A PARAMETRIC STUDY OF AIRCRAFT LANDING-IMPACT, WITH EMPHASIS ON NOSE GEAR LANDING CONDITIONS

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Abstract

A parametric approach to simulation of landing impact, with pitching and heaving degrees of freedom of the aircraft motion, has been used to determine the response of the main and nose gears. Compared to each gear's independent behavior, there are important differences in the landing conditions and in the resulting vertical loads and displacements when these aircraft motions are included. For main gears, the maximum vertical loads are almost linearly dependent on the sinking speed but there is some variation in the proportion of kinetic energy absorbed. For nose gears no similarity validity exists with single gear results. Correlation with aircraft sinking speed is absent and the response is sensitive to the values of initial pitch angle and pitch inertia. This is due to the equivalent mass at this location being greatly affected by these input quantities and by the aircraft scale.

1 Introduction

In a general sense, the analytical solution for aircraft landing-impacts has received very poor attention, within the broad range of its dynamic behavior. One reason for this neglect is that during the more common tail-down landings, all of the weight is first carried on the main gears. When determining the most critical landing conditions and loads on these gears, a simplification is often made. It is reasonably but inaccurately assumed that there is no need to include the pitching motion of the aircraft and the response of the nose gear. This attitude also prevails within the Civil Airworthiness Regulations [1], which call for main gear simulation and dynamic testing without considering the response of the rest of the aircraft. Only it's mass and the external landing conditions are required as input. The use of aircraft elasticity effects (which are mostly beneficial to reducing the loading) has only recently been allowed into the simulations for determining the main gear design loads, according to the latest version of the requirements in [1]. Pitching (free-body) motion also confers the same kind of benefit, but it is not prescribed nor are its effects usually included.

For the nose gear landing impacts the situation is not taken very seriously either. On most aircraft only about 10% of their total aircraft weight is carried there. These gears are still regarded as "ancillary" in the regulations - an inheritance from the days of the tailskid. The landing conditions that are taken as applicable to nose gears are modifications of those used on main gears, with the same sinking speeds and an equivalent mass that is a function of longitudinal deceleration and center of gravity height. These assumptions and methods of finding the landing impact conditions at the nose are inappropriate. Particularly the formula used for determining the equivalent mass is unrealistic, and (as seen in [2] for example) the effect of this mass on the loads was not properly understood.

Particularly for use in the fatigue loads-spectrum is it necessary to take the average conditions and to use factual values of loads, based on experience. Consequently the design criteria that are specified in [1] (after a suitable adjustment to more typical sinking speeds), can scarcely be considered as a suitable means for determining the actual landing conditions. Nor are they satisfactory for finding the resulting loads that are felt by an aircraft that is being tested or is in use. A complete simulation of the aircraft motion is the means needed to overcome these inaccuracies.

However not all aircraft and their gears behave in the same way, and the large range of possibilities in size, weight and motion complicates the situation. To understand the implications of what different aircraft provide in the way of landing gears and what these gears do to the aircraft, their landing characteristics must be examined parametrically.

2 Description of Parameters

The British system of physical units will be used throughout this work. Lengths are taken in feet (ft.), masses are provided in slugs and time passes in seconds (sec.). The mass unit of one slug is preferred, because it causes a force of one pound (lbf.) to be felt when the associated acceleration is one ft./sec./sec. The acceleration of gravity used here is **g** = 32.2 ft./sec./sec. with the result that one slug weighs 32.2 lbf., when this state of equilibrium is reached on the earth's surface.

2.1 Choice of The Base-Line Aircraft and Its Landing Condition

In this parametric study it is first assumed that all the aircraft under consideration have their landing gears arranged in a nose-wheel (or tricycle) layout with their main gears located behind the center of gravity. As this is the most common configuration, it is the behavior of the aircraft having this kind of gear array that is of interest. Even though not all aircraft necessarily adhere to the formal tricycle layout, the results of this motion study may still be applicable.

The performance of the aircraft in pitch and heave, together with the influence of its sinking (and forward) speeds, is to be examined. Consequently the kinds of data used here are related to these directions only. The following aircraft properties are taken as input data to the simulation program. Their number has been restricted, with the aim of only using those that are absolutely necessary.

Mass Properties

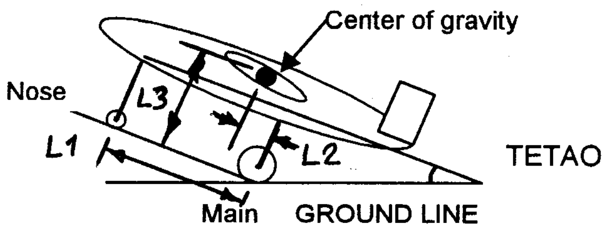
The size of the starting configuration is chosen as a geometric mean between the smallest and largest sizes of aircraft being covered by the study. The range in sizes lies between landing weights of aircraft of almost the ultra-light size of 1,610 lbf. (50 slugs) and of the "jumbo-jet" size of 644,000 lbf. (20,000 slugs). Hence the base-line mass works out to be **W** = 1,000 slugs (which corresponds to an aircraft weight of 32,200 lbf.). Thus the smallest aircraft being considered is 1/20 of the base-line mass and the greatest is 20 times this value.

The other mass dependent property of importance is the moment of inertia in pitch about the center of gravity. This quantity depends on the proportion of fuel being carried, mostly at or near the center of gravity, compared to the payload, which is usually centered slightly ahead of this position and spread along the length of the fuselage. A pitching moment of inertia **I** = 144 K.slug ft. is typical for a passenger-carrying aircraft of the base-line size. In this case it is due to a radius of gyration of the mass of **k** = 12 ft. (which is slightly less than half of the distance between the nose gear and the center of gravity, see below).

Geometric Properties

For such an aircraft it is assumed, that the fore/aft distance between the main and nose gears is **L1** = 30 ft., with the center of gravity located at 10% of this spacing, or **L2** = 3 ft. ahead of the main gear. For purposes of ease of analysis, the legs of the gears are arranged to be at right angles to the horizontal reference line of the aircraft which itself is parallel to the ground, when the gears are fully extended. Such an aircraft is assumed to have its center of gravity at a height **L3** = 7.5 ft. from the ground-line in this condition. The significant geometric properties are shown in Figure 1. No side-ways dimensions are included, since we are concerned only with variations in the longitudinal/ vertical plane of symmetry.

