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SURVEY OF IMPACT DAMPER PERFORMANCE

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ABSTRACT

The impact damper is a simple device in which inelastic collisions can produce high damping in vibrating systems over a wide range of frequencies. But it is hard to analyze because the inelastic impacts make the system nonlinear. Fifty years of study of special cases have failed to produce an overall picture of the complex behavior of this physically simple system. Previous predictions of its damping have been limited to narrow regimes of behavior.

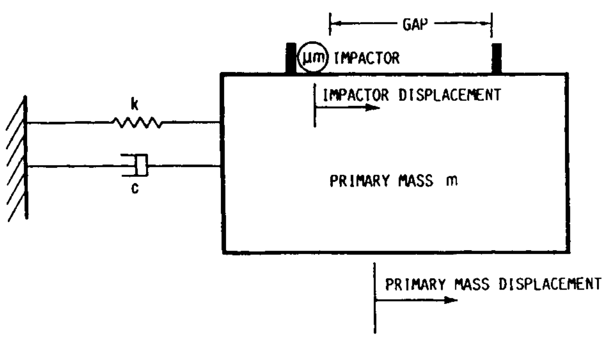
The present study obtains an overall picture by utilizing time-history solutions of the system motion for the oscillator in free decay. The impactor behavior depends very strongly on oscillator amplitude, and free decay can sample the full range of behavior from an infinite number of impacts per cycle at high amplitude to no impacts at low amplitude. This overall picture cannot be obtained by analysis of steady-state forced response. Yet the predictions are relevant to forced response behavior when the damping is relatively light.

Three major regimes of impactor behavior are shown to exist: (1) a low amplitude range, with less than one impact per cycle and very low impact damping, (2) a useful middle amplitude range with at least one, but a finite number, of impacts per half cycle and good impact damping, and (3) a high amplitude range with progressively decreasing damping and an infinite number of impacts in each half cycle. For light damping the impact contribution to the damping in the middle range is (1) proportional to the impactor mass, (2) additive to the proportional damping of the oscillator, (3) a strong but unique function of the vibration amplitude, (4) proportional to $1 - \varepsilon$, where ε is the coefficient of restitution, and (5) very roughly inversely proportional to the amplitude. The system exhibits jump phenomena and period doublings which may be precursors of chaotic states. An impactor with 2 percent of the mass of the oscillator can produce a loss factor near 0.1, a very substantial level of damping for aerospace systems.

SYSTEM SCHEMATIC AND DECAY RATE

A harmonic oscillator containing a loose particle, or impactor, is represented below. Collisions at either wall are described by a coefficient of restitution model. External proportional damping is included in the analysis.

When the oscillator is released from rest at an initial displacement (measured in units of the impactor gap), the amplitude of oscillation decays as shown in the right-hand figure. The decay is not exponential, but instead approximates the linear decay of a dry friction damped system. Decay curves for three values of the impactor mass μ (expressed as a fraction of the oscillator's mass) are shown. The damping fraction of the oscillator is ζ. The behavior of the impactor at six values of amplitude is shown on the following pages.



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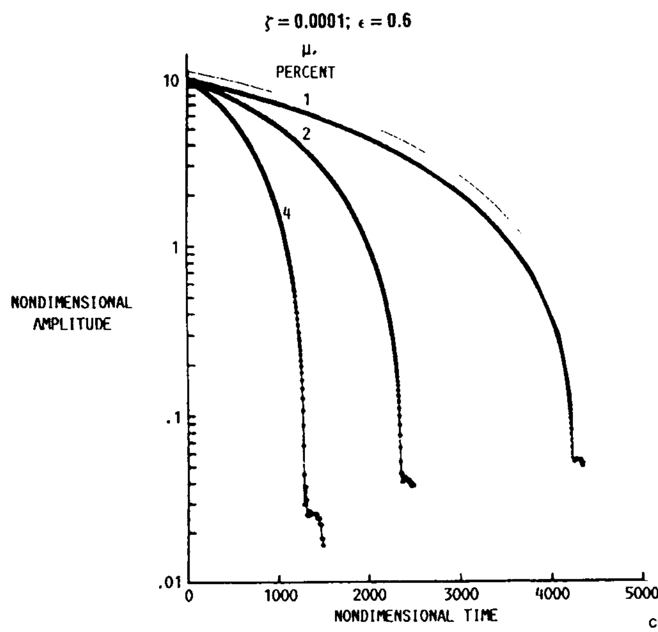

