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SUMMARY

An aircraft landing may be described as a controlled crash because a runway surface is intercepted. In a simulation model the transition from aerodynamic flight to "weight on wheels" involves a single computational cycle during which stiff differential equations are activated; with significant probability these initial conditions are unrealistic. This occurs because of the finite cycle time, during which large restorative forces will accompany unrealistic initial oleo compressions.

This problem was recognized a few years ago at Ames Research Center during simulation studies of a supersonic transport. The mathematical model of this vehicle severely taxed computational resources, and required a large cycle time. The ground strike problem was solved by a technique called "anticipation equations," as described here. The technique, although used extensively, has not been previously reported.

The technique of anticipating a significant event is a useful tool in the general field of discrete flight simulation. For the differential equations representing a landing gear model "stiffness," rate of interception and cycle time may combine to produce an unrealistic simulation of the continuum.

INTRODUCTION

In discrete real-time simulation with a constant cycle time T, pilot inputs and environmental conditions at time t generally result in forces and moments also applicable at time t. Within the discrete model, these contributions are then summed, and prior to real-world communication, a transition of states is made to time $t + T$. Most importantly, this transition assumes continuous behavior.

Total aircraft motion lends considerable credence to the assumption of continuous behavior, but at the subsystem level, highly nonlinear and cross-coupled subsystems may create exceptions to this assumption. One such exception occurs when a significant event occurs at some random point within a cyclic interval, where the event itself cannot be recognized until the next interval. Since the procedural flow in real-time computation is fixed, the subsystem itself may require adjusted states to accommodate this discrete phenomenon.

Specifically, landing gear models generally involve restorative forces that are hyperbolic functions of oleo compressions. Also, damping terms are generally nonlinear. The oleo compressions and rates are linear functions of the aircraft states. The aircraft states are themselves elements from sample data sequences within which continuity is an important assumption. Hence, a totally unrealistic set of initial conditions may occur at "ground strike" as a function of sink rate and cycle time. During the computation cycle in which ground interception is initially recognized, the geometrical translation of vehicle altitude, orientation, and rates to oleo compressions and rates may produce astronomical forces and moments. This happens because interception cannot be recognized until intersection actually occurs. With significant probability the initial conditions that activate the gear equations are not reasonable.

AIRCRAFT AND GEAR MODEL

To illustrate the landing shock problem, a supersonic transport model is used. This aircraft is extensively described in reference 1. Parameters are selected from Condition #2 of the reference, which is a landing configuration. Germane to this study are the pitching moment of inertia, $I_{yy} = 9{,}971{,}883$ slug-ft^2, the weight $W = 240{,}000$ lb, the longitudinal gear positions with respect to the c.g. $X_1 = 52.82$ ft (nose gear), $X_2 = X_3 = -3.27$ ft (right and left gears), and the fact that all static gear positions Z_G (strut extensions) are 14.5 ft below the c.g. prior to "weight on wheels."

The gear oleo forces F_n for the simulation are plotted in figures 1(a) and 1(b), and the oleo damping coefficients C_n are plotted in figures 1(c) and 1(d) as functions of oleo deflection. These functions are derived from data tabled and plotted in reference 1. The hyperbolic characteristic of these functions should be noted. However, the dominant computational problem is not necessarily related to the functional characteristics, but rather to the initial-condition mismatch of velocities and gear deflections when compression is first recognized by the discrete model.

Where h_n is the compression (negative number) of the n^{th} gear for function evaluation purposes and v_n is its rate of change, oleo reaction forces are computed for each gear as follows:

$$R_n = -1.3F_n + 144C_n v_n |v_n|$$

An example is described with appropriate figures to support the usefulness of the "anticipation algorithm." The reaction forces R_n with and without the algorithm are shown to produce considerably different behavior.

The lateral degree of freedom is not required for the example. The vehicle is simply raised to an approximate gear height of 4 ft with zero pitch angle and then dropped with an appropriate vertical velocity such that theoretical ground intersection (zero gear height) always occurs at the same velocity. A large intersection velocity of 16 ft/sec and a large cycle time of 60 msec are selected to illustrate the problem. Under these conditions, the gears intercept the ground in about eight cycles of T.

The "wake up" phenomenon (interception recognized) of gear strike has a uniform distribution over the cycle time T when the theoretical intersection velocity is held constant. This distribution may be imposed on a simulation model by a family of initial conditions.

A model is here developed in which intersection is coincident with interception (recognition). Then, for a cyclic interval T, the discrete phenomenon of interception is distributed in the interval immediately following the continuum phenomenon of intersection. This operation establishes a proper probability density that emulates discrete simulation.

Interception in K Cycles

In this section aerodynamics are ignored in order to set up a simple model. By placing the aircraft at a small height above the ground and simply dropping it, the exact ground intersection velocity may be controlled. The time of occurrence in the continuum may then be manipulated to occur on a discrete boundary, i.e., a multiple of the cycle time T.