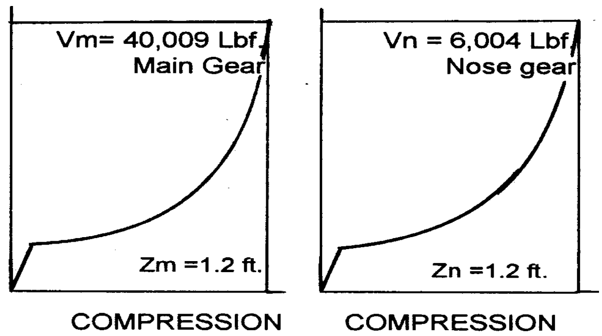
FIGURE 1 AIRCRAFT AND GEAR GEOMETRY



Vertical Load/Deflection and Damping Characteristics of the Gears

The deflections of the shock absorbers and tires are taken as acting together as a combined system. For the base-line aircraft, the total compressions of these two components on both main and nose landing gears is **z** = 1.2 ft. at the ultimate condition of full closure. Since the greatest vertical forces here are due to the "Reserve Energy" test case of impact, the associated decelerations (for an assumed 75% efficient compression of the combined systems) can be shown to be **delt nz** = 2.485 gs. Then the vertical force on each of the two main gears, assuming that on impact they take all of the vertical kinetic energy, is **Vm** maximum = 40,009 lbf., see Figure 2. Consequently the linearized "end-points" stiffness of the main gear is **Km** = 40,009/1.2 = 33,341 lbf./ft.

FIGURE 2 SHOCK ABSORBER COMPRESSION CURVES



For the nose gear it might be assumed that the loading conditions are directly proportional to those at the main gear when the "static" mass is taken.

However, in practice nose gears are made considerably stiffer than this. The reason for this will be discussed later when the associated landing conditions are better understood. Meanwhile it is tentatively assumed that the maximum vertical force that this gear is designed to carry is 40% of that taken by one of the two main gears and not 1/4.5 or 22.2% of the main gear values, which otherwise would be the case without this changed assumption. Then for the same motion and deceleration, the vertical force at the nose gear is **Vn** max = 6,004 lbf. see Figure 2, and the associated end-points stiffness is **Kn** = 13,337 lbf./ft.

These stiffnesses are not in proportion to the static loads on the respective gears and consequently when standing with its weight on the ground, the nose gear shock absorber is the more extended one. By shortening the length of the rest of this gear it can easily be arranged for the aircraft to be at a level attitude on the ground for a particular weight and center of gravity position. The actual load/displacement curves for the shock absorbers and tires on the main and nose gears, will be assumed to have the same geometric form, that is in accordance with the gas compression laws of these two kind of compressing elements.

During landing impact the shock absorbers will also develop internal hydraulic damping forces. These forces are assumed to be produced by fixed size orifices, the pressure change across each being proportional to the square of the velocity of compression. No allowance for variable sized metering pins is made, for our purposes this is a less significant effect. The hydraulic damping coefficients are chosen at the design conditions, where the maximum closure rate of 10ft./sec. causes the same magnitude of hydraulic force (oil peak) as the subsequent maximum gas compression force. This is developed close to the end of the stroke (see above), when the closure velocity is zero. Consequently the hydraulic damping coefficient of the main gears work out to be **Fhm** = 400 lbf./(ft./sec.)^2. and for the nose gear this coefficient is **Fhn** = 160 lbf./(ft./sec.)^2.

During the return stroke, the positive recoil orifices that are fitted to the shock absorbers are assumed to develop forces that are four times these values. This is regarded as a reasonable approximation to the design situations that occur in practice.

Aerodynamics

The design value of the tail-down angle of pitch **TETA** is usually made to correspond to the condition where the rear fuselage just scrapes the ground at the fully extended position of the main gears. For aircraft with relatively short fuselages, this angle is made to correspond with the stalling angle, see Ref.1. However in practice when aircraft land, the tail-down pitch angle is not as high as the design value and actually most aircraft are pitched to an angle **TETA** of about 5 degrees at the instant of touch-down (in [3], for example). The base-line aircraft initial value of **TETAO** = 5.5 degrees, is assumed here.

The aerodynamic properties of the aircraft in lift result in this force almost being equal to the weight. This quantity is not made exactly equal to it because during the landing sequence the pilot wants to avoid "floating" just above the runway, for an extended distance. Consequently in practice he deliberately chooses a lift/weight ratio **L/W** that is slightly less than one. A value of **L/W** = 0.90 is assumed here. As the landing proceeds the pitch angle changes and associated with this so does the lift on the wing. It is assumed that the variation with pitch is linear and the value of the derivative **d(L/W)/dTETA** = 0.10 per degree. There are no other kinds of aerodynamic forces used in this analysis. The balance in pitch is caused by the turning moments from the tail-plane and elevator forces, being in opposition to the moments from the lift at the aerodynamic center. This balance is assumed to be maintained as the motion proceeds. This simplification is not far from what actually occurs during a landing, when the dominant effect of the vertical reaction on the main gears (together with the reduced forward speed), result in the nose of the aircraft tending to pitch down.

The associated horizontal ground speed on touch-down depends on the head-wind as well as the size of the lifting surfaces and flaps. For the base-line aircraft a ground-speed of 120 knots or **Vfs** = 176 ft./sec. is assumed as a likely value. The average sinking-speed during landing is less than **Vss** = 3 ft./sec. for many aircraft, see [3]. This should be compared with the usual design value for a once in a life-time occurrence operation of **Vss** = 10 ft./sec. according to the design regulations in [1]. A range of values of this quantity will be used.

Kinematics of Flight

The pilot performs a flare manouver or round-out from the final approach flight path (which by international agreement is nominally equal to 3 degrees). He then lands with a small but positive sinking-speed after the start of the runway. However this finite sinking-speed causes the total aerodynamic angle of attack to exceed, by a small amount, the nominal value of **TETA** = 5.5 degrees of pitch up angle of the nose. For an assumed average sinking-speed **Vss** = 2.5 ft./sec., this influence on the angle of attack is equal to **PHI** = arc sin (2.5/176) = 0.816 degrees. Hence the actual angle of attack in our case would be 6.316 degrees. Even when the sinking-speed is much greater, the angle of attack will not differ from this value. This is because the lift/weight ratio is held close to unity and the lift depends primarily on the forward speed. The pilot maintains this speed at a value that slightly exceeds that of the stall. Consequently it is the pitch angle that is varied at high sink rates. In the case of the sinking-speed **Vss** = 10 ft./sec., the increment in angle from this flight-path kinematic feature is 2.44 degrees and hence the value of **TETA** = 5.5 - 2.44 = 3.06 degrees. This reduction of pitch angle during landing at high rates of sink, helps to explain how nose gear landing impacts sometimes precede the main gear ones, with disastrous results in certain cases, see [4].