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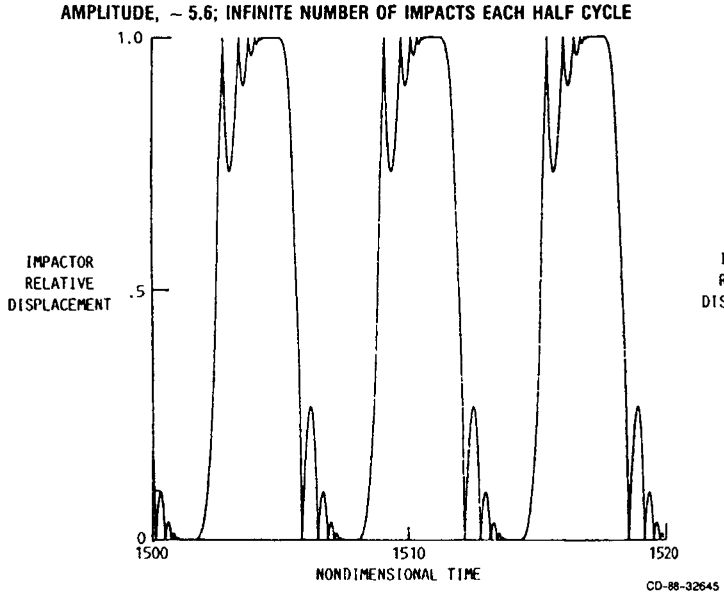
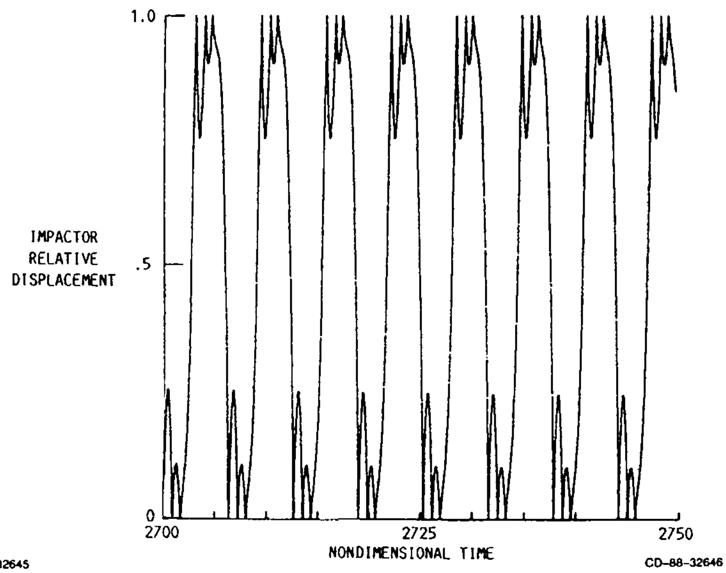
IMPACTOR BEHAVIOR FOR AMPLITUDE GREATER THAN THE IMPACT GAP

At high amplitudes the impactor bounces an infinite number of times on one side of its cavity (like a ball bouncing to rest) before crossing to the other side. This is shown at the left where the impactor position is measured relative to the cavity walls. Time is measured in nondimensional units. When the amplitude decreases sufficiently, a finite number of impacts occurs in each half cycle (below a nondimensional amplitude of about 5 for the parameters used). An example with three impacts per side is displayed in the figure on the right. The number of impacts may be even on one side and odd on the other, as shown in the bottom figure.