The wheel height h_n of the n^{th} gear is given with respect to the height of the vehicle c.g. h by

$$h_n = h - z_G \tag{1}$$

where the noncompressed gear extension z_G = 14.5 ft. For any time t until wheel intersection with the ground occurs, the rate of change of altitude is given by

$$v = -gt + v_o \tag{2}$$

and the wheel rate of change $v_n = v$ while the vehicle is airborne. In terms of the selected velocity of interception v_I, the initial vertical velocity v_o may be determined by setting the time of intersection to an integer multiple K of the cycle time,

$$K = \text{Least Integer} \left[-\frac{v_I}{gT} \right] \tag{3}$$

so that the initial vertical velocity may be used to account for the remainder:

$$v_o = v_I + gKT \tag{4}$$

The velocity of intersection v_I is selected in this study to be 16 ft/sec (negative value) because it nicely segments the graphical presentations into two distinct regions. In terms of transport aircraft operations this value is too high.

The height of the c.g. of the vehicle is given by

$$h = h_o + v_o t - gt^2/2 \tag{5}$$

and is equal to z_G upon wheel intersection with the ground. Hence, the initial altitude is determined from

$$h_o = z_G + KT(gKT/2 - v_o) \tag{6}$$

Intersection occurs at exactly K cycles of T using h_o and v_o, and the intersection rate of change is $v_I = -16$ ft/sec.

Using the above equations, ground intersection is placed on an exact discrete cyclic interval. In flight simulation, however, intersection invariably occurs within a cyclic interval and has a uniform distribution. In the following section this transformation is performed by dividing the interval T into M equal subintervals.

Temporal to Spatial Substitution

Because of the cycle time T, a uniformly distributed temporal uncertainty occurs in the time of a discrete event in the continuum. This may be transformed into a distribution of initial conditions. The (previous) interval of cycle time is divided into M points m = 1, 2, ..., M giving the time of intersection:

$$t_{Im} = (K - m/M)T \tag{7}$$

and this produces a parametric set of initial conditions at $t = 0$ as follows:

$$v_{Om} = v_I + gt_{Im} \tag{8}$$

$$h_{Om} = z_G + t_{Im}(t_{Im}g/2 - v_{om}) \tag{9}$$

For $M = 10$ these initial conditions produce the behavior shown in figures 2(a) through 6(a), as will be described later.

Procedural Flow

All force and torque contributions, including those contributed by the landing gear, are summed at the end of the k^{th} cycle in which the time $t = kT$. Accelerations and moments are thus applicable at the beginning of the k^{th} interval (concurrent with pilot inputs). At the end of the k^{th} interval, the integrations are performed; they consist of a predictor to create velocities and rates applicable at the end of the interval, and a corrector (since updated velocities are then known) to create positions and angles. These velocities, rates, angles, and positions are all applicable at the end of the k^{th} interval, or more specifically, at $t = (k + 1)T$. Among these values are the new altitude and orientation of the vehicle. At this point the interval is completed.

Although the ground may have been intercepted during the interval, no time exists in real-time simulation to recompute the total forces and torques at some intermediate point and recalculate the entire kinematic model. During the next cycle in which $t = (k + 1)T$, the landing gear equations may have to deal with unrealistic initial deflections and velocity conditions. Compression braking, steering and sideslip relationships may then combine to produce rather unrealistic vehicle behavior. For this reason, the landing gear module itself should anticipate the event.

ANTICIPATION

Landing-gear equations at Ames Research Center are typically modularized into two separate subroutines: (1) a standard routine that determines strut deflections and rates as part of the kinematic model, and (2) GEARS, a vehicle-specific routine that creates strut forces from kinematic information. Geometrical relationships are applied to produce gear force- and moment contributions in the vehicle axes set within the standardized module, Simulation Transition Routine Including All Kinematic Equations (STRIKE). This model is based upon our earlier model called BASIC as outlined in reference 2.

Anticipation, described herein as using only kinematic terms, is restricted to the standard subroutine STRIKE. The anticipation algorithm assumes that aircraft-specific nonlinear forces await in the subroutine GEARS for each single cycle when the ground is intercepted by a landing gear. Noncoincident gear strike is handled by the algorithm, which prevents unusual vehicle orientations upon touchdown.

The Algorithm

In this section the algorithm within STRIKE is outlined. This algorithm should not be confused with the equations already presented that have been used to define the example. The algorithm itself assumes nonaccelerated ground interception in its prediction logic. This assumption is well supported by typical landing behavior, especially because only one discrete computer cycle is involved.

