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BAND-PASS SHOCK AND VIBRATION ABSORBERS FOR APPLICATION TO AIRCRAFT LANDING GEAR

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SUMMARY

A new class of frequency-selective shock absorbers called band-pass shock absorbers which were conceived as a means of overcoming some of the limitations of conventional shock absorbers is described. These shock absorber designs are introduced, special emphasis being given to their use in landing and taxiing problems of high-speed aircraft. For such aircraft operated on rough land or water runways, conventional oleo struts approach a rigid condition for bumps with steep slopes and thereby develop and transmit severe shock loads to the aircraft fuselage. The operation of the band-pass shock absorbers in the reduction of loads in certain selected frequency ranges is described. Theoretical equations are derived and solutions are made for several cases for the purpose of comparing the low-pass and conventional shock-absorber actions. The results indicate that the band-pass shock absorbers should alleviate high-frequency or rapidly applied impact loads but should retain the characteristics of conventional oleo struts when taxiing and design landing loads are slowly applied. A number of variations in design are presented for low-pass shock absorbers and reference is made to double-acting band-pass vibration absorbers for other applications.

INTRODUCTION

This paper is concerned with a new series of frequency-discriminating shock absorbers with special reference to landing-gear applications. These new filter-action absorbers, called band-pass shock absorbers, were originated at the Langley Aeronautical Laboratory in an attempt to overcome some of the limitations of conventional shock absorbers. For example, in the case of aircraft operation on a land or water runway of a given roughness, as the aircraft speed increases, the relative slope of a bump increases and leads to more and more rapid rates of load application. Since the force transmitted by a conventional landing-gear oleo strut increases roughly as the square of the telescoping velocity, these struts tend to become quite rigid; thus, severe shock loads are developed and transmitted to the aircraft for high frequencies or rates of load application. One of the band-pass shock absorbers, called the low-pass shock strut, was conceived to overcome this limitation and still retain the characteristics of a conventional shock strut for low-frequency applications.

Although an experimental investigation of these band-pass shock absorbers has not yet been possible, publication of the available information on the principles of operation of these devices is considered desirable. The purpose of this presentation is to review these principles of operation briefly for some simple configurations which have been conceived and to present a few specific applications of these devices. Example struts for different frequency ranges or load-application rates are described. Simplified theoretical comparisons are made between a low-pass strut and a conventional oleo strut for a simple single bump and a compound bump consisting of two superposed sine waves of different frequencies. An appendix which contains the theoretical equations utilized in these comparisons is included.

PRINCIPLES OF OPERATION

Low-Pass Shock Strut

The simplest type of band-pass shock absorber to describe is probably the low-pass landing-gear oleo strut. Therefore, it is convenient to consider this design first, since the operation of the other types of band-pass shock struts can be easily visualized if the action of the low-pass strut is understood. The low-pass strut is of special interest for modern high-speed aircraft which utilize small hard tires for land operation or possibly hydro-skis for water operation. The landing gear of such aircraft with conventional oleo struts have satisfactory load characteristics when operated on smooth runways having only long undulations. However, when operated over small steep bumps, the aircraft may experience severe pulse-type loads. If a low-pass strut is substituted for the conventional oleo strut, these pulse loads may be alleviated. The action of the low-pass strut is to filter out these rapidly applied loads while substantially retaining the required load-arresting qualities of a conventional shock strut for normal landing and taxiing operations. This action is illustrated in figure 1(a) where the landing gear is riding over a small steep bump or wave without forcing the upper mass of the aircraft to follow the bump contour; however, the aircraft would be forced to follow, with reduced amplitude, the contour of the long hill or swell (fig. 1(b)).

Before the details of the simplified band-pass strut are discussed, it might be helpful to review the action of the conventional landing-gear oleo strut shown in simplified form in figure 2(a). This strut consists of a lower cylinder which contains the hydraulic fluid; an upper tube, the lower end of which acts as a piston and has an orifice; and, in many cases, a metering pin which varies the orifice size as a function of the strut telescoping displacement.

This strut operates in the following manner. When an upward axial force is applied at the base of the lower cylinder, fluid is forced from this cylinder through the orifice into the upper cylinder which has been previously pressurized with air for taxiing and reextending the strut. For a given size bump having a gradual slope, the strut telescopes easily and small loads are applied to the aircraft. As the slope of the bump increases, however, the strut must telescope at a greater rate. Since the pressure drop across the orifice is roughly proportional to the square of the telescoping velocity, the greater the slope of the bump, the more resistance the strut exhibits (that is, the more rigid it becomes) until for very steep bumps it is practically a rigid bar.

Since the orifice area of a conventional shock strut can be varied as a function only of the displacement and not of the slope of the bump, it cannot be designed to alleviate loads from steep bumps. The low-pass shock strut is intended to eliminate this disadvantage by having a main orifice of variable size which depends on the rate of loading. For this strut the orifice size increases as the rate of loading or frequency of load application becomes more rapid; thus, the transmitted load is reduced. This action does not imply a constant-force shock strut.

Figure 2(b) shows, in simplified form, modifications which would convert a conventional fixed-orifice strut into a low-pass strut. In this low-pass strut the orifice size is varied by a pressure-actuated metering pin, controlled through the piston and cylinder combination shown in position (fig. 2(b)) and in an expanded section view (fig. 2(c)). Actually, many other types of variable-flow valves may be used and the metering-pin-type valve is shown for illustration only.