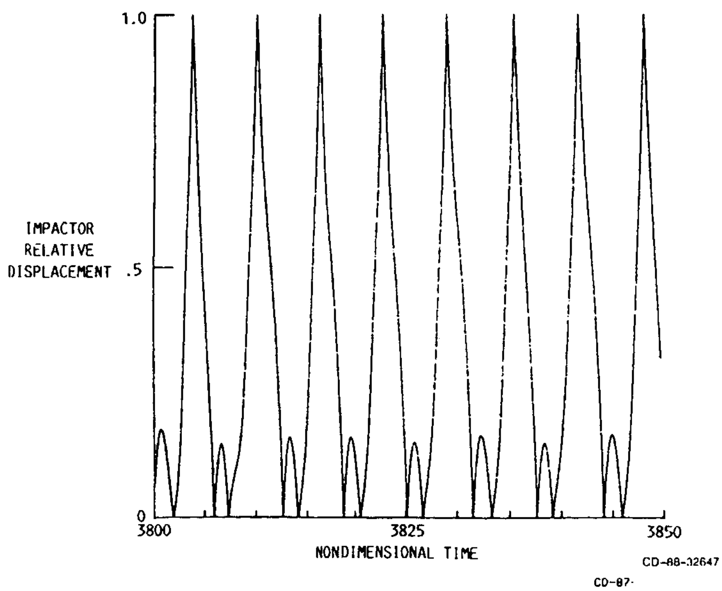
AMPLITUDE, ~ 5.6; INFINITE NUMBER OF IMPACTS EACH HALF CYCLE



AMPLITUDE, ~ 2.6; THREE IMPACTS EACH HALF CYCLE



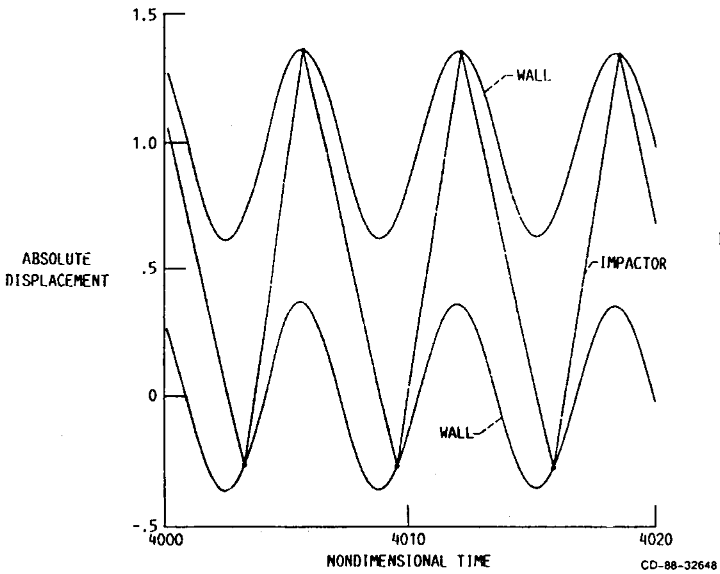
AMPLITUDE, ~ 0.6; ONE IMPACT PER HALF CYCLE ALTERNATING WITH TWO



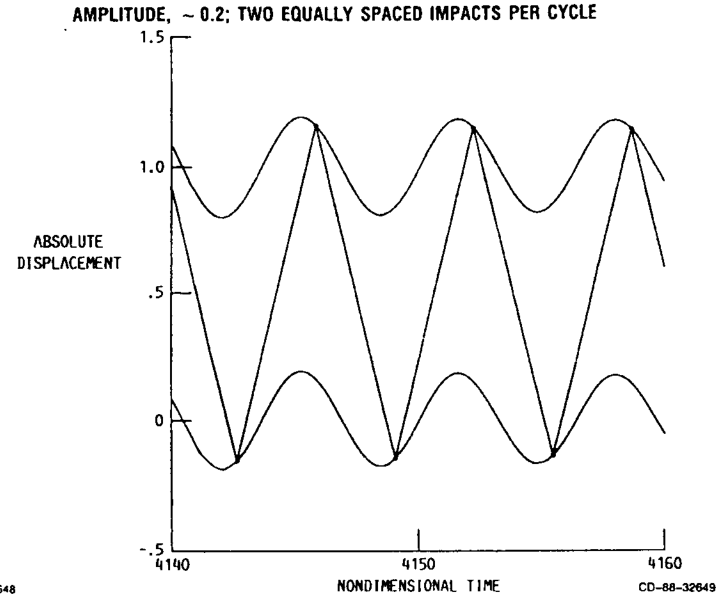
IMPACTOR BEHAVIOR AT AMPLITUDES BELOW ONE

When the amplitude becomes small enough that only one impact occurs in each half cycle, very good damping is obtained. Rather surprisingly, the impacts need not be equally spaced in time, as shown in the figure on the left. The plots show the absolute displacement of the impactor and of both walls in order to clearly reveal the asymmetrical behavior. At somewhat smaller amplitude, the system locks into a symmetrical pattern of equally spaced impacts and produces its best damping (figure at right). At still lower amplitude, impacts in each half cycle become impossible (bottom figure), and the damping falls abruptly.

