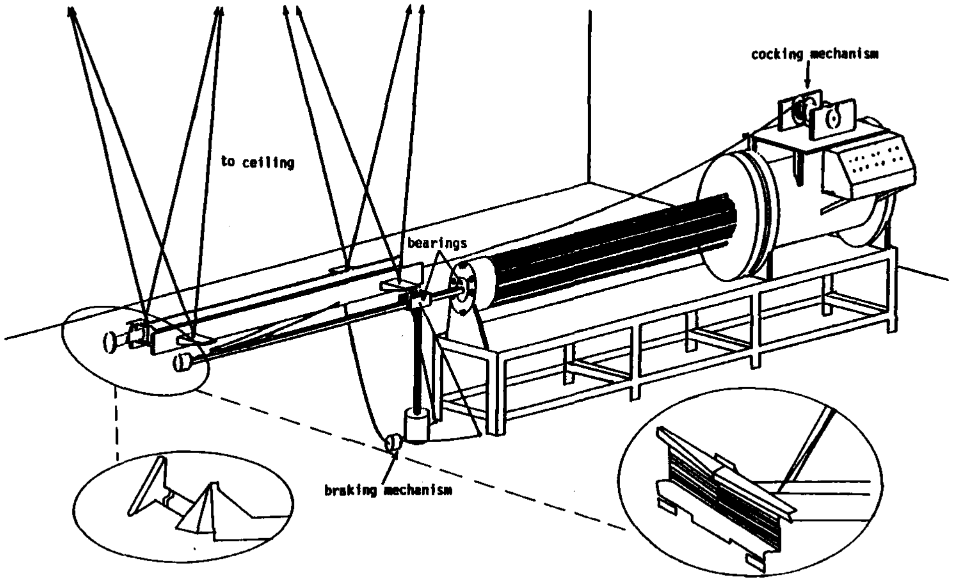

Fig. 2—*The areas in the ellipses represent some different front-end configurations. One ellipse contains a steering wheel assembly that has been placed on the front of the ballistic pendulum. The other ellipse represents a 1969 Malibu front-end*

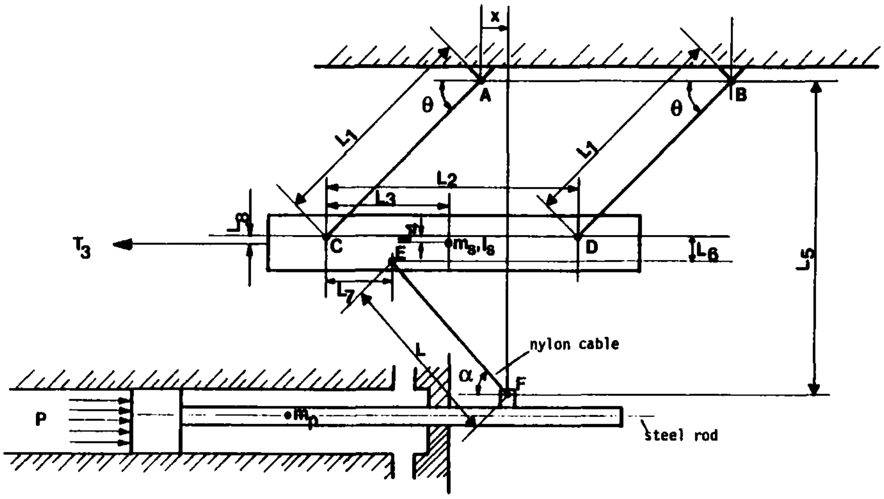

Fig. 3—*The following symbols represent*

L = *length*
T = *tension*
A–F = *various points in the system*
m_s = *mass of the system*
I_s = *moment around the center of mass*
x = *motion of the steel rod and piston*
P = *pressure in piston barrel*
m_p = *mass of the piston*
α = *angle between nylon cable and a horizontal + line*
θ = *angle between support cable and horizontal line*

position with respect to the center of gravity of the piston for each test design change. To do this, a finite-difference model was developed. This model is described below.