The simplified low-pass strut operates in the following manner. When the hydraulic pressure p_l in the lower cylinder is increased because an upward load is applied at the base of the strut, fluid is forced through the main orifice and also into the control cylinder through the large-diameter tube or passage shown at the left of the strut. This tube is so designed that it presents a low impedance to the fluid flow. The fluid level in the control cylinder is regulated by the "airdome" pressure p_c. It should be emphasized at this point that the key to the operation of this strut is primarily the rate of flow of fluid into the control cylinder which, in turn, depends on the rate of change of the hydraulic pressure in the lower cylinder p_l.

For a low rate of loading, that is, one where the force increases slowly with time, the fluid flows slowly and easily through the small orifice in the control piston and thus allows the steel spring in the control cylinder to maintain this piston in its bottom position. For this case the strut behaves as a conventional fixed-orifice strut. For a high rate of loading, however, the pressure p_l rises rapidly and forces fluid into the control cylinder at such a high rate that it cannot bleed through the orifice in the piston fast enough to permit equalization of the pressures above and below the control piston. The piston therefore rises and increases the opening in the main orifice so that the fluid flows through this orifice at a much higher rate; the pressure p_l is relieved and the developed load is thereby reduced. As the loading pulse passes and the rate of loading drops off, the control piston is forced back down against its seat by the metal spring, and again closes down the main orifice to its low rate setting. Certain parts in the strut valving are subject to high accelerations and should therefore be as light as possible to permit strut operation over a wide frequency range.

Although the extreme low- and high-frequency cases have been described as separate actions, it should be borne in mind that a gradual transition exists in some region between the two for an intermediate band of frequencies. Therefore, at any time during a combined action resulting from the simultaneous application of both low- and high-frequency forcing functions to the strut, the equilibrium level of the fluid in the control cylinder is determined by the instantaneous magnitude of the low-frequency pulse in existence at the time.

Before the principles of operation of band-pass shock struts for other frequency ranges are discussed, it would probably be advantageous to introduce a slightly more complex low-pass strut which is illustrated in figures 3(a) and 3(b). In this configuration dump valves have been arbitrarily added to the strut. The quick-return dump valve adjacent to the main orifice has been added to facilitate rapid recycling of the strut for cases where it is desired to have the maximum possible strut length available for each new bump encountered. This rapid recycling might be of special interest in successive impacts on closely spaced water waves. This dump valve is so designed that, whenever the pressure in the upper cylinder exceeds the pressure in the lower cylinder, fluid returns to the lower cylinder and thus re-extends the strut. The fluid-return dump valve in the metering-pin-control piston has been added to allow the control cylinder to empty between successive high-frequency impulses. Otherwise, a series of steep, closely spaced bumps could tend to fill this cylinder with fluid and reduce the high-frequency isolation capabilities of this strut. This dump valve is designed to allow a quick return of the fluid from the control cylinder to the lower strut cylinder whenever the pressure above the control piston exceeds the pressure below it. For landplanes, snubbers may be of more interest to prevent rebound after contact than recycling dump valves. The low-pass shock absorber may be compared to a low-pass electrical-filter network. In the same manner as electrical filters can be designed to pass different bands of frequency, the band-pass shock absorber can be modified to pass and absorb different bands of frequency. Shock absorbers covering other pass bands are described subsequently. It is pointed out that, although the main purpose of these absorbers is to damp vibrations and shocks selectively, they may also be used as frequency-selective force and vibration transmitters in machinery requiring such frequency-selective excitation.

High-Low Band-Pass Shock Strut

The high-low band-pass shock strut may be defined as one which tends to isolate two bodies from each other against the transfer of loads or motions having an intermediate frequency or rate of application while allowing the transfer of low- or high-frequency loads or motions to occur. At the same time, such low- or high-frequency loads or motions would be damped by such a strut to a greater extent than those with intermediate frequencies. This type of shock strut might be preferred over the conventional shock strut in a vehicle, for example, for those applications where a frequency-spectrum analysis of disturbances imposed on the vehicle indicated the most severe loads or motions at some specific intermediate band of frequencies. It might also be preferred where disturbances applied at certain resonant frequencies of the vehicle or other device result in the development of excessive loads or motions.

One form of a high-low-pass shock strut might be obtained by altering the low-pass strut of figure 3(a) through substitution of the control cylinder of figure 3(c) for that shown in figure 3(b). This alteration consists of the insertion of the high-frequency cutoff orifice and, where required, the control-cylinder dump valve in the passage leading from the lower strut cylinder to the control cylinder.

The operation of the high-low band-pass strut is similar to that of the low-pass strut with the following differences. The high-frequency cutoff orifice, like the one in the control piston, offers very low impedance to the flow of fluid at low and intermediate loading rates but does greatly reduce the flow at high loading rates. Thus, at low frequencies the strut behaves as a fixed-orifice strut. At intermediate frequencies the control piston would be actuated to increase the main orifice size and thus reduce loads whereas at high frequencies, since practically no fluid could get to the control piston because of the flow restriction caused by the high-frequency cutoff orifice, this piston would remain close to its seat and the strut would also behave as a conventional fixed-orifice shock strut.

Intermediate-Band-Pass Shock Strut

The intermediate-band-pass shock strut may be defined as one which tends to isolate two bodies from each other against the transfer of loads or motions for all frequencies or rates of application with the exception of an intermediate band of frequencies for which the loads or motions may be transmitted. The relative damping would be considerably greater over this intermediate range than over the rest of the frequency spectrum. This type of shock strut might be preferred instead of the conventional strut, for example, for the case where it is desired to transfer motions or energy to a device in a certain frequency range while preventing all undesirable secondary vibrations or motions from feeding across the strut in either direction.