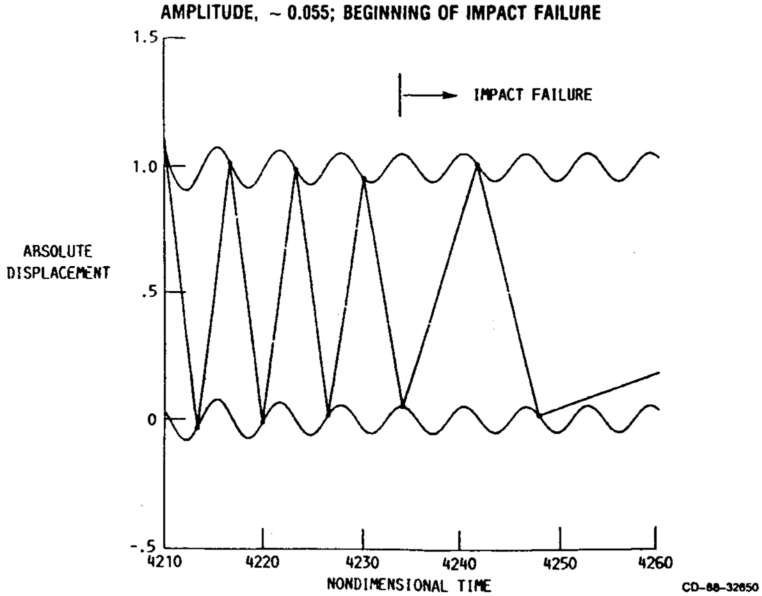
AMPLITUDE, ~ 0.4; TWO UNEQUALLY SPACED IMPACTS PER CYCLE



AMPLITUDE, ~ 0.2; TWO EQUALLY SPACED IMPACTS PER CYCLE

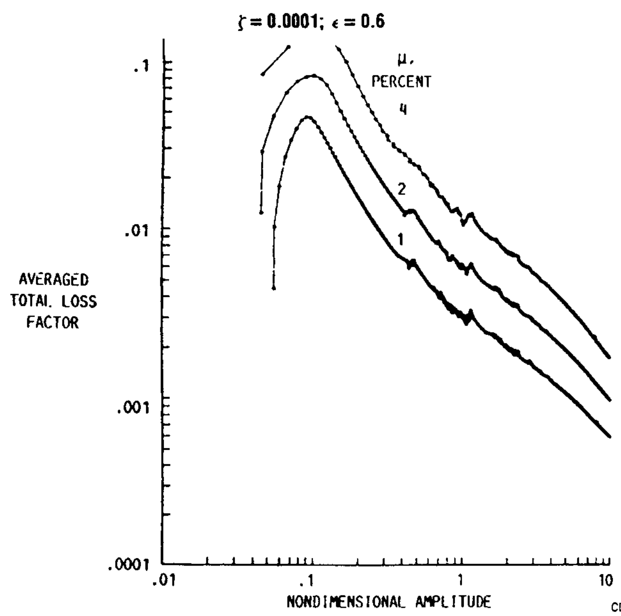


AMPLITUDE, ~ 0.055; BEGINNING OF IMPACT FAILURE



LOSS FACTOR AND ITS PROPORTIONALITY TO IMPACTOR MASS

The loss factor (the fraction of oscillator energy dissipated per radian) is plotted as a function of amplitude for three values of impactor mass fraction in the left-hand figure. Note that at the amplitude where the best damping occurs, an impactor with only 2 percent of the mass of the oscillator can dissipate nearly 10 percent of the oscillator's energy per radian, or about 50 percent of the energy in one cycle. This level of damping is substantial compared to that normally encountered in many aerospace systems and could, therefore, have a major effect in suppressing resonant vibrations and vibration instabilities. If the loss factor is divided by the impactor mass fraction and plotted as a function of amplitude, as in the right-hand figure, it can be seen that damping is rather closely proportional to impactor mass fraction.



