THE PHYSICAL BASIS OF IMPACT INJURY AND ITS PREVENTION

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INTRODUCTION

Effective prevention of injury in aircraft crashes and the investigation into injury occurrence in those crashes requires a knowledge of how impact injury occurs and how protective techniques work. This review will examine the physical underpinnings of the art of impact protection as applied to vehicular impacts. The same principles apply to terrestrial vehicles, aircraft, and spacecraft in a wide range of impacts and other sudden accelerations. Because they happen so rapidly, they are sometimes difficult to understand in terms of our slower moving daily experience. Some of the understandings may even be counter-intuitive as a result of the need to observe the event from various frames of reference.

The review must therefore begin with some basic physics and apply those principles to the collision event. Approaches to describing crash motions and crash severity will be outlined before describing how to analyze occupant motions in a crash. The physics of injury will be briefly reviewed and applied in defining injury mechanisms and injury criteria. Finally, general approaches to crash protection will be addressed along with some perspectives on how to analyze and assess the effectiveness of crash protection. Example cases will be presented with the oral presentation to illustrate the application of the principles reviewed in the paper.

The effort to understand crashes, injury, and injury protection at this level will be well-rewarded through the development of improved insight into the process of crash protection in automobiles, aircraft, and other vehicles.

PHYSICAL PRINCIPLES

The Laws Of Motion

We begin our study of impact injury with a brief review of physics since the terms and methods used to study motion are necessary in understanding impacts. Failure to appreciate and rigorously apply the principles of physics has led to many misunderstandings about how impact injuries occur and how they can be meaningfully addressed.

Some definitions may be helpful at the outset. An impact is a short duration force event which typically alters the motion of an object. Force is simply a push or pull. Motion is change of an object's position as measured in some frame or reference. Velocity is the rate change of that position with respect to time. Acceleration is the rate of change of an object's velocity with respect to time. Position, velocity, and acceleration are all vector quantities, meaning they have both a magnitude or size, and a direction.

The first of Newton's Laws of Motion states that an object at rest or in motion will remain so unless acted upon by some force. The second law states that when a force acts on an object, the object is accelerated in a manner which is directly proportional to and in the direction of the net force acting and inversely proportional to the mass of the object. The equation for this law is

$$\mathbf{F} = \mathbf{m} \cdot \mathbf{a}$$

Mass can therefore be thought of as the resistance an object has to being moved. Mass is not weight. Weight is rather a force, namely the upward force provided on an object by a scale, for example, to balance the force of gravity acting on an object's mass. Gravity is also a force. In a vacuum at the earth's surface, the force of gravity will produce an acceleration downward of 9.81 meters per second per second (1g) on any unsupported object since the force of gravity is also proportional to the object's mass. The unit of g is a unit of acceleration, not a unit of force. The term g-Forces is a misnomer.

The third law of motion states that, for every action, there is an equal and opposite reaction. In other words, if we bump heads, the force on each head is equal in magnitude but oppositely directed.

The Physics of Collisions

This brings us to collisions. Let's start by considering two perfectly spherical and perfectly rigid balls of equal mass moving through space directly at each other, each with equal but oppositely directed velocity. After they collide, they will be moving directly away from each other, but the rest of the description will have remained the same. In effect, the two balls instantaneously traded velocities at the point of collision. This would be described as an idealized elastic collision.

Two equations can be written to describe this behavior. The first goes by the name of conservation of momentum and uses the quantity mv for momentum which is simply mass times velocity and remains a vector quantity. In our collision,

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$$m_1v_1 + m_2v_2 = m_1v_1' + m_2v_2'$$

where the primed terms refer to the post-collision values. The second equation is referred to as conservation of energy and uses the quantity 1/2 mv^2 for kinetic energy which is simply half the mass times velocity squared and is not a vector quantity. In our collision,

$$\frac{1}{2} m_1v_1^2 + \frac{1}{2} m_2v_2^2 = \frac{1}{2} m_1v_1'^2 + \frac{1}{2} m_2v_2'^2$$

At first glance, it may not seem that the energy equation adds much understanding to the event, but it actually does for several reasons. Some will become apparent as we explore the applicability of these equations to more general classes of collisions. Others are wrapped up in the different ways that momentum and energy undergo changes. Momentum is changed by force acting over time, a quantity known as impulse. Energy is changed by force acting over distance, a quantity known as work. For constant force values, momentum change for an object is force times the time duration over which it acts. Energy change for an object is force times the distance over which it acts.