Where $h_n(t)$ is the height of the n^{th} gear (positive = above) at time t, $v_n(t)$ is its derivative, T is the cycle time, and N is the number of gears, the algorithm is applied as follows:

1. Set $I_H = 0$. If this flag remains reset throughout the the algorithm then all gears are airborne.

2. For each gear ($n = 1, 2, \ldots, N$), continue through step 8.

3. Compute $h_n(t)$ and $v_n(t)$ analytically from the aircraft states and geometric relationships.

4. If $h_n(t) < 0$, set $I_H = 1$, $I_n = 1$, and go to step 8. The gear is already on the ground. Anticipation is improper.

5. If $h_n(t) \geq 0$, linearly estimate the next cycle: $h_n(t + T) = h_n(t) + Tv_n(t)$.

6. If $h_n(t + T) > -e$, where e is a small deadband, set $I_n = 0$, and go to step (8). The n^{th} gear is not projected to excessively hit the ground during the next cycle.

7. If $h_n(t + T) \leq -e$, set the flag $I_H = 1$ and set $I_n = 1$. Put the gear on the ground immediately by setting $h_n(t) = h_n(t + T)/2$ (a negative value).

8. If $n < N$, return to step 2. (Continue for each gear.)

9. If $I_H = 1$, at least one gear is compressed. Solve gear reaction forces using $h_n(t)$ and $v_n(t)$ for each gear where $I_n = 1$. (Call up the aircraft-specific GEARS.)

10. Sum all gear force and moment contributions by using geometrical relationships.

11. Gather all force and moment contributions and integrate vehicle kinematics for output at $t + T$.

The Inactive Anticipation Band

Anticipation is not performed if a gear is already on the ground. A further extension of this logic, which is included in the anticipation algorithm, is that if the anticipated deflection is less than a designated small value, then projection is not performed. This inactive band is a characteristic of most on-off or "bang-bang" control systems, but here we should just read "bang" because the algorithm operates only for a single cycle (unless the gear actually bounces). The requirement for an inactive band was discovered by some "hotshot" pilots who found that if they landed with negligible sink rate, they could skip over the runway as if it was made of glass.

A rule of thumb exists for determining a maximum dead band for discrete computation: If the initial deflection will cause a next cycle reversal in that strut's deflection, then the differential equations are definitely not being solved sufficiently fast for that particular sink rate. Of course, the worst possible deflection is selected from the spectrum of possibilities over the cycle time T. Maximum deflections that do not produce an immediate reversal are minimally acceptable without modification. The determination of this value requires an unusual amount of overhead in real-time simulation. It is sufficient to approximate a value based upon an anticipated maximum sink rate.

For this study a dead band was established by observing the divergence caused by initial oleo deflections (at 16 ft/sec) greater than some value. Divergent behavior was indeed caused by the reversal phenomenon. The value of $e = 0.48$ ft is used in the example because it is one-half of the full deflection observed in one cycle time with the large 16 ft/sec sink rate. The response with initial deflections less than this value of e are satisfactory without anticipation. This value has been used for a wide variety of aircraft landing-gear systems.

RESPONSES

Four seconds of data are given in figures 2, 3, and 4, showing oleo behavior for ten separate runs with a uniformly-distributed time of intersection (over one $T = 60$ msec). The original model, shown in figures 2(a), 3(a), and 4(a), has both a family of convergent curves represented by initial "wakeup" deflections less than about one-half of a foot, and a divergent family of curves represented by initial deflections greater than this value. Figures 2(b), 3(b), and 4(b) show that the anticipation algorithm modifies only the divergent curves by transforming them into the set of convergent curves.

In figures 4(a) and 4(b) the landing shock phenomenon is shown in terms of vehicle pitch angle. Pilots would clearly react without the anticipation algorithm.

Figures 5(a) and 5(b) show an expanded view of the single interval in which nose-gear intersection occurs, and show exactly how the problem is handled prior to its actual occurrence by the anticipation algorithm. Figures 6(a) and 6(b) show similar patterns for the main gear. Because intersection has been anticipated the entire statistical spectrum of unrealistic behavior shown in figures 2-6(a) is compressed to the tight bands shown in figures 2-6(b). From time-scale studies, it is clear that these curves are converging on the true solution to the differential equations.

CONCLUSIONS

In discrete real-time simulation an event may occur at some point within a cyclic interval. This event, which is generally a function of dependent variables, may or may not be significant to successful simulation. The probability of significance can be established from the physics of the situation; it has been well established here for the case of landing shock.

When the probability of occurrence of a significant event within a cyclic interval is established from the physics of the situation, these same physics may be used to anticipate the event, and project the requisite dependent variables for a smooth transition through the event. This anticipation technique is quite successful for handling the landing shock phenomenon by using simple linear projection.

By extension of this material, the concept of anticipation also has application to the more general subject of stiff-control-system nonlinearities.

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2. McFarland, Richard E.: A Standard Kinematic Model for Flight Simulation at NASA Ames. NASA CR-2497, Jan. 1975.