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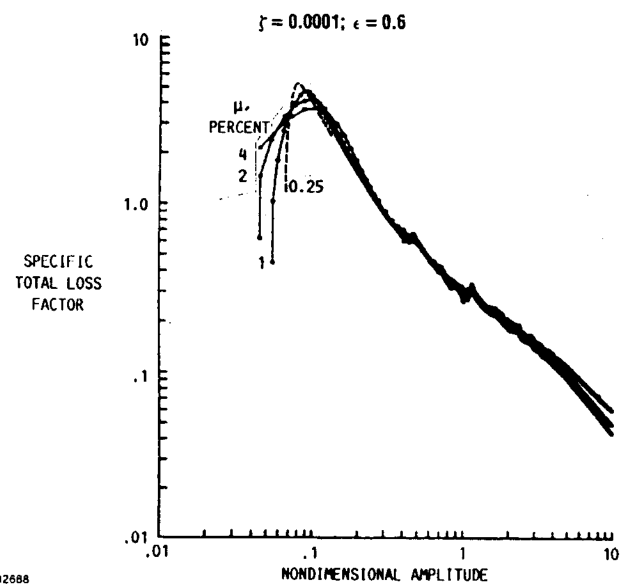

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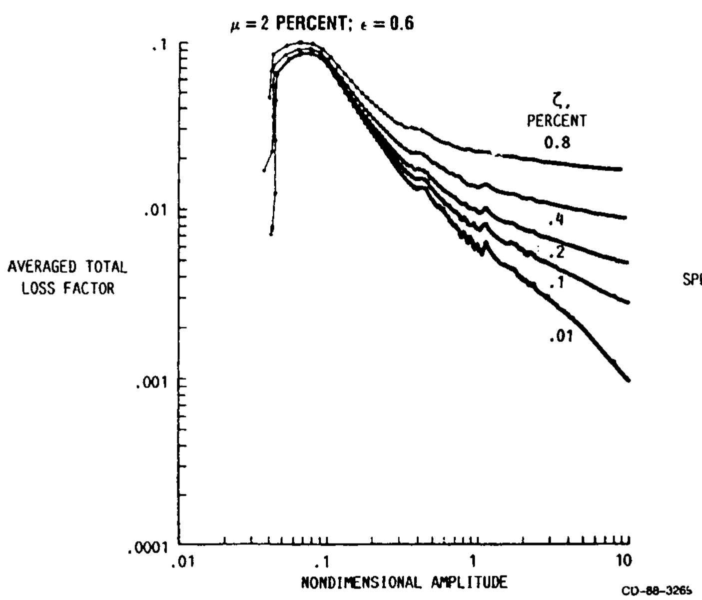
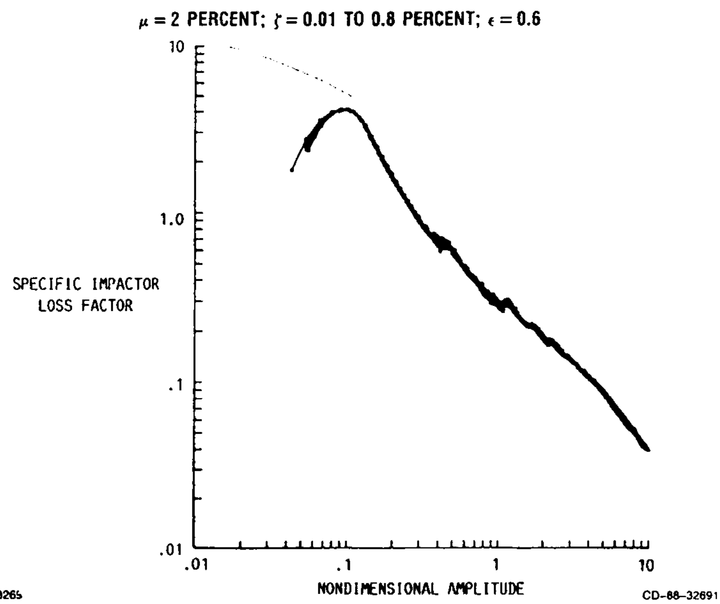
ADDITIVITY OF IMPACT DAMPING AND PROPORTIONAL DAMPING