3 The Simulation Procedure

3.1 Description of Computer Program

The basic principle used in this procedure is the integration of the equations of motion in heave and pitch. The simulation of the motion commences at the point of tire touch-down. The initial conditions of the variables are set to represent this stable point on the flight-path. The integration then proceeds, being performed according to the pre-determined motion of the aircraft and its variable geometric and mechanical constraints. These forces depend on the displacements of the main and nose landing gears and also on the lift characteristic. The forces and turning moments that result are used together with the mass properties to obtain the current vertical and angular accelerations. On integration these provide the succeeding velocities and displacements for the next cycle of calculation.

The program starts by reading the input data, most of which has been described above. After the sizes of the tables have been specified, the shock absorber and tire compression characteristics are input in their tabular forms. In addition, some zero values of the initial conditions of motion are read. Also input is the anticipated duration of the simulation, together with the increment of time to be used for each calculation step. The program echo-prints all of these data. It subsequently prints the titles for the output results. Before the iteration loop is started, certain quantities are fixed for subsequent use.

After entering the loop, the first set of printed output results at **time** = 0, does little more than confirm that the initial conditions have been correctly set. For the cycle that follows, the initial compressions are found from the sinking-speed multiplied by the time increment. These displacements are introduced into a sub-routine for interpolating from the look-up tables, to obtain the values of the compression forces. These forces and their associated moments then are applied using Newton's Second Law of Motion to determine the accelerations in heave and pitch. Integration of these values provides the velocities and displacements that are needed for use during the subsequent iteration. As the calculation proceeds, changes are made to the geometry of the positions of the landing gear forces. This and other motion-dependent effects are included in the later cycles. Each cycle after the first, starts by printing out a set of results gathered from the previous set of calculations.

In the usual case of a tail-down landing, the results of this analysis show the manner of development of the vertical forces at the main gears together with their displacements and motions. Subsequently the nose-down pitching causes the nose gear to strike the ground and the vertical and pitching motions to eventually reverse their directions. Should the full stroke of the shock absorbers and tires be exceeded, the gear "bottoms" and the simulation stops prematurely, after supplying an appropriate comment.

By the use a number of simulations having progressively smaller time intervals, it is possible to determine the interval below which no significant improvement in the accuracy of the results may be obtained. This procedure was used for all of the work to follow.

3.2 Results of the Simulation - Description of the Landing Process

The results of a typical simulation contain the following stages in the symmetric landing motion.

a) At the initial landing condition, lift almost equals weight, but there is a finite sink rate. The aircraft is balanced in pitch without angular motion. The pitch angle is small and positive, causing a component of sinking speed along the gears' compression axes to slightly exceed that of the aircraft. The wing angle of attack is greater than the pitch angle by a small amount, that is proportional to the ratio of sinking and forward speeds.
b) On impact the main gears start to compress. The vertical loads on them grow, and cause the aircraft to pitch nose down (i.e. at a negative rate). The decreasing angle of pitch has the effect of reducing the aerodynamic generated lift/weight ratio. Kinetic energy from the mass and sinking speed is absorbed within the main shock absorbers together with some potential energy, due to the subsequent loss of balance between lift and weight.
c) The vertical loads on the main gears first reach peak values, due to the maximum velocity of the shock absorber closures,

causing their internal hydraulic damping forces to dominate. With the subsequent reduction of this speed but continued closure, it is the turn of the gas compression characteristics to cause a second peak to occur in the time-history of the shock absorbers' vertical forces. At this moment the vertical motion is arrested. The peak in loading is simultaneously felt at the axles and on the ground.

d) The motion of the main shock absorbers then reverse. Due to the internal friction, a step reduction occurs in the time-history of the axial forces. These continue to reduce with time as this motion proceeds. The aircraft does not normally bounce back into the air - sufficiently large recoil damping having been provided by secondary hydraulic orifices.

e) After a delay that depends on the initial conditions, the negative rate of pitching motion causes the nose gear to strike the ground. (It is assumed that there is no change in the aerodynamic pitching moments due to the pilot's control or other ground-related influences.) The pitch angle of the aircraft at this instant is close to zero. It may even be negative, because the main gears can have already started to extend. The nose gear impact combines the momentum of the vertical motion (not fully absorbed at the main gears), with rotation. This angular motion is due to the inertial response of the aircraft to the pitching moment supplied from the main gears' reactions. After the nose gear has landed, this energy in aircraft pitch motion is transferred into the nose gear shock absorber and the aircraft's negative pitching motion is arrested and eventually reversed.

f) The nose gear experiences the same kinds of internal load time-history as the main gears, with the hydraulic and gas load peaks being developed in turn. Depending on the conditions on nose gear landing, a clear separation between these peaks does not necessarily occur.

g) When the momentum is transferred to the nose, there are reduced reactions on the main gears. However after the pitching rate is reversed, these loads increase again. Although it is not provided in this numerical analysis, a second cycle of heaving and pitching motion results, with associated increases in the wing lift too. Compared to the first cycle, the size of these motions and the changes in the forces are diminished.

h) The braking forces and aerodynamic drag help to reduce the horizontal speed of the aircraft. Eventually the reactions on all the gears reach their static values without lift, after all the energy of the motion has dissipated.

4 The Numerical Simulations

4.1 Choice of Input Parameters

The effects of variation of the various physical quantities are explored here. Our process of investigation is now applied to the following kinds of input parameters.

1 Initial Pitch Angle (tail-down angle) **TETAO**

2 Aircraft Sinking-Speed on Impact **Vss**

3 Aircraft Radius of Gyration in Pitch About the Center of Gravity **k = SQR(I/W)**

4 Relative Scale or Size of Aircraft (Compared to Base-Line Aircraft) **W**

The first 3 kinds of these parameters are relatively straight forward and their variation is considered to apply independently. However in the case of the last parameter, aircraft relative scale, a number of these different input quantities change in combination with the mass **W**, which is regarded here as the basic measure of the scale of the aircraft.