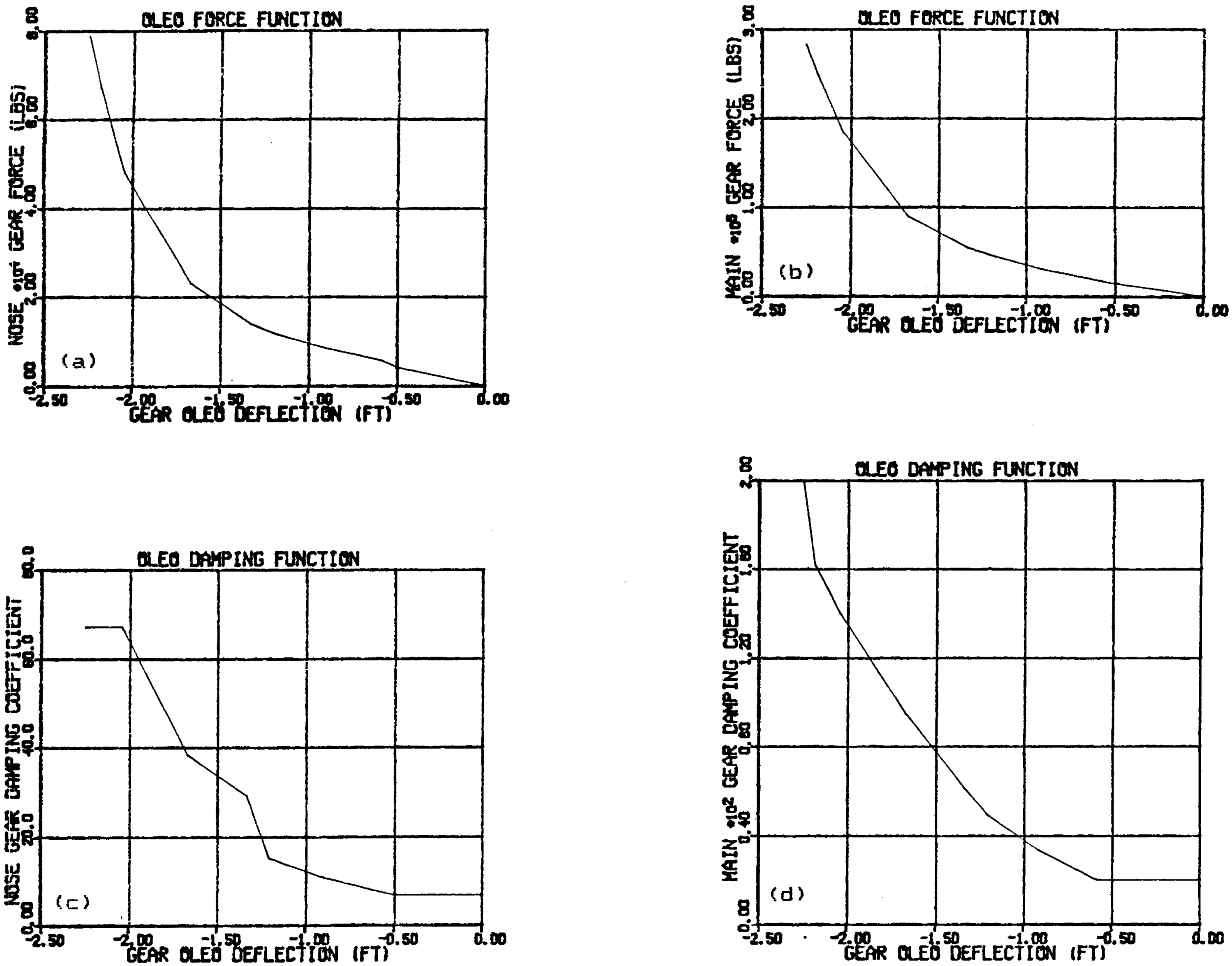

Figure 1.- Oleo characteristics. (a) Nose gear force. (b) Main gear force. (c) Nose gear damping. (d) Main gear damping.