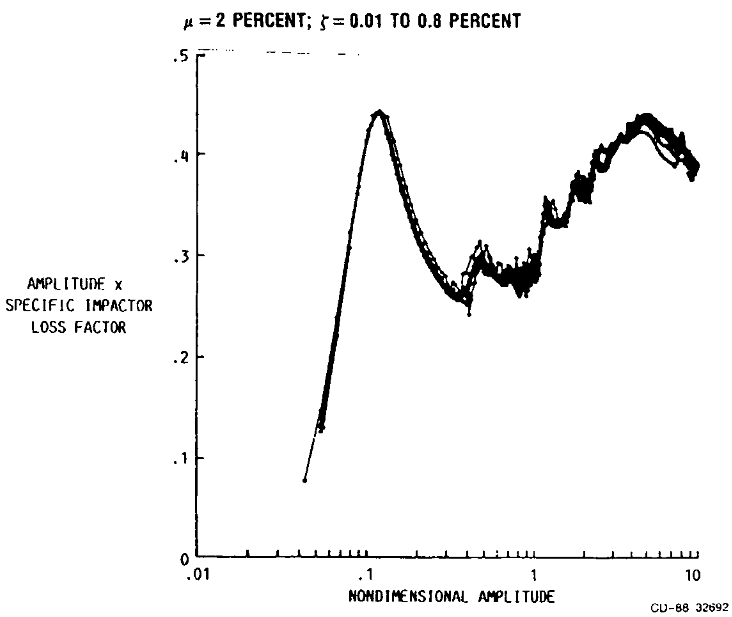
Whether the contributions of impact damping and proportional damping are simply additive should be questioned in a nonlinear system. However, for the light to moderate damping regime explored herein, these contributions are additive, as shown below. The loss factor is shown at the left for several values of the proportional damping of the oscillator. On the right, the loss factor corresponding to proportional damping has been subtracted from each curve to yield the contribution due to the impactor alone, and a single curve results, proving additivity.