In our previous collision example, the time duration and distance for the collision forces were infinitesimally small, so the force magnitude was infinitely large. For a slightly more realistic situation, consider balls made of a strange elastic material which pushes back with the same force no matter how deeply you indent it, but it will always rebound completely to its original shape. Now the collision will produce the same post-collision results but the collision will have a real time duration and distance over which the collision forces act. Assume a mass for each ball of 1 kilogram, a velocity for each ball of 1 meter per second and a restoring force for each ball, when indented, of 10 newtons. When the balls collide, they will slow down as they mutually indent each other, coming to a complete stop together at maximum indentation before rebounding back to achieve velocities equal in magnitude to the pre-impact velocities, but oppositely directed.

We can calculate the collision time since we know that momentum change is equal to the impulse:

$$mv = \mathbf{F} \cdot t$$

$$1 \text{ kg} \cdot 1 \text{ m/sec} = 10 \text{ kg-m/sec}^2 \cdot t$$

$$t = 0.1 \text{ second to come to a stop}$$

It will take another 0.1 second to rebound back for a total collision time of 0.2 second.

We can calculate the indentation distance since we know that energy change is equal to the work:

$$\frac{1}{2} m\, v^2 = F \cdot x$$

$$\frac{1}{2} \cdot 1 \text{ kg} \cdot 1 \text{ m}^2/\text{sec}^2 = 10 \text{kg-m/sec}^2 \cdot x$$

$$x = 0.05\text{m or } 5 \text{ cm}$$

The two results are consistent since each slowing ball will have an average speed of 0.5 m/sec operating for 0.1 sec during which 0.05 meters of distance would be covered (since distance equals average speed times the time duration).

We can also calculate the acceleration level. Since we know that 1 m/sec of velocity was reduced to zero in 0.1 seconds, the constant acceleration level was

$$(-1.0\text{m/sec})/0.1\text{sec} = -10 \text{ m/sec}^2$$

for the ball with a pre-impact positive velocity. We also know that this constant acceleration of a little more than 1 g acted for a total of 0.2 seconds to build up the same velocity in the other direction. An equal but opposite acceleration acted on the other ball for the same time duration. The total velocity change for one ball would be -2.0 m/sec and +2.0 m/sec for the other.

The impulse for a ball in the collision has a magnitude of 2 newton-sec since it is computed as constant force (10 newtons) times time (0.2 sec) with the direction for the impulse on the other ball being opposite. The energy change for each ball in the collision is 1/2 mv^2 or $1/2 \cdot 1 \text{ kg} \cdot (1 \text{ m/sec})^2$ or 0.5 newton-meters to stop it and another 0.5 newton-meters to get it back to 1 m/sec in the opposite direction. The total energy change for each ball is therefore 1 newton-meter. Please note carefully that the energy change for a 2 m/sec velocity change would be

$$\frac{1}{2} \cdot 1\text{kg} \cdot (2 \text{ m/sec})^2 = 2 \text{ newton-meters}$$

if the velocity went from 2 m/sec to zero. If you calculated the energy change for a 2 m/sec velocity change from 4 m/sec to 2 m/sec, you would get 6 newton-meters. For a 2 m/sec velocity change from 10 m/sec to 8 m/sec you would find an energy change of 18 newton-meters. Each of those collisions could have the same impulse. The critical observation to make is that energy change ascribed to a collision depends upon your frame of reference. However, an object or person experiencing a collision will "feel" it in only one way. The severity of a collision can be mischaracterized if energy change is utilized from the wrong reference frame.

The most meaningful description of a collision is to describe the acceleration-time profile of a relevant point as measured from a non-accelerated non-rotating reference frame. This profile is often called the crash pulse. Velocity change can then be determined and overall severity assessments made on the basis of the square of the velocity change to avoid the reference frame problem mentioned above. Comparing the severity of two impacts can still be difficult since time durations and acceleration-time profiles can differ in significant ways for impacts with identical velocity changes. We will address some of those difficulties presently.