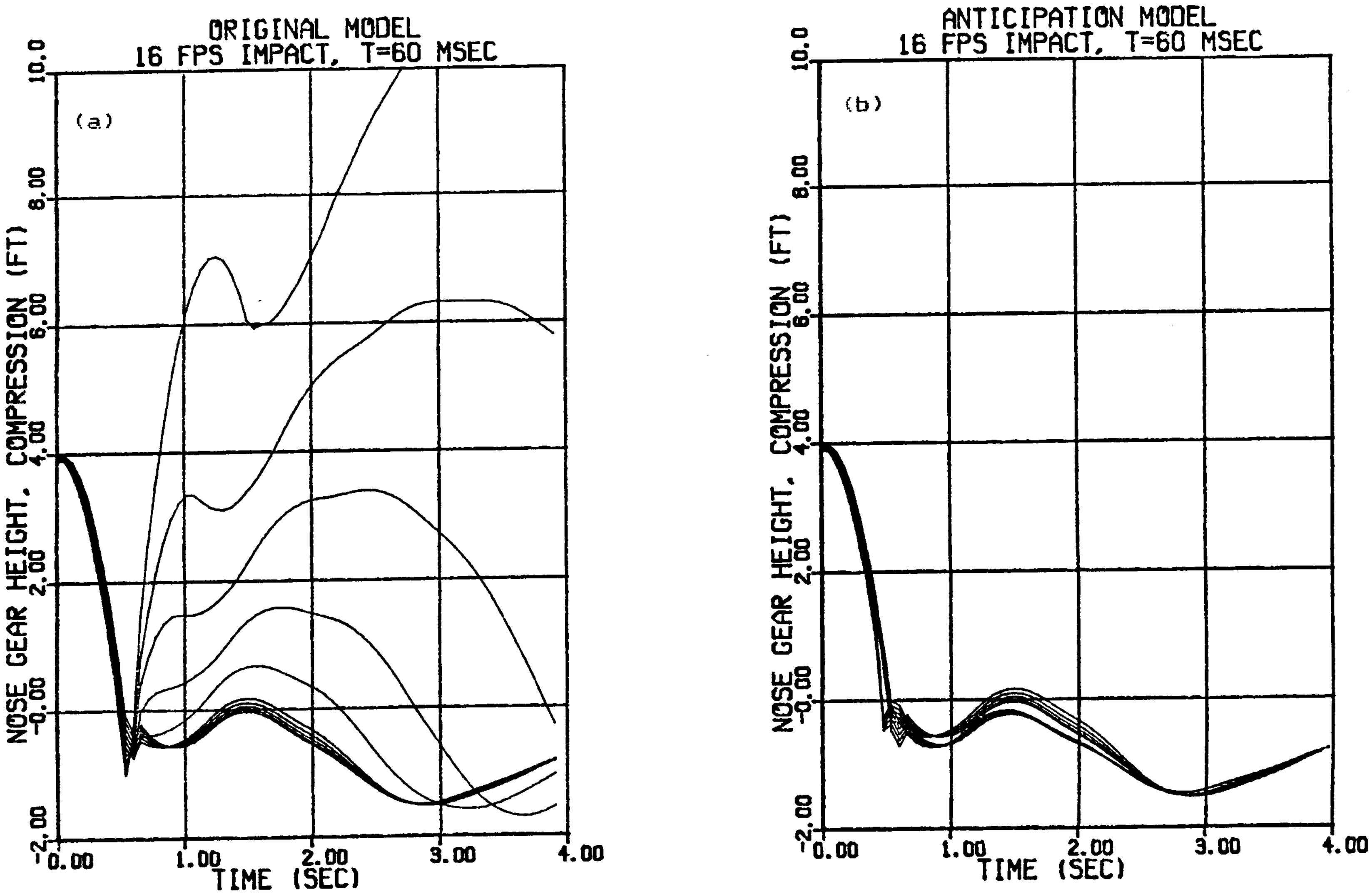

Figure 2.- Nose gear time history. (a) Original model. (b) Anticipation model.