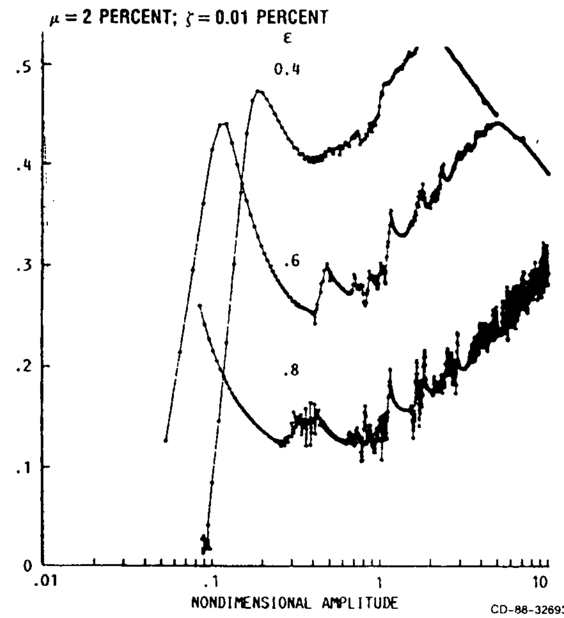


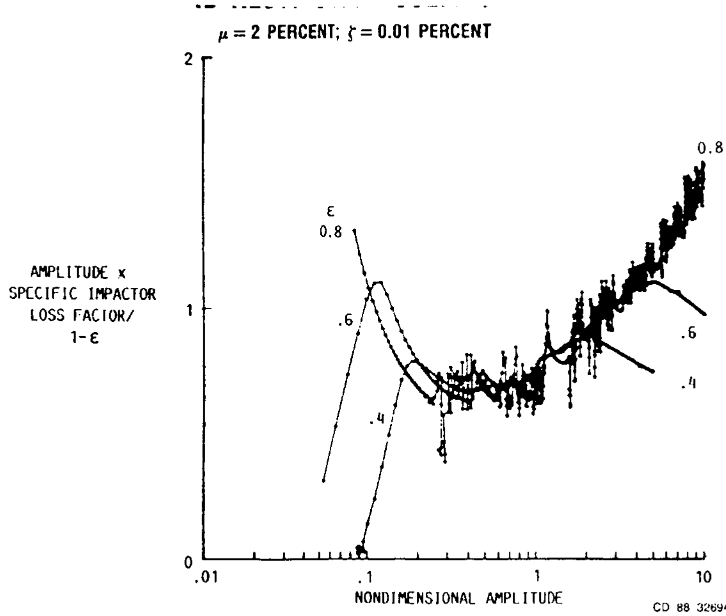


DAMPING DEPENDENCE ON AMPLITUDE AND RESTITUTION COEFFICIENT

It has been known that the loss factor due to impact damping, like that of dry friction damping, is roughly inversely proportional to amplitude. The plot on the left shows the degree of deviation from that dependence. The ordinate variable is amplitude times the specific loss factor, which for exact inverse proportionality would plot as a horizontal straight line. For the amplitude range between 0.1 and 10, the ordinate lies within about 30 percent of its mean value. A similar plot on the right shows the dependence on the restitution coefficient, and the replot at the bottom shows that damping is reasonably proportional to one minus the restitution coefficient.