One form of intermediate-pass strut might be obtained through altering the high-low pass strut of figures 3(a) and 3(c) by modifying the shape of the metering-pin head to the form shown in figure 3(d). The operation of this strut is similar to that of the high-low band-pass strut with the exception that the main orifice is opened wide for low- or high-frequency loads and is closed down to a small size for intermediate frequencies or rates of load application. It is thus apparent that loads having high and low rates of application would not be transmitted while intermediate loading rates would be transmitted as in a conventional fixed-orifice shock strut.

High-Pass Shock Strut

The high-pass shock strut may be defined as one which tends to isolate two bodies from each other against the transfer of loads or motions having low frequencies or rates of application while allowing the transfer of high-frequency motions to occur. At the same time such high-frequency motions would be damped to a much greater extent than the low-frequency motions. Such a device might be utilized in a system where it is desired to transfer impulsive or oscillatory motions between two bodies in a high-frequency range while preventing the excitation of a low-frequency resonance. A high-pass strut might also be considered as one in which exponential damping proportional to some power of the strut telescoping velocity could exceed the usual power of two achieved with turbulent-damping devices. This action results in a sharper cut-off on the response curve of load transmission plotted against frequency of application.

One form of a high-pass shock strut might be obtained through altering the low-pass strut of figure 3(a) further by substituting the control cylinder of figure 3(e) for that shown in figure 3(b). This alteration consists of the substitution of a solid control piston for the one shown in figure 3(b), the insertion of the high-frequency cutoff orifice, and also, where required, use of the control-cylinder dump valve in the passage leading from the lower strut cylinder to the control cylinder as was done for the high-low-pass strut.

Most of the details of the operation of the high-pass strut may be obtained from the descriptions given for the low-pass and high-low-pass struts with the following differences. Since the control piston is solid so that there is no flow through it, this piston would be raised at low frequencies or loading rates to open the main orifice wider and thus reduce the loads. At high loading rates, the fluid could not enter the control cylinder because of the restriction of the high-frequency cutoff orifice; this condition would make the strut behave as a conventional shock strut for the higher frequency disturbances.

ILLUSTRATIVE CONFIGURATIONS

Single-Action Shock Absorbers

Rate-sensitive struts.- An alternative form of a simplified low-pass shock absorber is shown in figure 4(a) to illustrate that band-pass shock struts can be designed in many ways. In this design the main-orifice valve is controlled by the device in the perforated case. Essentially, the action is parallel to that previously described in the section on low-pass strut operation and is as follows:

When a loading function is slowly applied, the fluid in the lower cylinder passes through the perforated case and flows through the main orifice while simultaneously exerting a compressive force on the Sylphon Bellows containers. Since the two lower containers are filled with fluid, no compression of these occurs but the upper air-filled container is slowly compressed. Since, however, fluid can flow through the bleed orifice between the two lower containers, the plunger remains in its initial position, the volume in the lower container being reduced as much as that in the upper air-filled container. The spring force in this case is sufficiently large to maintain the plunger in its original position. When the compressive load on the strut is removed, the reverse action takes place. Thus, for low rates of loading this strut behaves as a conventional fixed-orifice strut. For high rates of loading, however, fluid cannot flow through the bleed orifice fast enough and, as a result, the plunger is withdrawn from the main orifice; thus, the strut is allowed to telescope easily with the consequent generation of only a small load.

Combined displacement and rate-sensitive struts.- In order to apply the band-pass principle to shock struts for which it is also necessary to control the damping as a function of strut-telescoping displacement, the design of figure 4(b) is included. This displacement type of damping control is of interest, for example, in landing gears for which it is desired to reduce the spin-up drag loads on contact of the wheel with the ground.

In this design an enlarged hollow metering pin is employed which is so contoured that the main orifice opening is controlled exactly as is that for the conventional shock strut employing a metering pin. The flow through the orifice around the outside of this metering pin thus takes care of the variation of strut force with telescoping displacement. For the variation of strut force with frequency or rate of load application, the fluid is allowed to flow through the interior of the metering pin. In this arrangement, the control cylinder is part of the base of the metering pin. In order for the fluid to travel from the lower strut cylinder to the upper cylinder, it enters the metering pin through the slots indicated (fig. 4(b)) which are distributed radially around the base of the pin. The compressible medium shown inside the valve plunger may be any nonsaturable compressible medium such as sponge rubber with nonconnected air holes distributed through it.

The action of this strut is similar to that of the previously described low-pass struts and may be briefly summarized as follows: For low loading rates, fluid flows around the outside of the metering pin through the main orifice and also through the slots and bleed orifice into the base of the metering pin. As the fluid enters the region below the plunger, the compressible medium is reduced in volume to maintain equal pressures on both sides of the plunger and allow the spring to maintain the plunger in its closed position. As the load drops off, the reverse action takes place. For high rates of loading, however, fluid cannot flow through the bleed orifice fast enough and, as a result, the pressure difference above and below the plunger forces the plunger down and allows the fluid to flow into the upper strut cylinder through the metering pin. As the rate of loading drops off, this channel is again closed off. This strut design has the advantage that the control-cylinder components can probably be adjusted or interchanged through the bottom of the strut without disassembly of the strut or landing gear. This feature is advantageous in that it might allow the same strut to be used for different types of aircraft or other vehicles. Of course, the displacement-controlled damping feature could be eliminated, if desired, by using a straight tube for the metering pin.

With the strut design of figure 4(b) during the decay of a high-frequency pulse, fluid could flow from the upper cylinder back down to the lower cylinder through the metering pin. This property allows the strut to recycle itself for high-frequency pulses. However, this flow can also occur for the decay of low-rate loading pulses and would allow the strut to snap back to its extended condition. For an aircraft landing, which is a low-rate pulse, this condition would result in a rebound of the aircraft into the air. The frequency-sensitive buffer system shown at the intersection of the two strut cylinders and in the exploded view of figure 4(c) is designed to prevent this rebound.