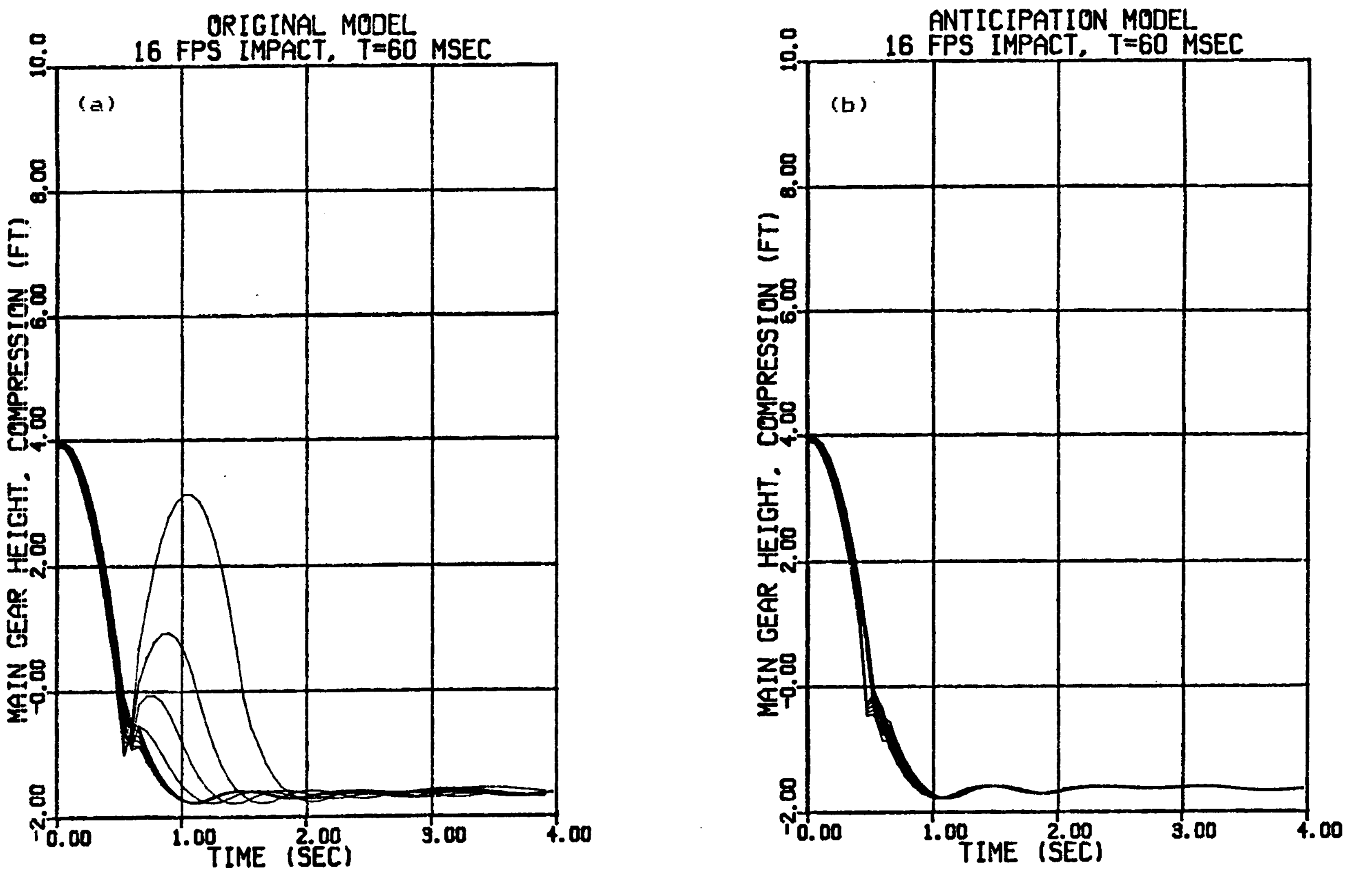

Figure 3.- Main gear time history. (a) Original model. (b) Anticipation model.