Thus far, we have addressed simple collisions of elastic balls with constant forces during the collision. Another type of collision could be visualized in which the balls deform but do not rebound. An example would be dropping a lump of soft modelling clay on the floor. These are called inelastic or "hit and stick" collisions. They can be analyzed in the same fashion as the first half of an elastic collision. Conservation of momentum equations still hold. Conservation of energy equations still hold too, but you must account for the work done in deforming the object which is not given back on rebound. That reduces the velocity change by 50% and reduces the energy change by as much as 75% depending on your reference frame. It also reduces the time duration by 50% for colliding objects of the same stiffness.

It is also helpful to consider a different kind of deforming ball in a collision with an increasing restoring force the more you indent it. Suppose you had one which produced an acceleration-time profile that looked like an isosceles triangle for the elastic case. It can be shown that such objects in our earlier collision scenario would have a peak acceleration at the top of the triangle which would be exactly twice the value of the constant force collision when the velocity changes and time durations are the same. The peak acceleration for the inelastic triangular pulse is also twice the value for the constant force case. This allows us to use the fairly simple constant acceleration calculations and then substitute the triangular pulse at twice the peak acceleration when we are done. This turns out to be much closer to the behavior of real crashes.

Another way to adapt our calculations to real crashes is to observe that a collision into a barrier, like the ground, can be treated similarly, usually neglecting gravity since it is typically a minor consideration compared to crash forces. Our equations then reduce to an impulse equation where the momentum change is equal to the area under the force-time curve and an energy equation where the energy change, including the work done in deforming structure, is equal to the area under the force-distance curve.

Real collisions fall somewhere between the elastic and inelastic case, described by a term called the coefficient of restitution. If there is rebound from a collision with a fixed barrier with equal and opposite velocity to the approach velocity, then the coefficient of restitution is one. If there is no rebound, the coefficient of restitution is zero. Rebound with half the magnitude of the approach velocity implies a coefficient of restitution of one half.

We now have enough tools to handle a lot of simple crashes, as long as there isn't much rotation. Rotation brings in a significant added complexity since there is a whole parallel set of considerations for rotation that are analogous to what we have just described for translational motion. You can describe angular position or orientation just as you can describe translational position. Angles are used for the description instead of distance, but you still need a frame of reference, ultimately one that can be considered as non-rotating. You then have angular velocity, angular acceleration, angular momentum, angular impulse, angular force (torque) and angular energy. The angular analog to mass is the moment of inertia which is an object's resistance to rotational acceleration. It is typically different depending on which axis you try to rotate it about.

Many collisions and crashes involve substantial rotations which can significantly effect vehicle motions, occupant motions, and injury outcomes. We will address some of those complexities as we proceed without invoking the full translational and angular equations necessary for a comprehensive reconstruction. Suffice it to say here that simple crash force calculations for a single impact crash can often proceed on the basis of computations for the center of gravity motion of the vehicle, with angular motion often required to be taken into account for multiple impact crashes.

The outline of the basic approach is as shown below for a crash as shown in Figure 1, where the flight path angle is typically different from the aircraft angle, where the airspeed is known, and where the aircraft slides to rest after leaving an impact ground scar. First compute the horizontal velocity after the ground scar as $v'_{horiz} = [2\,\mu g d_s]^{1/2}$ where μ is the coefficient of friction during the slide distance and g is 9.81 m/sec^2 (the acceleration produced by gravity). The coefficient of friction can be estimated, or assessed from experimental data. A value of 0.3 - 0.5 is not atypical for aircraft sliding on ground without plowing. We know that the aircraft's vertical velocity must go from its initial value v_{vert} to zero in the distance.

$$d_{vert} = d_{crush} + d_{scar\ depth}$$

We also know that the aircraft's horizontal velocity must go from its initial value v_{horiz} to v'_{horiz} in the distance of the ground scar length (d_{horiz}). Measurements on the aircraft and the ground scar provide these data. We then compute

$$v_{horiz} = v_{initial} \cos \text{(Flight path angle)}$$
$$v_{vert} = v_{initial} \sin \text{(Flight path angle)}$$