This buffer operates in the following manner: During compression of the shock strut, fluid flows into the annular space between the cylinders through the high- and low-frequency return orifices and also through the space between the outer edge of the sliding ring and the inner wall of the lower cylinder. The sliding ring is forced up against its stop during this part of the stroke and the slow-return dashpot, indicated in figure 4(c), is filled with fluid. For a high-frequency rebound the strut is allowed to reextend rapidly since any snubbing action is delayed by the time required for the ring to reseat itself by forcing the fluid out of the slow-return dashpot. The ring is a loose fit in this dashpot so the clearance between the two forms a leakage path which takes the place of an orifice. A loose fit was chosen for the ring, in general, to prevent its binding on the upper cylinder. Thus, for a high-frequency rebound the fluid returns from the annular region between the cylinders in the same way that it entered. For a low-frequency rebound, however, there is ample time to force the fluid from the slow-return dashpot to reseat the ring to cover the high-frequency return orifices. Therefore, the fluid must return to the lower cylinder through the small low-frequency return orifices so that the strut rebound velocity is reduced to a reasonable value.

Double-Action Shock Absorbers

Although the shock absorbers previously described have been of the single-action type for application mainly to the landing of aircraft, double-acting band-pass shock absorbers may be considered also. These absorbers, which are of the hydraulic, friction, and electrical varieties, have also been designed for the various types of response characteristics such as low pass, high pass, and so forth. These double-acting shock absorbers are of special interest as frequency-discriminating vibration absorbers since they can deal with impulses transmitted as either tensile or compressive loads. These double-acting shock absorbers are not described in this paper; the principles of operation of the single-acting shock absorber can easily be extended to the double-acting case.

A possible example of an application of a band-pass shock absorber for vibration absorption might be the isolation of a helicopter rotor from the fuselage. A low-pass shock absorber used in this way could couple the rotor to the fuselage for low-frequency forcing functions such as maneuvers and would be tuned to damp oscillations in this low-frequency range while isolating the high-frequency rotor vibrations from the fuselage. Although a double-action shock absorber might be used for this purpose, it is possible that a single-action shock strut with either air or oil springs could be employed.

Generalized Configuration

In order to include all the shock absorbers discussed herein in a single generalized configuration, the block diagram of figure 5 is included. In this figure the input or exciting motion is applied to one end of the controllable instantaneously variable damping device or medium shown at A which operates on the motion to produce the output motion. The differential-sensing element B senses the difference between the input and output loading functions (whether of a displacement, velocity, or force nature) and is able to transmit this difference as a workable signal or motion either in or out of phase with the original input function. This difference is received by the phase shifter or differentiator C which is capable of shifting the phase over the desired frequency range of input functions where required by the design or choice of sensing elements so that the resulting control signal or motion will be of the correct phase when applied to A to damp the motion or to absorb the shock. The correctly phased control signal is received by the frequency-selective filter D which is so arranged as to increase or decrease the damping or shock-absorbing effectiveness of damper A over certain designated frequency ranges so that the desired type of damping characteristic against frequency or rate of applied load can be achieved. The frequency-modified control signal is then applied to the damping controller or amplifier E which is so constructed that signals or motions picked up by the sensing element can be amplified to the proper strength and/or converted to the proper form to control instantaneously the damping or shock-absorbing qualities of damper A as required.

Figure 5 can be applied to the single-acting low-pass shock absorber of figure 3, for example, as follows: The damper A is represented by the hydraulic fluid and the main variable-flow orifice and valve head. The differential-sensing element B is represented by the fluid level in the control cylinder. The phase shifter or differentiator C is represented by the spring in the control cylinder in combination with the bleed orifice in the control piston. The frequency-selective filter D is also represented by this orifice and spring combination. The damping controller E is represented by the control piston and rod extending to the main valve head.

EXAMPLE SOLUTIONS COMPARING LOW-PASS AND CONVENTIONAL SHOCK STRUTS

A simplified theory has been derived to compare the low-pass and conventional fixed-orifice shock struts. The theoretical equations are included in the appendix of this paper. Two cases are analyzed by theoretical methods. The first considers the shock imposed in traveling over a simple steep bump and the second treats compound bumps. In these treatments the orifice areas of the conventional fixed-orifice and the low-pass struts are assumed to be identical when the low-pass strut of figure 3 is in its low-frequency configuration, that is, with the control piston down on its seat. Although it was impractical at this stage to select optimum strut characteristics for the cases treated, the comparisons are believed to be conservative.

Simple Bump

For the first example of motion over a simple bump, the case of a carrier landing over an arresting-gear cable has been selected. (See fig. 6.) The cable is shown in the lower part of figure 6 with an arbitrary bump faired over it; this bump represents very roughly the vertical motion of the wheel. An idealized comparison of the incremental accelerations of the aircraft due to the cable is presented for a representative conventional fixed-orifice strut and an equivalent, supposedly practical low-pass-strut configuration shown in the upper part of figure 6. In this comparison, the solution given in the appendix is further simplified by assuming that the main orifice could be opened to three times its original area with no time lag during passage of the wheel over the cable. These accelerations which are superposed on the landing acceleration are high since they represent the extreme case of a rigid airplane and a bottomed tire. Thus, only the shock struts are being compared for effectiveness in reducing the load. It is reasonable, however, to assume that, for the design landing condition, the tires might be completely bottomed while running over the arresting gear cable. Also, although it is difficult to evaluate the effects of aircraft flexibility at this stage, it is apparent that, if structural elasticity did not greatly relieve the load shown for the conventional shock strut, the gear would fail. The load reduction achieved by the low-pass strut might prevent such failures. Other visualized single-bump cases for which the low-pass strut might reduce the loads are:

(1) Hydro-ski seaplane running over a log

(2) Military aircraft landing in a chuckhole or elevation difference at intersection between metal sections on fabricated runways on insufficiently maintained fields during wartime

(3) Ski-plane landings over uneven ice fields

(4) High-speed landings on concrete runways on which there are differences in elevation between adjacent slabs.