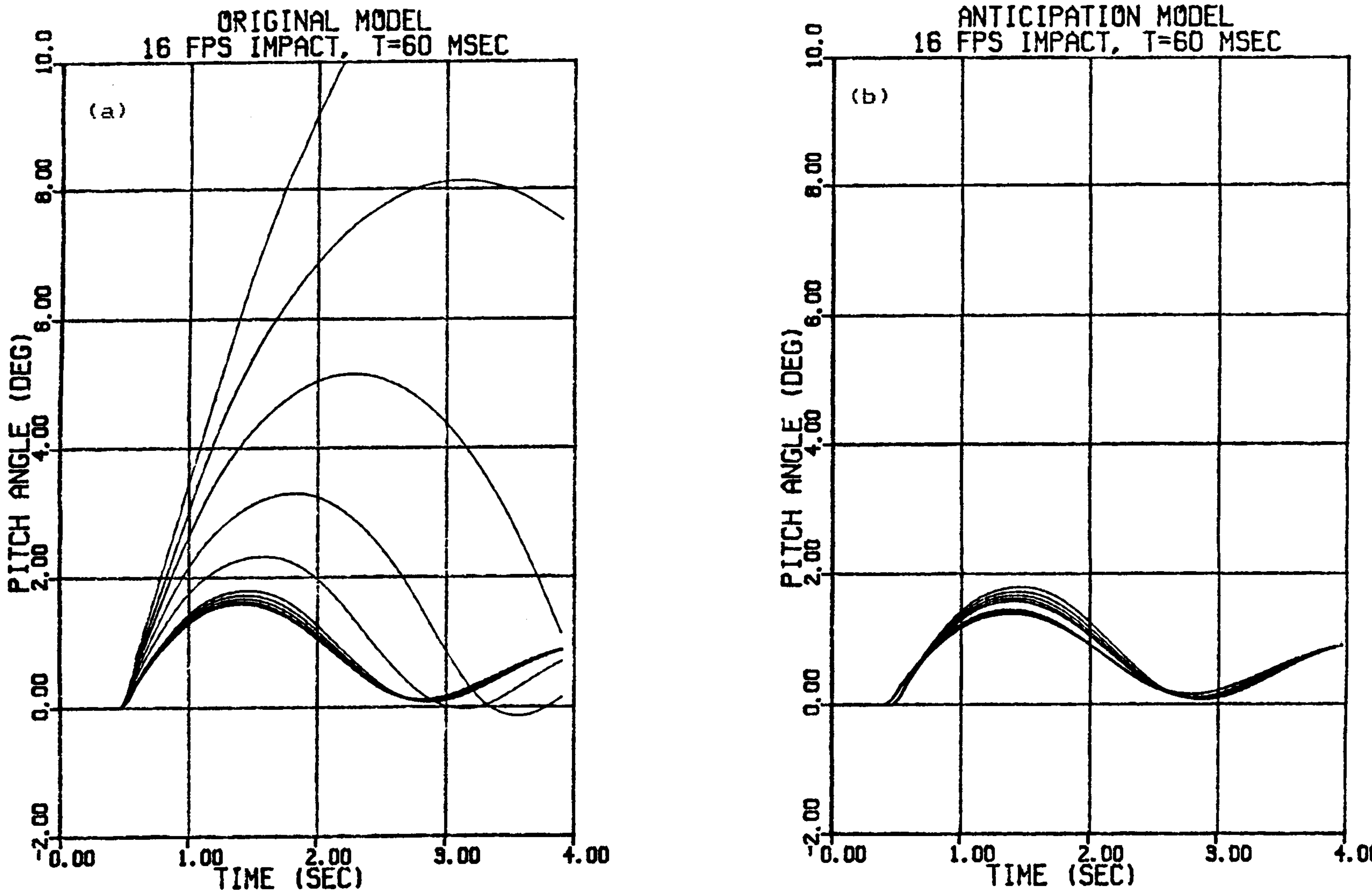

Figure 4.- Pitch angle time history. (a) Original model. (b) Anticipation model.