We then can solve for average or constant force accelerations with respect to the earth.

$$(a_{horiz})_{AVG} = (v_{horiz}^2 - v'^2_{horiz}) / 2gd_{horiz}$$

$$(a_{vert})_{AVG} = (v_{vert}^2)/2gd_{vert}$$

Pulse times can then be computed.

$$\Delta t_{horiz} = (v_{horiz} - v'_{horiz})/a_{horiz}$$

$$\Delta t_{vert} = v_{vert}/a_{vert}$$

This implies constant acceleration or rectangular pulses. Triangular pulses would have twice these values at peak. For a crash with no rotation and no roll or yaw, the accelerations at each point in time can be easily resolved into aircraft axes using the pitch attitude at impact (θ) assessed by observing the aircraft crush.

$$a_{forward} = a_{horiz} \cos\theta + a_{vert} \sin\theta$$
$$a_{vertical} = -a_{horiz} \sin\theta + a_{vert} \cos\theta$$

The values must be computed at each time step. With roll and yaw involved, more complex matrix transformations are required. For many events, however, the calculation methodology outlined here can provide useful first estimates of the center of mass accelerations.

An important final observation is in order here. The preceding calculations and most detailed accident reconstructions relate specifically to the aircraft center of mass. They do not define the aircraft accelerations at all points. Reconsider our deforming ball collisions. They were better behaved than the imaginary rigid ball collisions where accelerations were infinite. The center of mass of the deforming ball was able to change velocity slower while the zone of deformation deformed. That doesn't apply to a part of the ball in the zone of deformation. In fact, the point of the ball that first contacts a barrier (or another similar ball) still gets a nearly infinite acceleration of nearly zero duration. This is yet another reason why real impacts of aircraft and people are so difficult to characterize.

The Principles of Occupant Kinematics

The calculations of collision physics are principally based on the second and third laws of motion. Kinematics is based principally on the first law. Occupant kinematics relates to the motion of an occupant with respect to his vehicle without regard to the forces that create the motion. This is precisely because forces on the occupant typically don't create the displacements of occupants with respect to aircraft during crashes. Instead, the displacements are produced by crash forces on the aircraft while the occupant continues to obey Newton's first law.

In crash test films made with on-board cameras, it appears that occupants may be suddenly "thrown" forward. In reality, the pre-crash forward motion of the aircraft is rapidly stopped because it hits the ground. The camera, which is screwed to the aircraft, also stops rapidly. The occupant, who is not screwed to the aircraft, continues to move because he hasn't been notified of the crash yet. He displaces with respect to the aircraft and the camera not because he is "thrown" forward. If anything the aircraft and camera are being "thrown" rearward. The forces on an occupant, in this setting of a frontal barrier crash are actually rearward forces from restraints, angled seat bottoms, and front structures. They just occur a bit later than the crash forces on the vehicle. It will be helpful in understanding injury protection to rigorously track the directions and sources of the forces being applied.

Occupant kinematics is helpful in assessing injury and its prevention even though forces are not directly taken into account. Fundamentally the computation of occupant kinematics involves assessing two trajectories or motion paths. The first is the trajectory that the occupant would follow if the crash had not occurred. The second is the trajectory that his surroundings follow as a result of the crash. If a forward moving vehicle strikes a barrier, the occupant continues to move forward with respect to the slowing aircraft. The timing and extent of that motion can be assessed if you have reasonable estimates of the acceleration-time profiles of the occupant's surroundings. If a falling helicopter strikes the ground, the occupant continues to move downward with respect to the slowing aircraft. From these types of observations, people have sometimes been lulled into the mistaken notion that occupants simply move toward the point of impact. That is not true. Occupants obey Newton's first law. Consider an unrestrained occupant in a taxiing aircraft which strikes a tree with its right wing. Comparison of occupant and aircraft trajectories will reveal that the occupant moves forward and increasingly to the left with a respect to the aircraft as the aircraft is slowed and rotated clockwise. The occupant's trajectory with respect to the aircraft will actually be a curved path, forward and curving to the left. He certainly does not go toward the right wing point of impact!