Compound Bumps

In operations over rough land and water runways, compound bumps may be encountered which are composed of superposed bumps or waves of different frequency as shown in the lower part of figure 7. The effective composite surface profile shown is made up of large bumps 1 foot high by 100 feet long combined with small bumps 4 inches high by about 17 feet long. The actual bumps for this case could be much higher but, because of tire flexibility or penetration of the ski into the surface, the actual displacement of the lower attachment point of the shock strut is reduced to the effective bump height which is plotted in the lower part of figure 7. The shock-strut dimensions and appropriate constants used in the sample solution are listed in the appendix. The vertical acceleration of the aircraft is presented in the upper part of figure 7. The conventional shock strut exhibits high loads for the high-frequency bumps or in the region of the steep wave fronts whereas the low-pass strut greatly reduces these loads. The actions of both struts for the low-frequency component of the input function are fairly similar.

CONCLUDING REMARKS

In this paper, a new class of frequency-selective, filtering-action shock absorbers having the collective title of "band-pass shock absorbers" have been introduced and their principles of operation have been described. These shock absorbers may be designed to isolate two bodies from each other over certain ranges of exciting frequencies or rates of load application while coupling them over the remainder of the frequency spectrum. In the coupling region the damping forces exerted by the shock absorber would be high compared with the damping over the remainder of the frequency spectrum.

A simplified theoretical solution was made to compare the effectiveness of the low-pass shock strut with a conventional strut for a landing-gear application. Attention was given to two different assumed bump encounters: (1) a single bump such as is encountered by running over a carrier arresting-gear cable and (2) a combined bump made up of superposed sine waves of widely different wave length representing taxiing on rough runways or in water waves. The results show that, although both shock struts transmitted approximately the same load to the aircraft for long smooth bumps or waves, the low-pass strut greatly alleviated the loads transmitted for small steep bumps or waves. Thus, for the case of the high-speed aircraft having a relatively stiff landing gear, the rapidly applied shock loadings encountered on rough land and water runways would be alleviated while the vertical taxiing loads and design landing shocks would be developed and absorbed as in conventional gears. The degree of load alleviation attainable with these band-pass shock absorbers in practice has not been determined experimentally.

Langley Aeronautical Laboratory,
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APPENDIX

SIMPLIFIED EQUATIONS OF MOTION FOR LOW-PASS SHOCK STRUT

Derivation of Theoretical Equations

The object of the following analysis is to give some insight into the behavior of low-pass shock struts. Simplified equations of motion for the low-pass shock struts shown in figure 3 are developed. For these equations the following symbols are used:

A internal cross-sectional area of main cylinders

a internal cross-sectional area of control cylinder

C hydraulic-force coefficient

$F(t)$ upward force on shock strut

$f = 1 + \frac{K_s}{K_a}$

$h = \frac{\epsilon}{a}\sqrt{\frac{2K_s}{\rho a}}$

$j = \frac{m_a}{K_a A}$

K_a air spring constant

K_s spring constant of metal spring in control cylinder

$l = \frac{\beta}{\alpha}$

m mass of airplane

p_c control cylinder pressure

p_l fluid pressure in lower strut cylinder

p_u air pressure in upper strut cylinder

$q = \frac{p_u A}{\alpha}$

$r = \frac{m}{\alpha}$

v	fluid velocity through frequency-control orifice
w	vertical displacement of upper surface of fluid in control cylinder
w_o	initial fluid level in control cylinder
x	vertical displacement of base of strut
y	vertical displacement of airplane mass which is concentrated at top of strut
z	vertical displacement of metering-pin control piston
α,β	constants; for fixed-orifice shock strut, $\alpha = 0$
ϵ	effective internal cross-sectional area of frequency-control orifice in control piston
ρ	density of shock-strut fluid

A dot over a symbol indicates a derivative with respect to time of the quantity represented by the symbol.

The simplifying assumptions of the analysis are:

(1) The upper cylinder air pressure p_u is taken to be constant over the entire strut travel (see ref. 1)

(2) The damping force is taken to be proportional to the square of the telescoping velocity (turbulent damping)

(3) The air spring (or an equivalent metal spring pushing down on the fluid in the control cylinder) is taken to be linear

(4) Viscosity and metal-to-metal friction are ignored

(5) The wall thickness of the upper and lower strut cylinders is assumed to be negligible (air and hydraulic areas are assumed to be equal).

The axial force equation on the shock strut thus becomes, for $F(t) > p_uA$,

$$F(t) = m\ddot{y} = p_u A + C(\dot{x} - \dot{y})^2 = p_l A \tag{1}$$

Thus, by differentiation,

$$\dot{p}_l = \frac{m}{A}\dddot{y} \tag{2}$$

Let the hydraulic-force coefficient C determined by the main-orifice opening be a linear function of the metering-pin control-piston displacement so that

$$C = \beta - \alpha z \tag{3}$$

where β and α are constants. (For the conventional fixed-orifice shock strut, $\alpha = 0$.)

Since the control-cylinder air spring was assumed to be linear,

$$wK_a = p_c a \tag{4}$$

and

$$w_o K_a = p_u a \tag{5}$$

where

K_a air spring constant

w_o initial fluid level in control cylinder

a effective internal cross-sectional area of control cylinders

When the forces on the control piston are equated,

$$p_l a = p_c a + K_s z = wK_a + zK_s \tag{6}$$

where K_s is the spring constant of the metal spring in the control cylinder.