FINITE-DIFFERENCE MODEL

The system as a whole is shown in Fig. 3. L_1 through L_8 are constant geometric parameters. L_1 in Fig. 3 is the distance from the striker to the ceiling between points A-C and B-D respectively. L_2 is the distance between the two contact points for the suspension strings C and D. L_3 is the distance from the contact point C to the center-of-mass in the horizontal direction. L_4 is the distance between the center-of-mass and a line between points C and D. L_5 is the vertical distance between the contact points F and A or B. L_6 is the distance between the contact point E and the line between C and D on the striker. L_7 is the distance between the contact points C and E in the horizontal direction. L_8 is equal to L_4. m_s and m_p are masses for the striker and piston, respectively. I_s is the moment of inertia of the striker with respect to the rotation center A-B. L is the length of the nylon cable (adjustable) which connects the striker with the steel rod.

In the numerical simulation, the nylon cable and the steel wires connecting AC and BD are assumed to be rigid, i.e., their lengths are assumed to not change. That is because all of them are in tension before the striker hits the test object and the simulation is performed to find the striker velocity and to insure that all eight cables had tension during the time that the pendulum moves from initial position to contact position at the moment of striking.

GOVERNING EQUATIONS FOR THE PNEUMATIC-BALLISTIC PENDULUM

Piston

The free-body diagram for the cannon piston in the cylinder with the steel rod attached is shown in Fig. 4a. T is the tensile force in the nylon cable. As a result of the driver piston contacting the cylinder walls and the acceleration rod contacting the bearings, there are viscous friction forces (f_v's), Coulomb friction forces (f_c's), torques (M's) and normal forces (N's). With a known T, we cannot find N_1, N_2, M_1, or M_2 from the two force-balance equations in vertical direction and the moment equation. So it is an indeterminate problem. In addition, N_1, N_2, M_1, and M_2 are only used for the calculation of the Coulomb's friction which is roughly proportional to a sin $\alpha \cdot T$. Therefore, estimating the total Coulomb friction force (f_c) we use:

$$f_c = f_{c1} + f_{c2} = C_c \cdot \sin(\alpha) \cdot T \tag{1}$$

where C_c is some constant, f_{c1} is the Coulomb force for the bearing, and f_{c2} is the Coulomb force for the piston.

Similarly, due to the difficulty in evaluating the contact area and lubrication conditions, the following simple form is assumed for viscous friction:

$$f_v = f_{v1} + f_{v2} = C_v \cdot \dot{x} \tag{2}$$

where f_{v1} is the viscous force for the bearing, f_{v2} is the viscous force for the piston, and $\dot{x}$ is the horizontal velocity. Approximate values of C_c and C_v have been obtained by experimental testing.

The air in the cylinder is assumed to be an ideal gas and the expansion associated with the piston acceleration is assumed to be an adiabatic reversible process. Then the pressure inside the cylinder is