Occupant kinematics in real crashes depend on the degree of coupling to the vehicle. An uncoupled occupant such as a person standing on the hood of an automobile striking an embankment will follow an entirely independent trajectory from that of his vehicle. An occupant perfectly restrained to his vehicle in a form-fitting, rigid cocoon will be constrained to follow his vehicle's trajectory, but his interaction with his cocoon will be that which will be dictated by his kinematic tendencies as he "tries" to maintain his current motion path at each point in time. Assessing the difference between the two trajectories and factoring in knowledge of constraints will allow meaningful evaluation of the direction, severity, and character of the occupant's interactions with his environment.

An example of this approach may be seen in the assessment of a head impact into aircraft structure during a helicopter crash. Suppose investigation showed a clear helmet imprint on a piece of structure and matching damage to the helmet. Using the accident reconstruction acceleration-time profiles relevant to that point of structure, the range of potential pre-impact head positions could be computed to allow the unconstrained head to reach that point of the structure and a range of impact velocities could be computed for pre-impact head positions within the possible range. Comparing the actual head impact severity with the computed range of

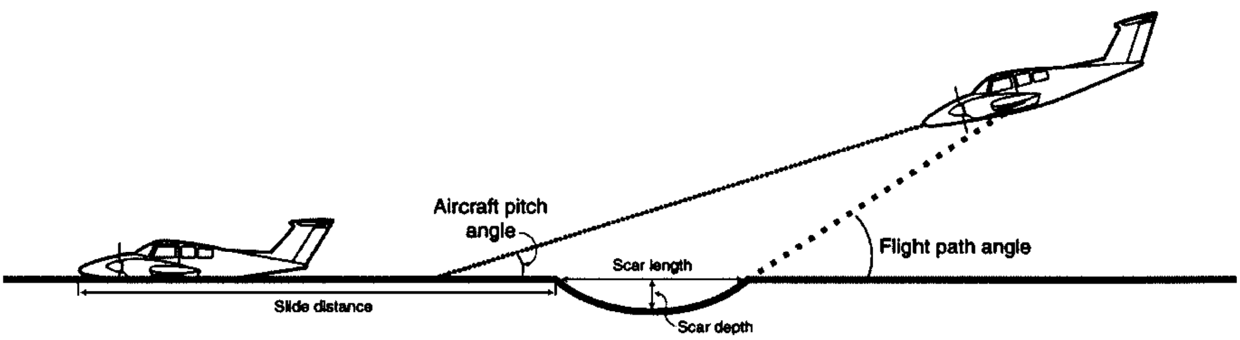

Figure 1. Aircraft pitch angle and flight path angle relating to a ground collision. Adapted from M.W. Dobbs.

velocities could allow an estimate of the occupant's head position immediately pre-impact.

Even when unconstrained motion of an occupant or body part is an unwarranted assumption, kinematic computations for unconstrained bodies can lead to useful assessments of the timing and character of occupant interactions with restraints, seats, or other structures. The method is relatively simple. One must simply integrate the acceleration-time curves for the relevant location or locations in the aircraft. This results in velocity-time curves for those points. These are then integrated again to produce displacement-time curves. At the points in time where displacements are sufficient to allow occupant contacts, the velocity curves can be consulted to assess maximum relative velocities for those contacts.

It may also be useful to employ one of several available computer simulations to assist in kinematic assessments. Caution is in order however since simulations, and indeed the kinds of calculations discussed here can create a false sense of precision when that sense is clearly unwarranted. No computer simulation of kinematics has been validated for all the applications which well-meaning people may dream up for it. Nor will such programs detect for you when a misapplication is being attempted. Errors in assumptions input data or reference frames may still lead to deceptively real-looking results. In the effort to understand a phenomenon as counter-intuitive as impact can be, there is no substitute for careful "Reality Checking" through the use of independent lines of analysis.

We have now discussed the basic tools used in understanding the impact event. It remains now to discuss their application in the assessment of injury causation and prevention.

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