The rate of flow of the fluid flowing into the control cylinder may be expressed as

$$\dot{w}a = a\dot{z} + v\epsilon \tag{7}$$

where v is the fluid velocity through the frequency-control orifice of effective area ϵ. The fluid velocity may be determined from Bernoulli's equation as

$$\frac{K_s z}{a} = \frac{1}{2} \rho v^2$$

or

$$v = \sqrt{\frac{2K_s z}{\rho a}} \tag{8}$$

where ρ is the density of the shock-strut fluid. Equations (7) and (8) combine to give

$$\dot{w} - \dot{z} - \frac{\epsilon}{a}\sqrt{\frac{2K_s z}{\rho a}} = 0 \tag{9}$$

and since, from the differentiation of equation (6),

$$\dot{w} = \frac{\dot{p}_l a}{K_a} - \dot{z}\,\frac{K_s}{K_a} \tag{10}$$

equation (9) may be rewritten

$$\frac{\dot{p}_l a}{K_a} = \dot{z}\left(1 + \frac{K_s}{K_a}\right) + z^{1/2}\,\frac{\epsilon}{a}\sqrt{\frac{2K_s}{\rho a}} \tag{11}$$

Combining equations (2) and (11) gives

$$\frac{ma}{AK_a}\dddot{y} = \dot{z}\left(1 + \frac{K_s}{K_a}\right) + z^{1/2}\,\frac{\epsilon}{a}\sqrt{\frac{2K_s}{\rho a}} \tag{12}$$

In order to solve equation (12), z may be obtained as a function of x, y, and time by combining equations (1) and (3) to give

$$p_l A = p_u A + (\beta - \alpha z)(\dot{x} - \dot{y})^2$$

or

$$z = \frac{\beta}{\alpha} + \frac{p_u A - m\ddot{y}}{\alpha(\dot{x} - \dot{y})^2} \tag{13}$$

Equations (12) and (13) may be rewritten as

$$\dot{z}f + z^{1/2}h = \dddot{y}j \tag{14}$$

$$z = l + \frac{q - r\ddot{y}}{(\dot{x} - \dot{y})^2} \tag{15}$$

where $f = 1 + \frac{K_s}{K_a}$, $h = \frac{\epsilon}{a}\sqrt{\frac{2K_s}{\rho a}}$, $j = \frac{ma}{K_a A}$, $l = \frac{\beta}{\alpha}$, $q = \frac{p_u A}{\alpha}$ and $r = \frac{m}{\alpha}$. Equation (15) may be differentiated with respect to time to give

$$\dot{z} = -\frac{2(q - r\ddot{y})(\ddot{x} - \ddot{y})}{(\dot{x} - \dot{y})^3} - \frac{r\dddot{y}}{(\dot{x} - \dot{y})^2} \tag{16}$$

Equations (14), (15), and (16) may be combined to give

$$\dddot{y} = \frac{\dfrac{2f(r\ddot{y} - q)(\ddot{x} - \ddot{y})}{(\dot{x} - \dot{y})^3} + h\sqrt{l + \dfrac{q - r\ddot{y}}{(\dot{x} - \dot{y})^2}}}{j + \dfrac{rf}{(\dot{x} - \dot{y})^2}} \qquad (\dot{x} > \dot{y}) \tag{17}$$

This equation can be solved by means of step-by-step processes to give the vertical motions of the aircraft upper mass m if the variation of x with time is known in addition to the constants defining the shock-strut mechanism.

Treatment of Discontinuities in Making Solutions

Inasmuch as the derived equations are highly nonlinear, the various discontinuities arising during solution must be taken into account. Equation (17) applies only for $\dot{x} > \dot{y}$. For $\dot{x} \leqq \dot{y}$, $\ddot{y} = \frac{p_u A}{m}$; for $x > y$, $\ddot{y} = \ddot{x}$; and for $x = y$, $\dot{y} = \dot{x}$. If x tries to become less than y, $\dot{y}$ remains constant, $\ddot{y} = 0$, and $\dddot{y} = 0$. The term z cannot be less than 0; if z tries to become negative, it is assumed to be zero. If $|r\ddot{y}|$ becomess less than $|q|$, it is assumed that $z = 1$. The term $\ddot{y}$ cannot be negative; if it tries to become negative, it is held equal to zero until $\ddot{x}$ becomes positive again and $\dot{x} \gtreqless \dot{y}$ and $x \gtreqless y$. Then $y_o = 0$, $\dot{y}_o = 0$, and $\ddot{y} = \ddot{x}$ until $\ddot{x} > \frac{p_u A}{m}$. If $\ddot{x}_o > \frac{p_u A}{m}$, then $\ddot{y}_o = \frac{p_u A}{m}$. For $F(t) \leqq p_u A$, $x = y$ for the fully extended strut position.

Shock-Strut Dimensions and Appropriate Constants

For Sample Solutions of Compound Bumps

The shock-strut dimensions and appropriate constants used for the sample solutions are as follows:

$m = 247$ slugs $= 20.6$ lb-sec^2/in.

$p_u = 200$ lb/sq in.

$A = 16$ sq in.

$\rho = 1.65$ slug/ft^3 $= 0.00008$ lb-sec^2/in.^{4}

$a = 0.75$ sq in.

$K_s = 375$ lb/in.

$K_a = 750$ lb/in.

$\epsilon = 0.008$ sq in.

Total length = 30 inches

Telescoping length = 14 inches

$\beta = 300$ lb/(ft/sec)^2 $= 2.08$ lb/(in./sec)^2

$\alpha = 300$ lb/(ft/sec)^2/in. $= 2.08$ lb/(in./sec)^2/in.