The geometries of the aircraft and of its landing gears are related to the relative scale. This term is expressed through the relative mass compared to that of the base-line aircraft. The geometric changes are according to:

a) Horizontal lengths along the fuselage, which affect the spacing between nose and main landing gears **L1** , the position of the center of gravity **L2** from the main gear and the pitching inertia expressed by the radius of gyration **k** . These three quantities are assumed to vary according to the cube root of the aircraft mass **W** (assumption of constant density).

b) Vertical height of the center of gravity **L3** - varies according to the sixth root of the mass, and not by the above rule. This variation in the height of the center of gravity is less than in the case of the horizontal distances. This result is found to be closer to how actual aircraft are designed.

c) The same variation with mass applies to the horizontal landing speed **Vss**. According to the classic theory the quantity should obey the famous "squared-cubed" rule, but in practice the wing-loading of the smaller aircraft is lower, the degree of refinement for high lift coefficients also becomes less and this is the overall result.

d) The strokes of the shock absorbers and the compressions of the tires **z** - vary according to the mass raised to the power of 1/5 .

This quantity is related to the energy absorbed by the landing gears during the landing impact, which itself depends directly on the mass, without any allowance for changes to the design sinking speed. Consequently the magnitude of the forces in the shock absorbers will vary according to the mass when raised to the power of 4/5 . This ensures that the various shock absorbers being considered are comparable as energy absorbing elements. This "stroke criterion" of mass raised to the power of 1/5 has been deliberately introduced here, so that for the 20 times greater scale aircraft, the length of the stroke corresponds to that found on the "Jumbo-Jets" of about 2.2 ft. Then for the base-line aircraft scale, the stroke is 1.2 ft. and for the lightest-aircraft scale that is 1/20 of the basic size, the stroke of about 0.66 ft. is used. All three values of these strokes are quite typical of design practice and the associated maximum compression loads also correspond.

4.2 Description of Results of the Simulations

A number of aircraft landing simulations were run on the computer and the resulting outputs were obtained in the form of time-histories. This output included the gear displacements, velocities and accelerations, together with the associated forces and absorbed energies. In terms of the design conditions and criteria, previous experience in working with the outputs has shown that there are three points in the time-history which are of importance. These are at the maximum gas compression force in the main gear, at the instant of nose gear touch-down and at its maximum gas compression force.

In order to appreciate these output data in parametric terms, the summarized results are presented graphically in Figures 3 to 6 and a description of their main features is given below.

4.2.1 Effect of Variation of Initial Pitch Angle (Tail-Down Angle) TETAO

This variation is shown in Figure 3. This variable has a large influence on the results. The first graph shows that the time taken for the nose gear to reach the ground is linearly proportional to the initial value of **TETAO**. Although the maximum vertical forces on the main gear are scarcely affected, there is a large variation in the subsequent pitching motion and in the force when the nose gear first touches-down and later when it reaches its maximum value. At **Vm** maximum the variation of lift/weight ratio **L/W** with initial angle of pitch is virtually nil, but later when the nose gear is involved, this ratio varies linearly in the opposite direction, with the greatest values present when the initial angle is small. At the time when the nose gear reaches its maximum load, the main gear takes progressively larger amounts of the total energy for smaller values of **TETAO**. However there is a maximum amount absorbed in these gears at the instant of nose gear first touch-down for an intermediate value of this angle. The energy in one leg sometimes exceeds half of the total kinetic energy at the initial impact of **EmO/2** = 25,000 ft.lbf. on the base-line aircraft, due to the potential energy from the height of the center of gravity at initial touchdown.

The slam-down vertical force on the nose gear from large pitch angles is smaller than the maximum loads it experiences from level landings. However the velocity of this landing (which is about 90% of the main gear design

FIGURE 3 a) EFFECT OF INITIAL PITCH ANGLE ON MOTION, FORCES AND ENERGY ABSORPTION ON MAIN LANDING GEARS at instants of time:

Vm maximum •—• Vn touch-down x—x and Vn maximum ⊖—⊖

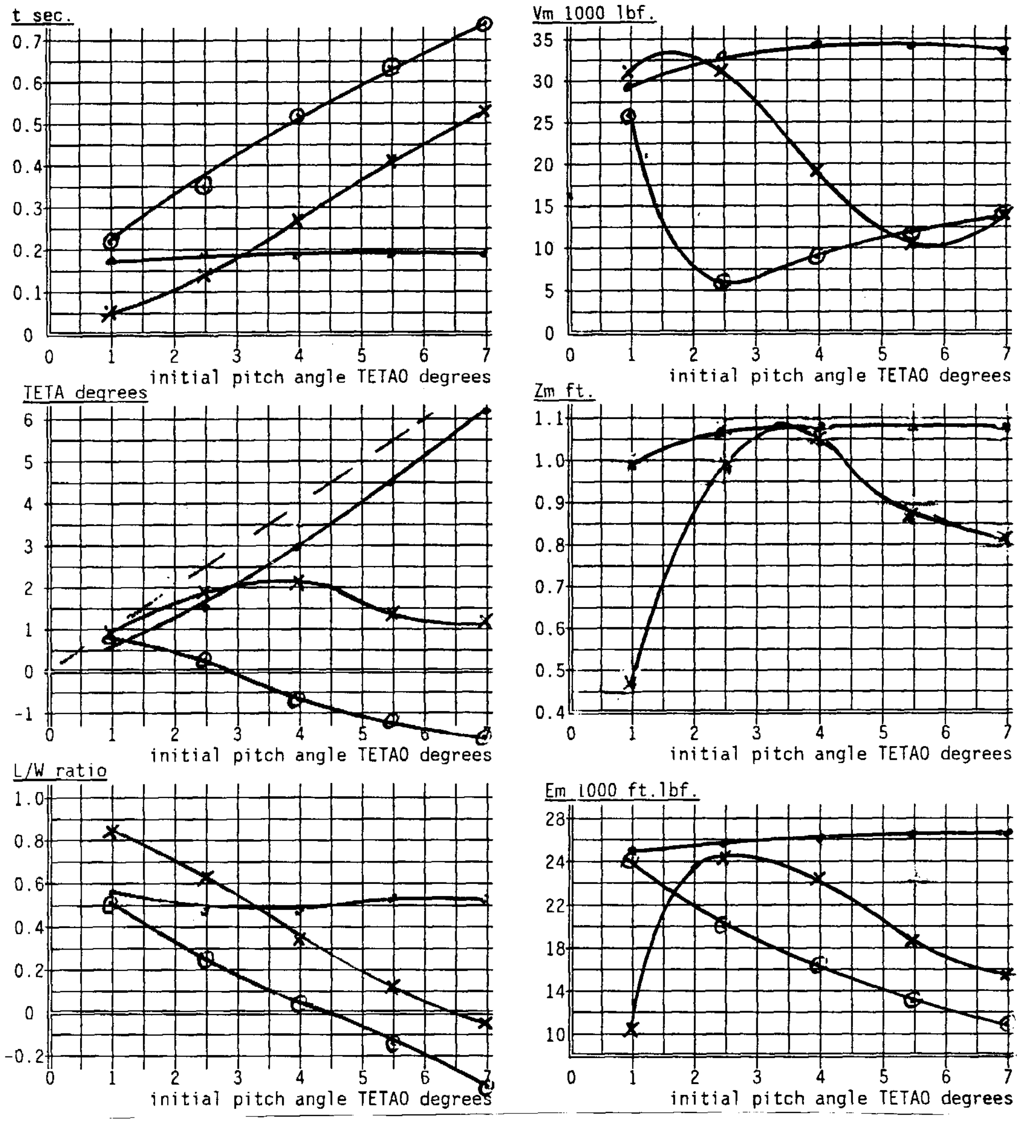


FIGURE 3 b) EFFECT OF INITIAL PITCH ANGLE ON MOTION, FORCES AND ENERGY ABSORPTION ON NOSE LANDING GEARS at instants of time:

Touch-Down •—• Vn Maximum Force x—x Maximum Compression ⊖—⊖ Energy Absorbed ⊠—⊠

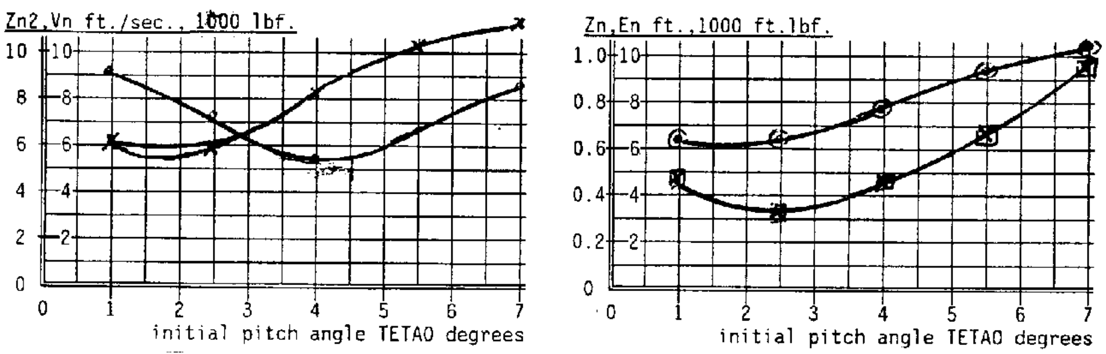


FIGURE 4 a) EFFECT OF SINKING SPEED ON MOTION, FORCES AND ENERGY ABSORPTION ON MAIN LANDING GEARS at instants of time:

Vm maximum •——• Vn touch-down x——x and Vn maximum ⊙——⊙

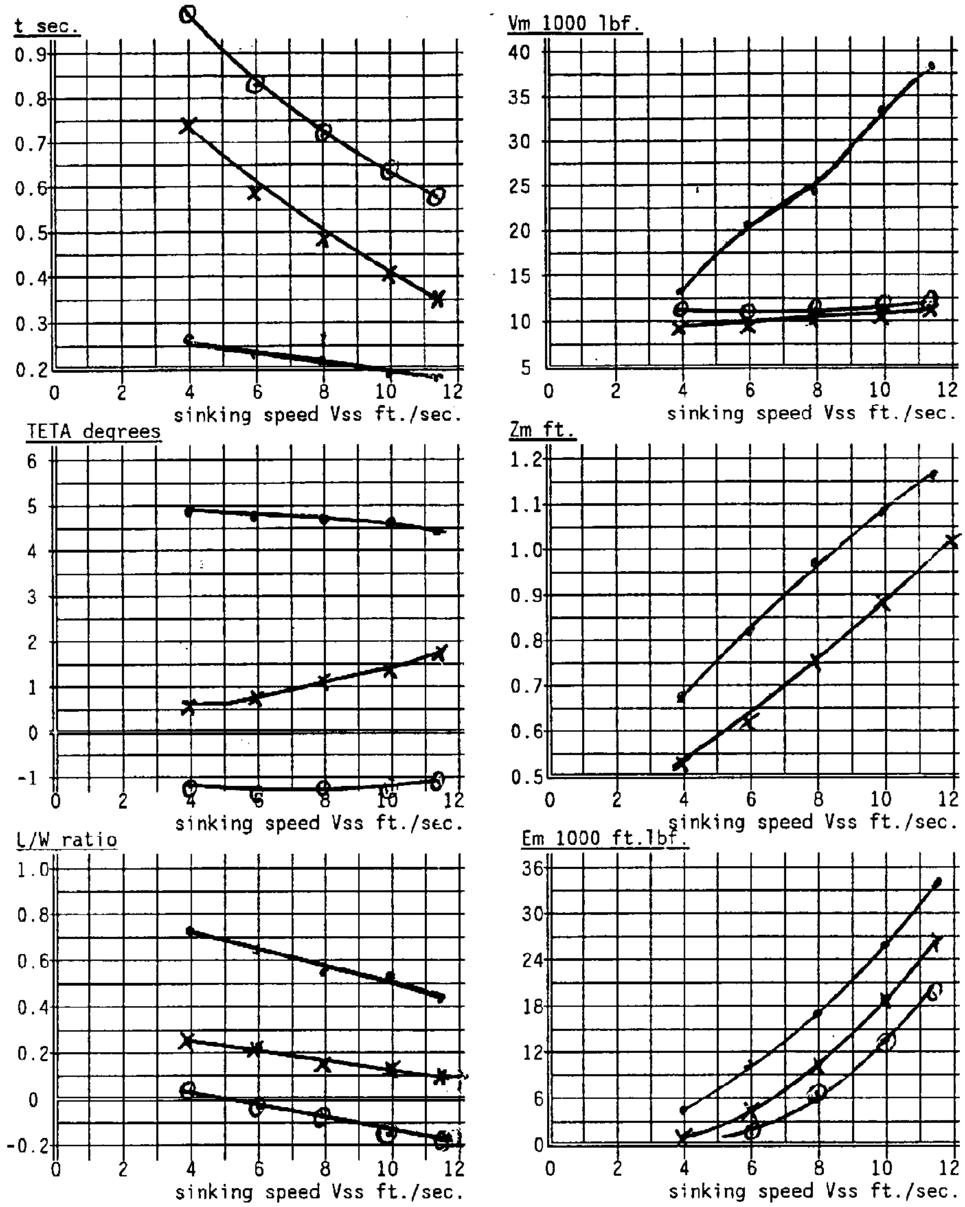
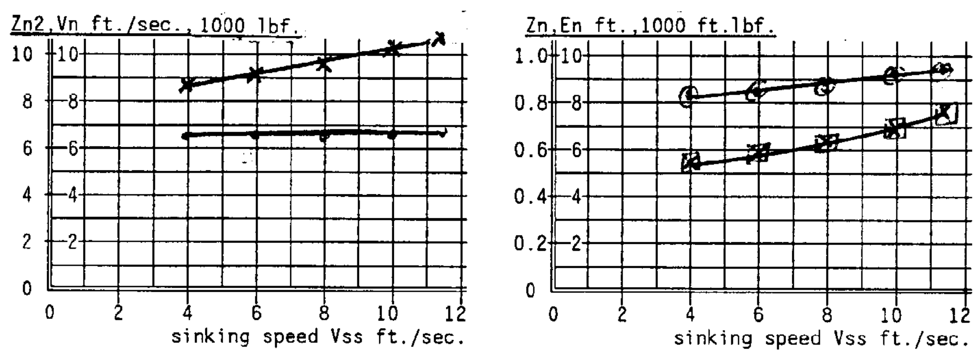