$$P = P_o/[1 + A(x - x_o)/V_0)]^k \tag{3}$$

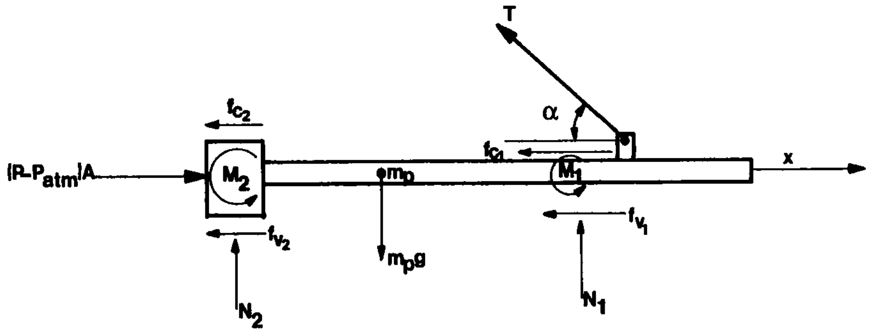

Fig. 4a—*The free-body diagram for the driver piston and steel rod*

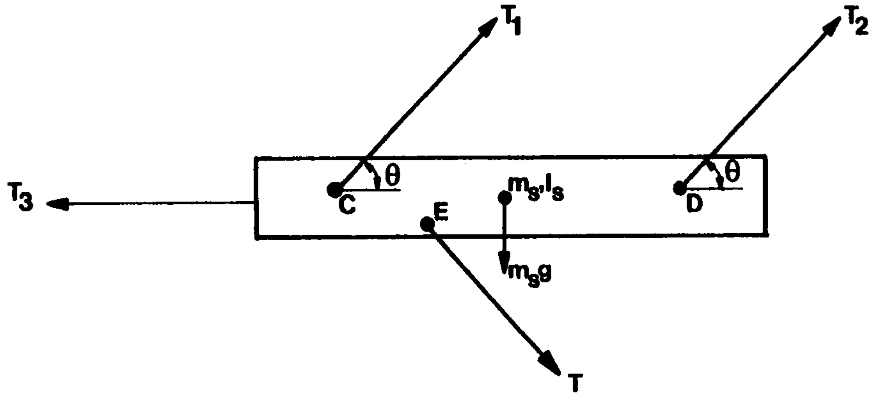

Fig. 4b—*The free-body diagram for the ballistic pendulum*

where P_o is the initial pressure, A is the cross-sectional area of the piston, χ_o is the initial translational displacement, V_o is the initial air volume, and k is the specific heat ratio of the air. The back pressure on the piston is roughly equal to the atmosphere pressure P_{atm}.

The equation of motion for the piston is

$$m_p \cdot \ddot{\chi} + C_v \cdot \dot{\chi} - A(P - P_{atm}) + [C_c \cdot \sin(\alpha) + \cos(\alpha)]\, T = 0 \quad (4)$$

This equation can then be used to predict the exact position, velocity, and acceleration of the piston and indirectly, the position, velocity, and acceleration of the ballistic pendulum at each instant in time.

Striker

Figure 4b is the free-body diagram for the ballistic pendulum. Where T_1 and T_2 are the tensions in the strings A-C and B-D, respectively. T_3 is the tension from the holding string and is practically negligible. If there is no rotation about point C, then,

$$L_2 \cdot \sin(\theta) \cdot T_2 - L_3 \cdot m_s \cdot g + [L_6 \cos(\alpha) - L_7 \cdot \sin(\alpha)] \cdot T = 0 \quad (5)$$

If there is no rotation about point D, then,

$$-L_2 \cdot T_1 \cdot \sin(\theta) + (L_2 - L_3) \cdot m_s \cdot g + [L_6 \cos(\alpha) - (L_2 - L_7) \cdot \sin(\alpha)] \cdot T = 0 \quad (6)$$

The equation of motion is:

$$T \cdot \cos(\alpha) \cdot [L_1 \cdot \sin(\theta) + L_6] + [T \cdot \sin(\alpha) + m_s \cdot g] \cdot L_1 \cdot \cos(\theta) = I_s \cdot \ddot{\theta} \quad (7)$$

The system is one of one degree-of-freedom so that θ, α, and χ are related by the following equation:

$$L_1 \cdot \cos(\theta) + \chi = L_7 + L \cdot \cos(\alpha) \quad (8)$$

$$L_1 \cdot \sin(\theta) + L_6 + L \cdot \sin(\alpha) = L_5 \quad (9)$$

Finally, there are seven unknowns: θ, α, χ, P, T, T_1, and T_2 and seven equations (numbers 3-9) which can be used to create a finite-difference model.

NUMERICAL SIMULATIONS AND RESULTS

With the initial cannon-cylinder pressure ranging from 5.0 to 100.0 psig, the striker velocity changes from 3.4 to 16.2 m/s. The errors of the simulation are, in general, within 5 percent compared to the experimental results. It is also observed that the tensions T_1 and T_2 are always positive, i.e., the striker is always horizontal during the motion, which is the desired test condition.

The versatility of the pendulum impactor is best demonstrated by the variety of fixtures which can be attached to it (Fig. 3), thus providing a wide range of impact conditions. One such fixture, a front-end from a 1969 Malibu, was mounted on a single-column support on the pendulum. On another occasion, the ballistic pendulum was fitted with a steering wheel assembly. In each case when the mass or moment of inertia changed, the appropriate calculations were made to determine the impact parameters associated with the pendulum.

ACKNOWLEDGMENTS

The authors wish to acknowledge Richard L. Stalnaker for the design of the original pneumatic-impact device of which the current system is a modification and improvement thereof. John W. Melvin is also acknowledged for his technical assistance and guidance. The authors are also grateful to the following for their technical assistance in the preparation of this paper: Wendy Gould, Valerie A. Karime, Peter Schuetz, Bryan Suggitt, Shawn Cowper, Don Erb, and Lillian Kim.

The research in this paper was partially funded by the Department of Transportation, National Highway Traffic Safety Administration, Contract No. DTNH83-C-17019.