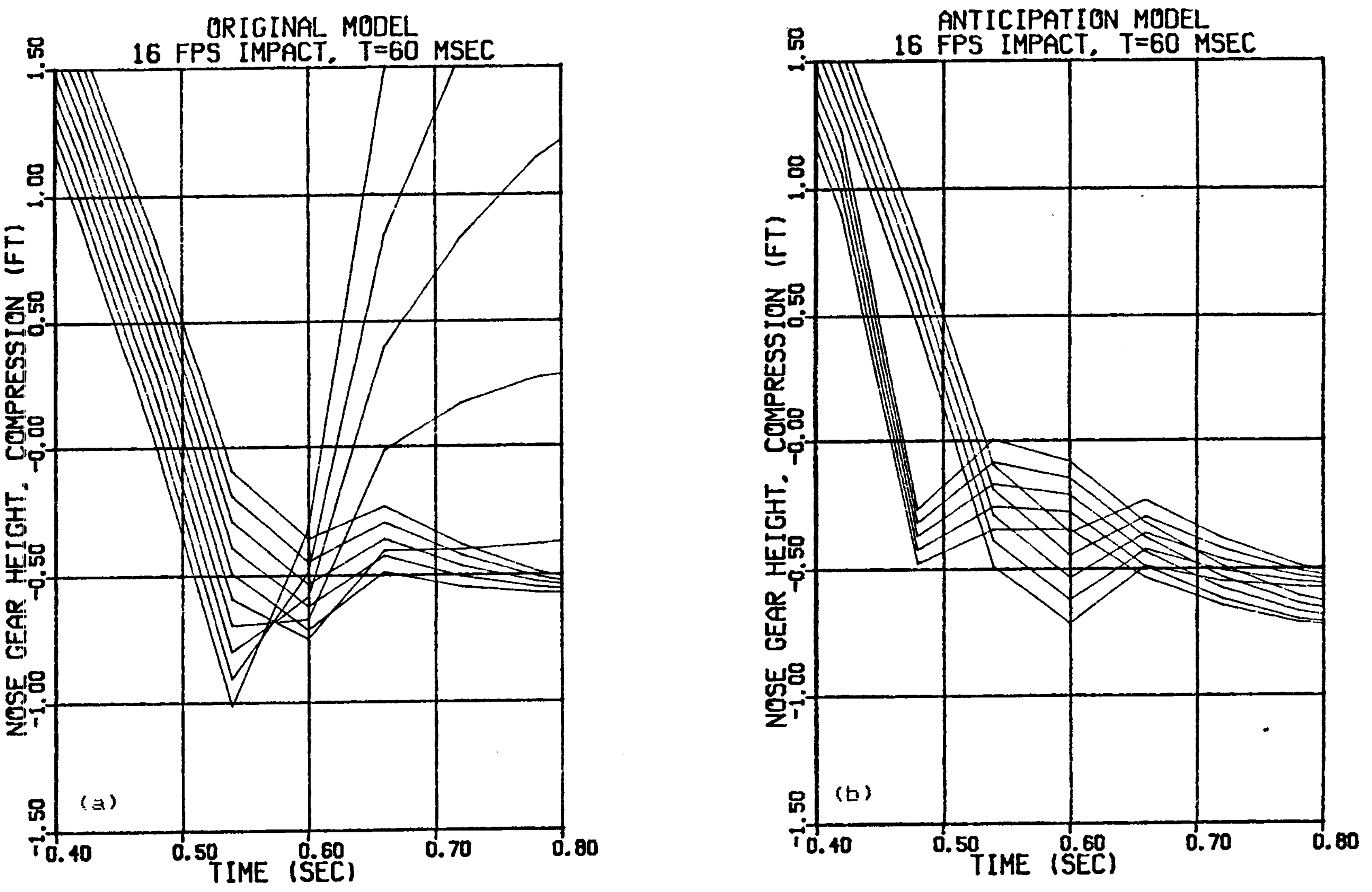

Figure 5.- Expanded-scale nose gear time history. (a) Original model.
(b) Anticipation model.

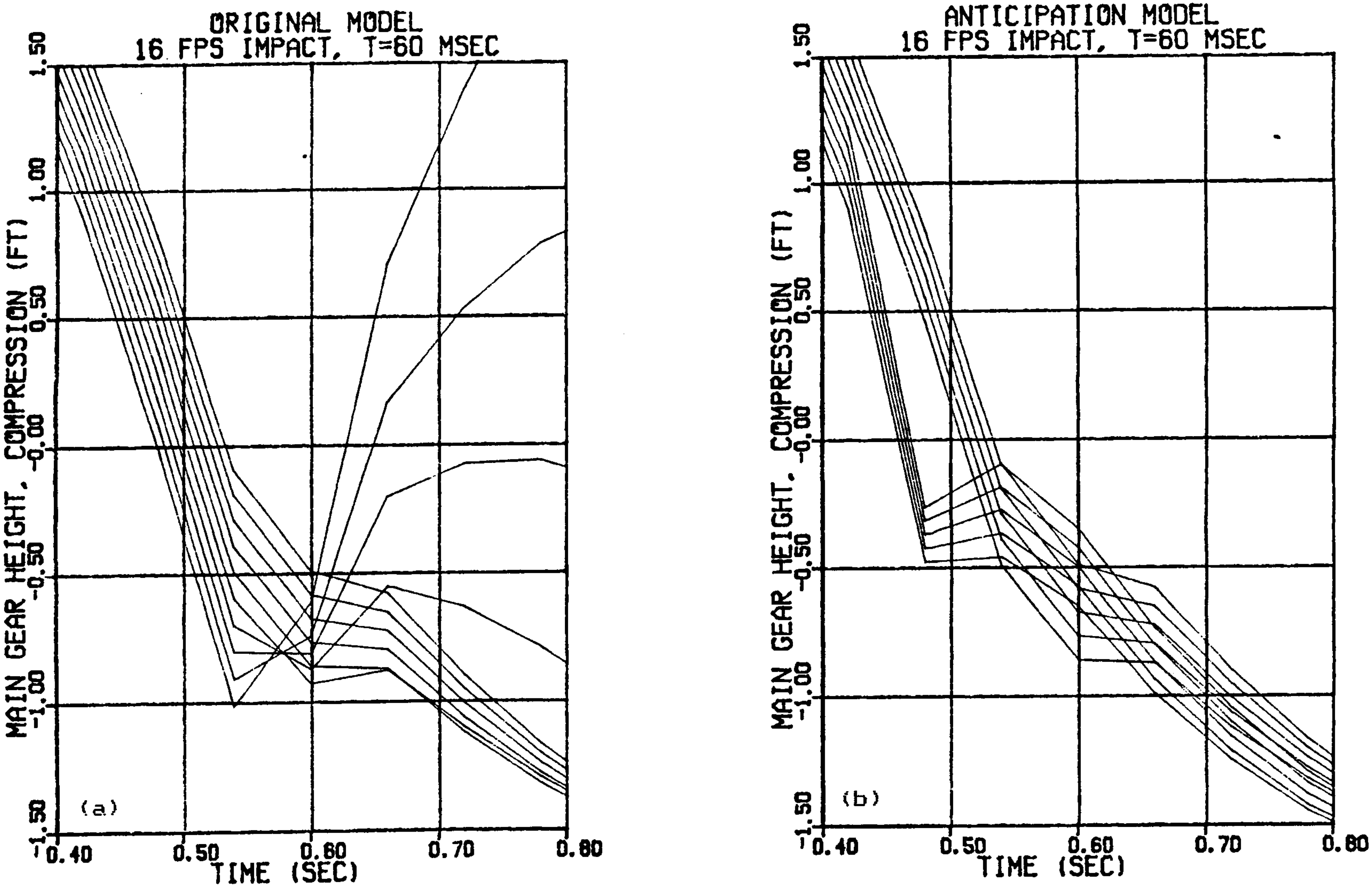

Figure 6.- Expanded-scale main gear time history. (a) Original model. (b) Anticipation model.

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16. Abstract

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