FIGURE 4 b) EFFECT OF SINKING SPEED ON MOTION, FORCES AND ENERGY ABSORPTION ON NOSE LANDING GEARS at instants of time:

Touch-Down •——• Vn Maximum Force x——x Maximum Compression ⊙——⊙ Energy Absorbed ⊠——⊠



value) is the same at the extreme angles of pitch, with a minimum intermediate value that is considerably less. As noted above, for the main gear this corresponds to a maximum energy absorption peak. On the nose gear, the energy absorbed from the slam down manuver and the associated maximum vertical forces are greater than for level landing, and the situations due to this operation should not be easily dismissed.

4.2.2. Effect of Variation of Sinking Speed Vss

This is shown in Figure 4. Unlike the previous kind of variations, here there is a continuous change in the output results without any intermediate maximum values being developed, a result that is expected. Of particular interest is the almost linear variation of the maximum vertical load on the main gears with sinking speed. Whilst the force coefficients and the compression curve are both non-linear, the manner by which they absorb the energy results in the above linear effect. The other surprise here is that on the nose gear there is almost no variation with the initial sinking speed of the aircraft, and only a small change in its associated absorbed energy. For the particular set of input data used here the initial velocity of nose gear touch down is almost constant at about 6.8 ft./sec. The only explanation for this lack of sensitivity is due to the moderating effect of the initial pitch angle, which is equal to the 5.5 degrees standard condition and the associated aircraft pitching motions. Due to the main gear influence, the energy transfer does result in somewhat reduced loads at the lower sinking speeds, but the effect is relatively small.

4.2.3 Effect of Variation of Moment of Inertia in Pitch I

This is shown in Figure 5. The variable used is actually the radius of gyration which is related to the pitching moment of inertia by **k = SQR(I/W)** .

It is no surprise in the first graph to find that the aircraft responds more rapidly when the pitching inertia is relatively small. But what is of great interest is that the vertical forces are almost unchanged at the times when the nose gear touches and develops its maximum values. Although the timing is affected, the positions at which the similar loads are felt are scarcely altered. With the exception of main gear compression at nose gear touch down, this lack of variation is generally true on this aircraft and landing gear combination.

For the nose gear however, the effect of reduced pitching inertia increases the speed of its initial touch down but reduces the associated force. This result is not so easy to understand, in view of the occurrence of greater sinking speeds with the low values of pitching inertia. The energy absorbed there does have a local minimum within the range of radius of gyration that was considered, but the effect is relatively small and it appears that the associated aircraft motion combines with the inertia effect to reduce its overall influence at the nose.

4.2.4. Effect of Variation of Aircraft Size W

The measure for scale is taken here as the mass compared to that of the base-line aircraft. As explained above there are a number of input quantities that must be varied together, to cover the changes due to this parametric variable. Unlike the previous sets of results, where the output was expressed directly in the resulting physical units, it is convenient here to normalize these values with a factor that converts them to the scale of the base-line aircraft. For the input parameters, these conversions are described in Section 4.1, and for the output quantities they are applied as follows. The linear dimensions are taken to the fifth root of the scale and the forces are taken to the 4/5 root of the scale, with the energies then in direct proportion to it. In Figure 6, the particular parameter has been written with an apostrophe sign (') to indicate these adjustments. The results are described below.

The effect on the timing is non-linear and as expected the smaller aircraft have the fastest responses. The maximum loads on the main gears appear to closely follow the above scaling laws, but at the times when the nose gear is being included it is apparent that the smaller scale of aircraft have an advantage in their loads being of a smaller proportion. The pitch angle response is almost unaffected by scale except at the instant of nose-gear touch down when the smaller aircraft have greater angles. However their lift/weight ratios become progressively smaller with reduced scale, due to a greater overall angular response.

Of interest is the local minimum in main gear shock-absorber compression at about the base-line aircraft, but as far as energy absorption is concerned there is a greater proportion taken in the main gears when the scale is reduced.

For the nose gear, there appears to be a continuous and useful reduction in sinking speed with diminishing scale, but until it has reduced by more than 1/8th. of the base-line, the relative forces on this gear do not usefully decrease to any greater advantage, an effect which only applies to the results at smallest scale that was taken. Both the scaled values of compression of these gears and their relative energy absorption requirements are advantageous, as the size reduces. The implication of all this is that for the large scale of aircraft, the effects on the nose gears become especially significant and it is here that the effects of the combined motion should be taken most seriously.

4.2.5 The Equivalent Mass At The Nose Gear

As was previously seen in the analysis by Chester [5] and in flight-testing by Chester and Brot [6], the explanation for the relatively large and apparently out of proportion forces on the nose gear is due to its equivalent mass. This artificial quantity is considerably greater than the "static mass" at the nose due to the contribution to it of the effects of the pitching moment of inertia. It is of interest to examine how the ratio of equivalent to static mass varies with the variation of the other parameters used above. These results are shown in Figure 7, where it is seen that the value of the equivalent mass is sensitive to the initial pitch angle and the radius of gyration in pitching. It is less affected by the aircraft scale and almost independent of the value of the sinking speed.