$f = 1.5$

$h = 37.6$

$j = 0.00129$

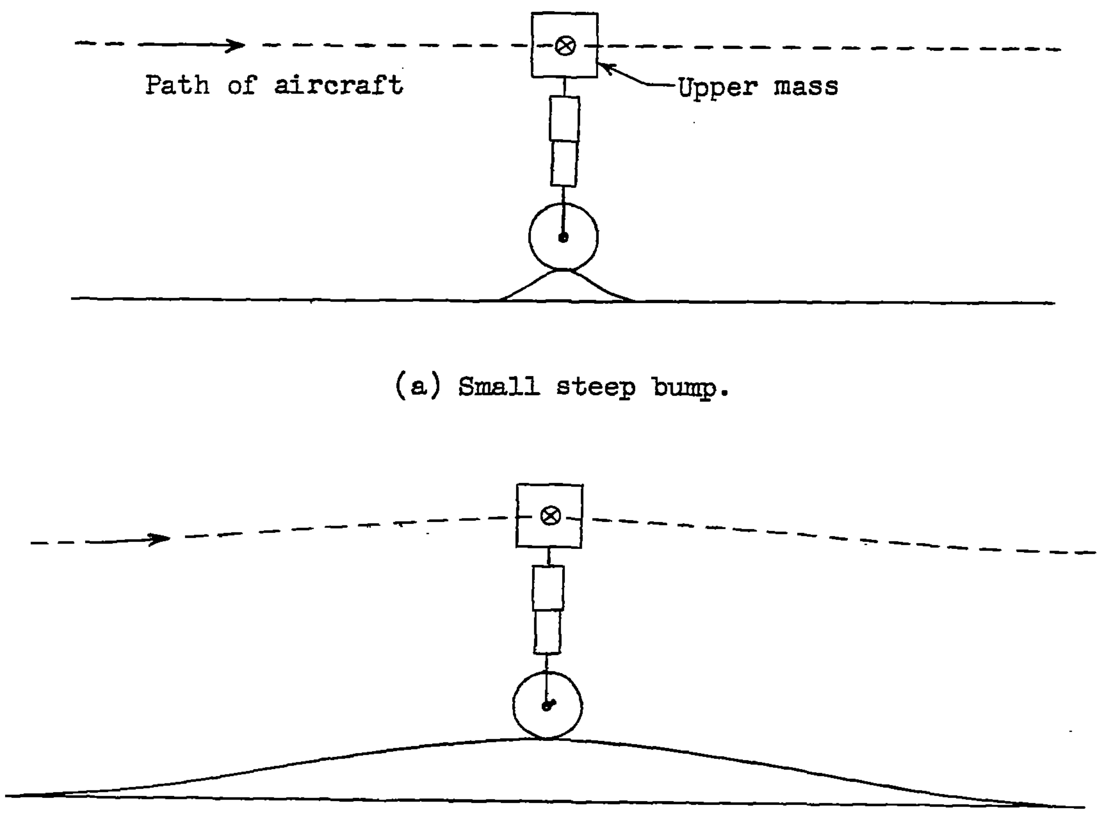
$l = 1$

$q = 1{,}543$

$r = 9.9$

REFERENCE

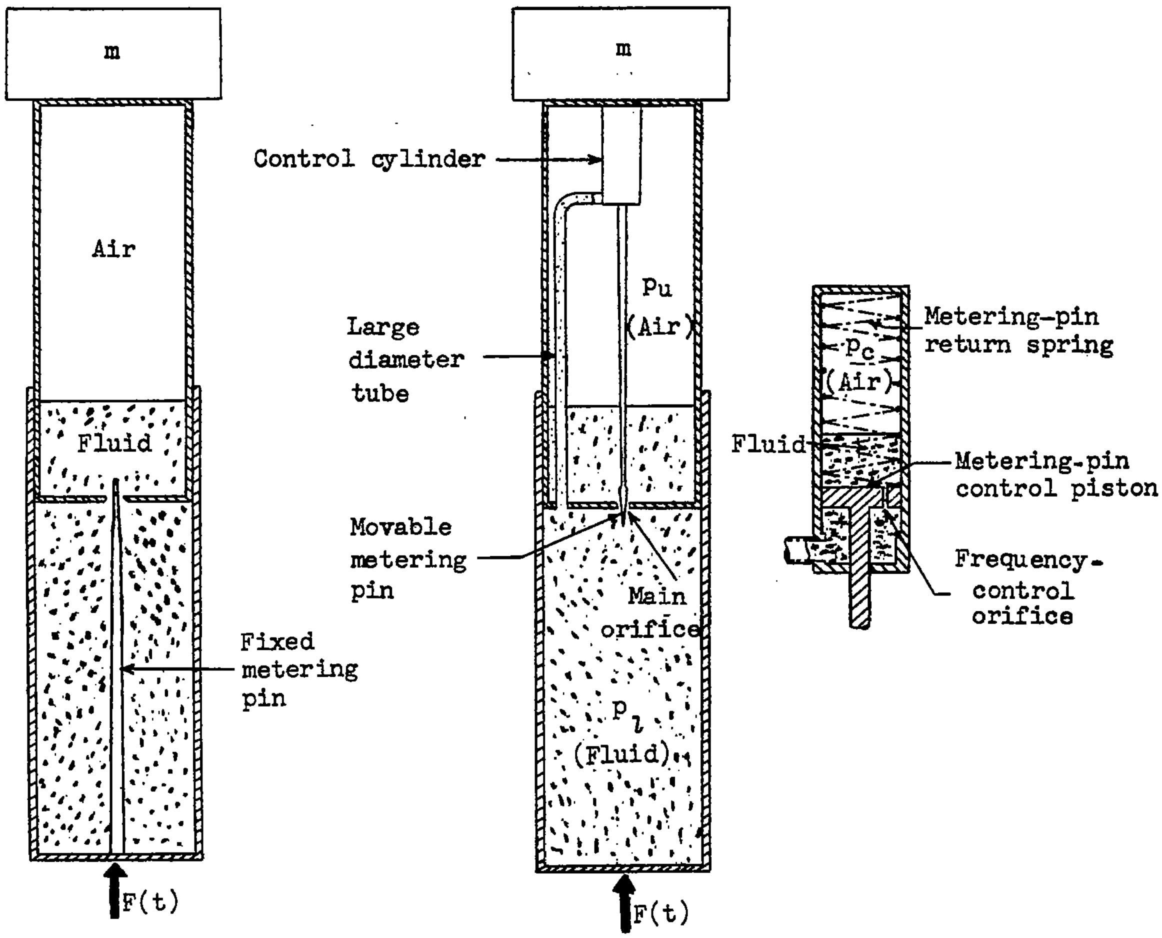
1. Milwitzky, Benjamin, and Cook, Francis E.: Analysis of Landing-Gear Behavior. NACA Rep. 1154, 1953. (Supersedes NACA TN 2755.)