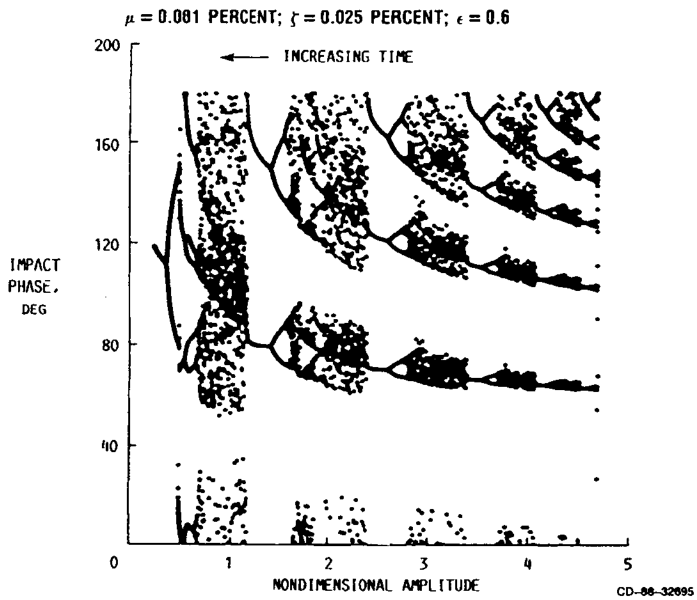


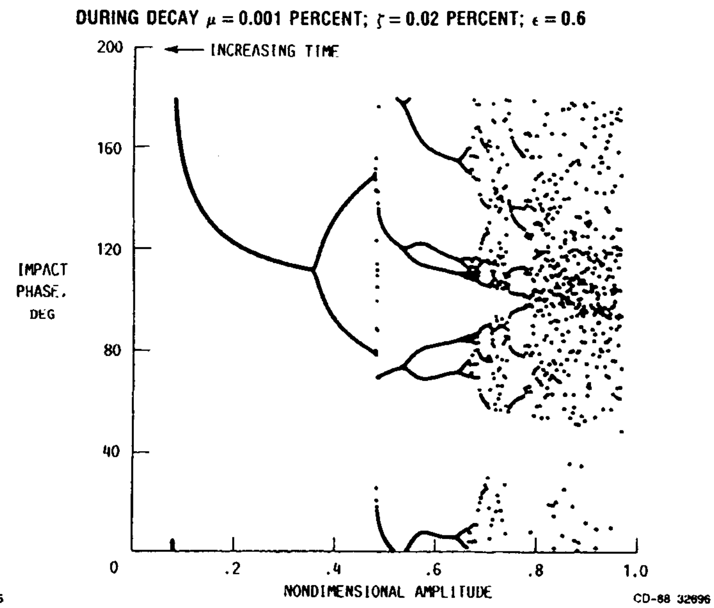


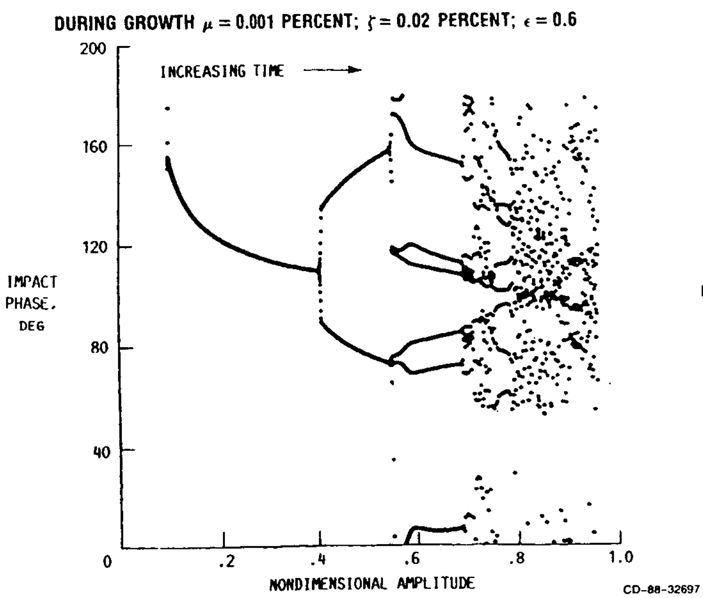


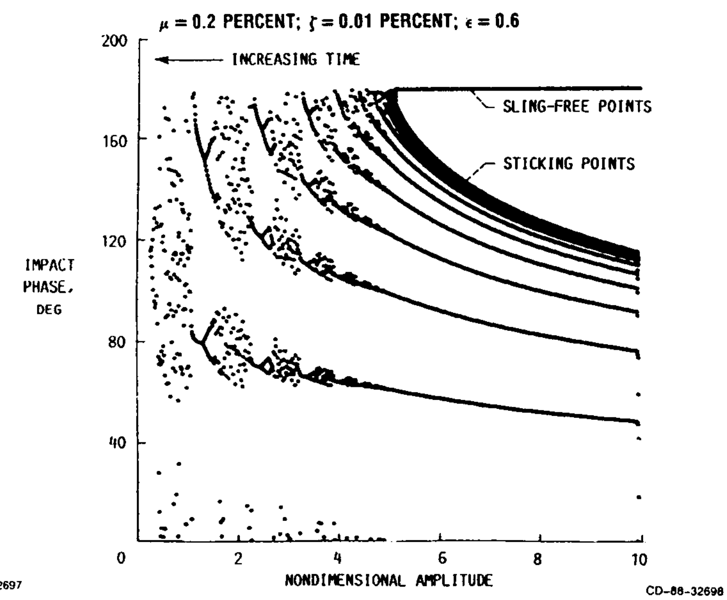
IMPACT PHASE, JUMP PHENOMENA, AND CHAOS

The figure at the upper left shows, for a very slow decay, exactly when impact occurs during each half cycle as a function of amplitude. At some amplitudes the impacts appear to be random; at others they are so regular that the circles representing their impact times merge to produce smooth continuous lines in the plot. In several places such a line splits into two (moving in the direction of increasing amplitude), and a period doubling occurs, suggesting that the random-looking regions are chaotic. A comparison of the upper right and lower left figures, in which the same amplitude range is traversed very slowly in opposite directions, reveals a type of jump phenomenon. The lower right figure shows impact phase angle for an impactor of useful mass over a large amplitude range which includes the infinite-bounce region.









CONCLUSIONS

Designed to operate near the most favorable amplitude, the impact damper provides very substantial damping per unit mass. An impactor with 2 percent of the mass of the oscillator can provide a loss factor of nearly 10 percent, a very high level for aerospace systems.

The free decay study provides a comprehensive picture of the extremely varied behavior exhibited by the impact damper. This behavior ranges from periodic motion to period doubling, jump phenomena, and chaos.

The damping provided is approximately predictable, since the free decay study has shown that the loss factor is proportional to the impactor mass fraction and to $1 - \varepsilon$ (where ε is the coefficient of restitution), and is roughly inversely proportional to the nondimensional amplitude.

CONCLUSIONS

- EXCELLENT DAMPING PER UNIT MASS
- FREE DECAY PROVIDES COMPREHENSIVE PICTURE
- DAMPING IS PROPORTIONAL TO
  - IMPACTOR MASS
  - $1 - \epsilon$
  - 1/AMPLITUDE
- SYSTEM EXHIBITS
  - PERIODIC BEHAVIOR
  - PERIOD DOUBLING
  - JUMP PHENOMENA
  - CHAOS

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