5 Summary/Conclusions

A parametric approach to simulation of landing impact with two degrees of freedom of the aircraft motion (in pitch and heave), has been used to determine the response of the main and nose gears. The results are for comparison to the dynamic behavior of each gear when it is treated as operating independently, as is commonly assumed.

It was found that there are differences in the landing conditions and in the resulting vertical loads and displacements of the gears when the aircraft motion is included. For main gears, the maximum vertical loads are almost linearly dependent on the sinking speed, but the energy absorbed sometimes exceeds the initial kinetic energy due to potential energy effects. Except for energy transfer to the nose, which subsequently tends to reduce the load, the main gear response may be reasonably predicted by single gear analysis.

However for nose gears there is no validity with the single gear results. In particular it was found that there is no correlation with aircraft sinking speed. However the response of nose gears is very sensitive to the values of initial pitch angle and pitching inertia. This is partly due to the equivalent mass at the nose being greatly affected by these input quantities and by the aircraft scale. Level landings are uncommon occurrences and design criteria based on them are insufficient to cover the most severe situations encountered on nose gears.

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FIGURE 5 a) EFFECT OF PITCHING MOMENT OF INERTIA ON MOTION, FORCES AND ENERGY ABSORPTION ON MAIN LANDING GEARS at instants of time:

Vm maximum Vn touch-down x——x and Vn maximum

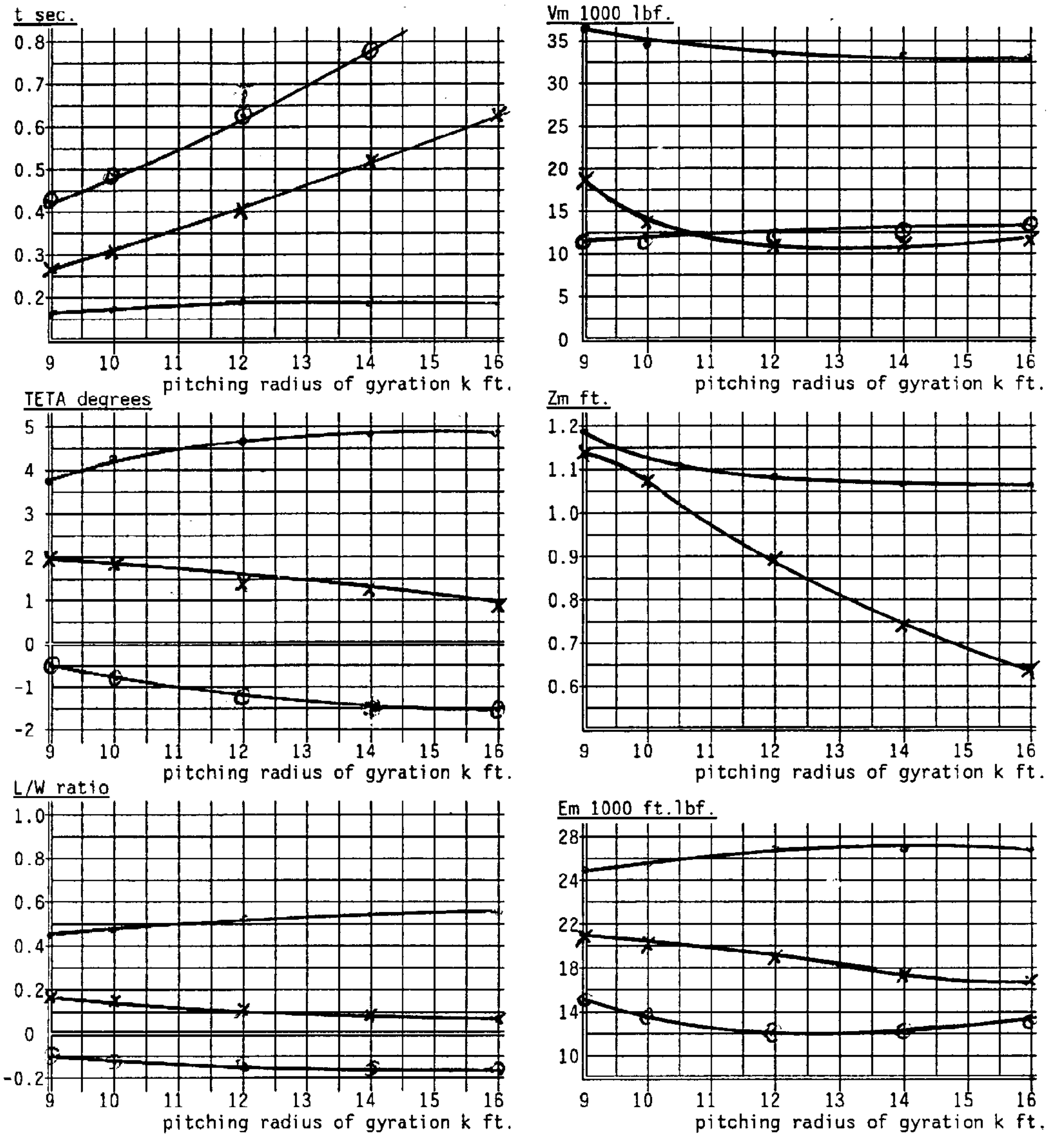

FIGURE 5 b) EFFECT OF PITCHING MOMENT OF INERTIA ON MOTION, FORCES AND ENERGY ABSORPTION ON NOSE LANDING GEARS at instants of time:

Touch-Down Vn Maximum Force x——x Maximum Compression Energy Absorbed

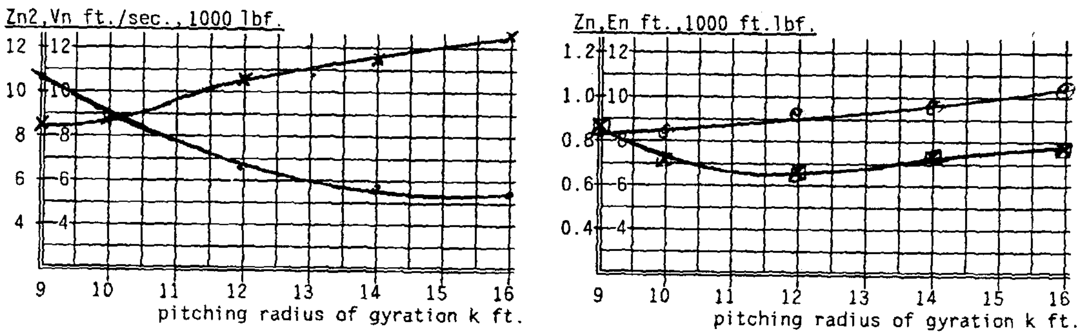

FIGURE 6 a) EFFECT OF AIRCRAFT SCALE ON MOTION, FORCES AND ENERGY ABSORPTION ON MAIN LANDING GEARS at instants of time:

Vm maximum •—• Vn touch-down x—x and Vn maximum ⊙—⊙

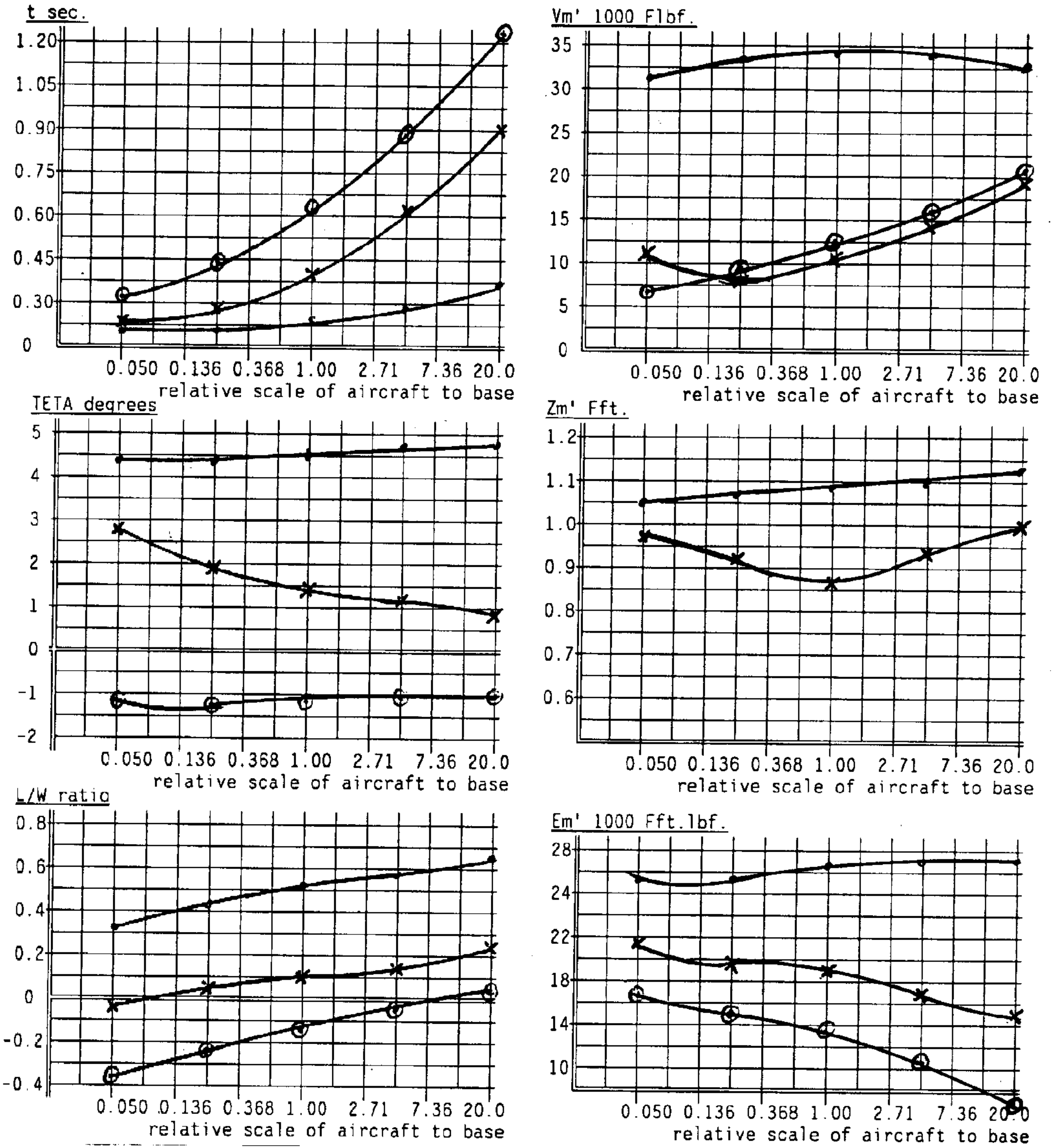

FIGURE 6 b) EFFECT OF AIRCRAFT SCALE ON MOTION, FORCES AND ENERGY ABSORPTION ON NOSE LANDING GEARS at instants of time:

Touch-Down •—• Vn Maximum Force x—x Maximum Compression ⊙—⊙ Energy Absorbed ⊠—⊠

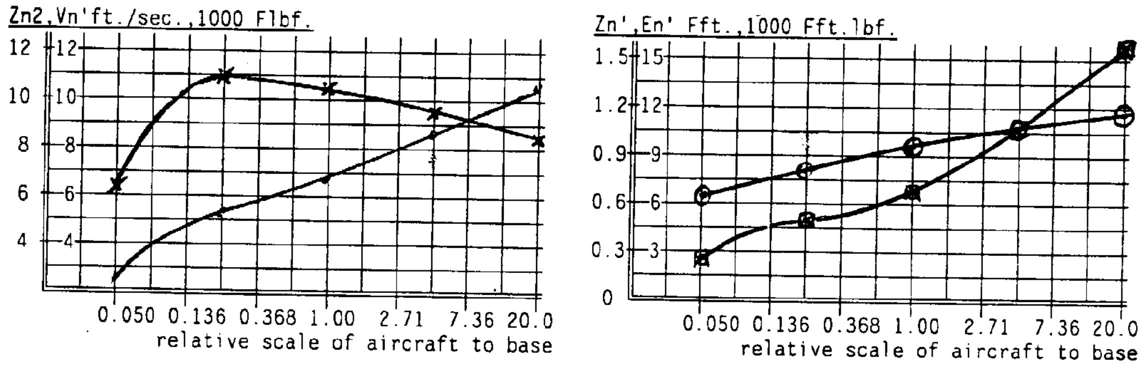

FIGURE 7 INFLUENCE ON THE RATIO OF EQUIVALENT/STATIC MASS WITH
a) **TETAO** b) **Vss** c) **k** AND d) aircraft scale