(a) Small steep bump.

(b) Large flat hill or swell.

Figure 1.- Effect of bump steepness on upper mass of aircraft during taxiing with low-pass shock strut.

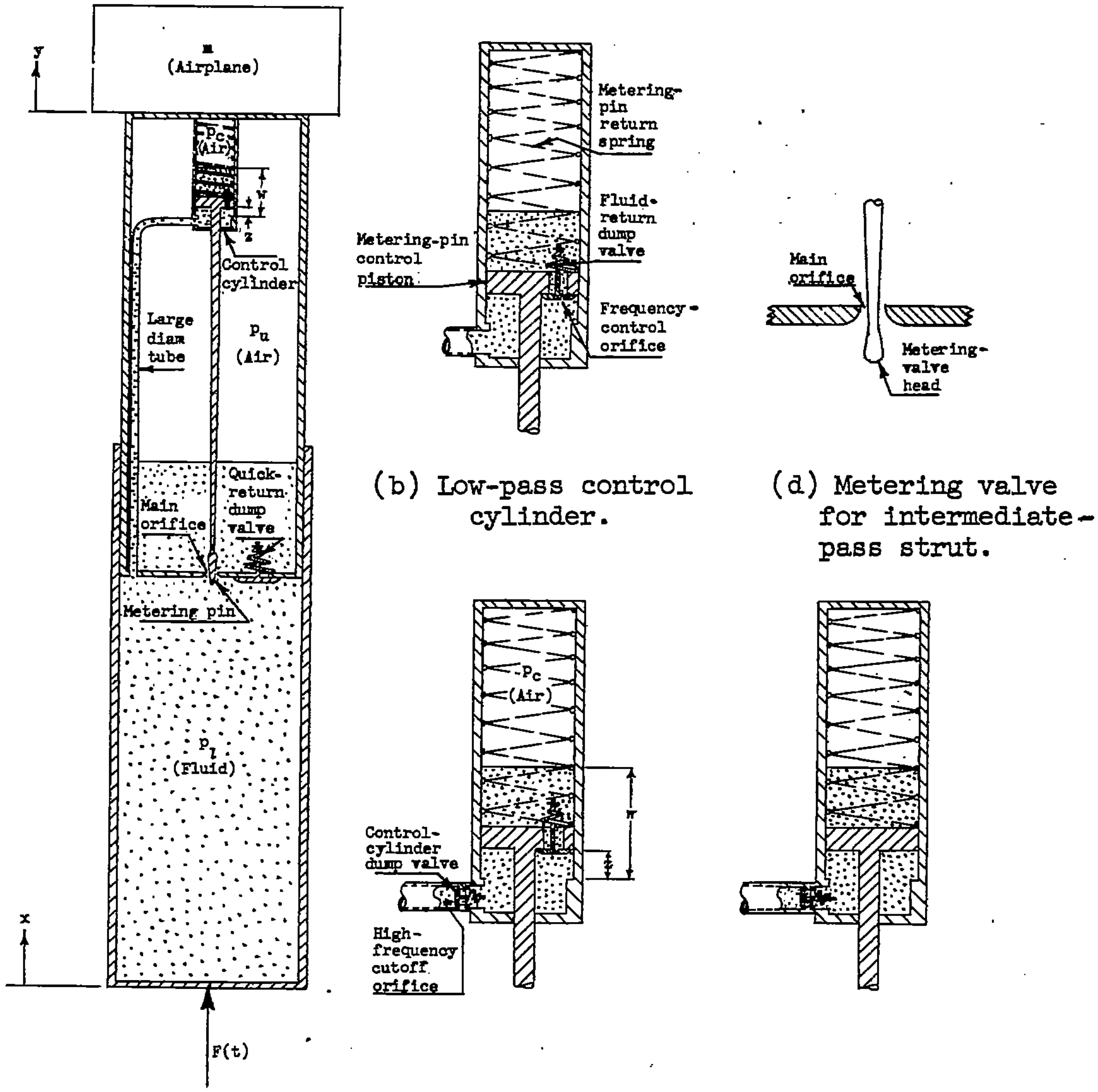


(a) Conventional shock strut.

(b) Low-pass shock strut.

(c) Section through control cylinder.

Figure 2.- Comparison of simplified versions of conventional shock strut with low-pass shock strut.



(a) Low-pass strut.

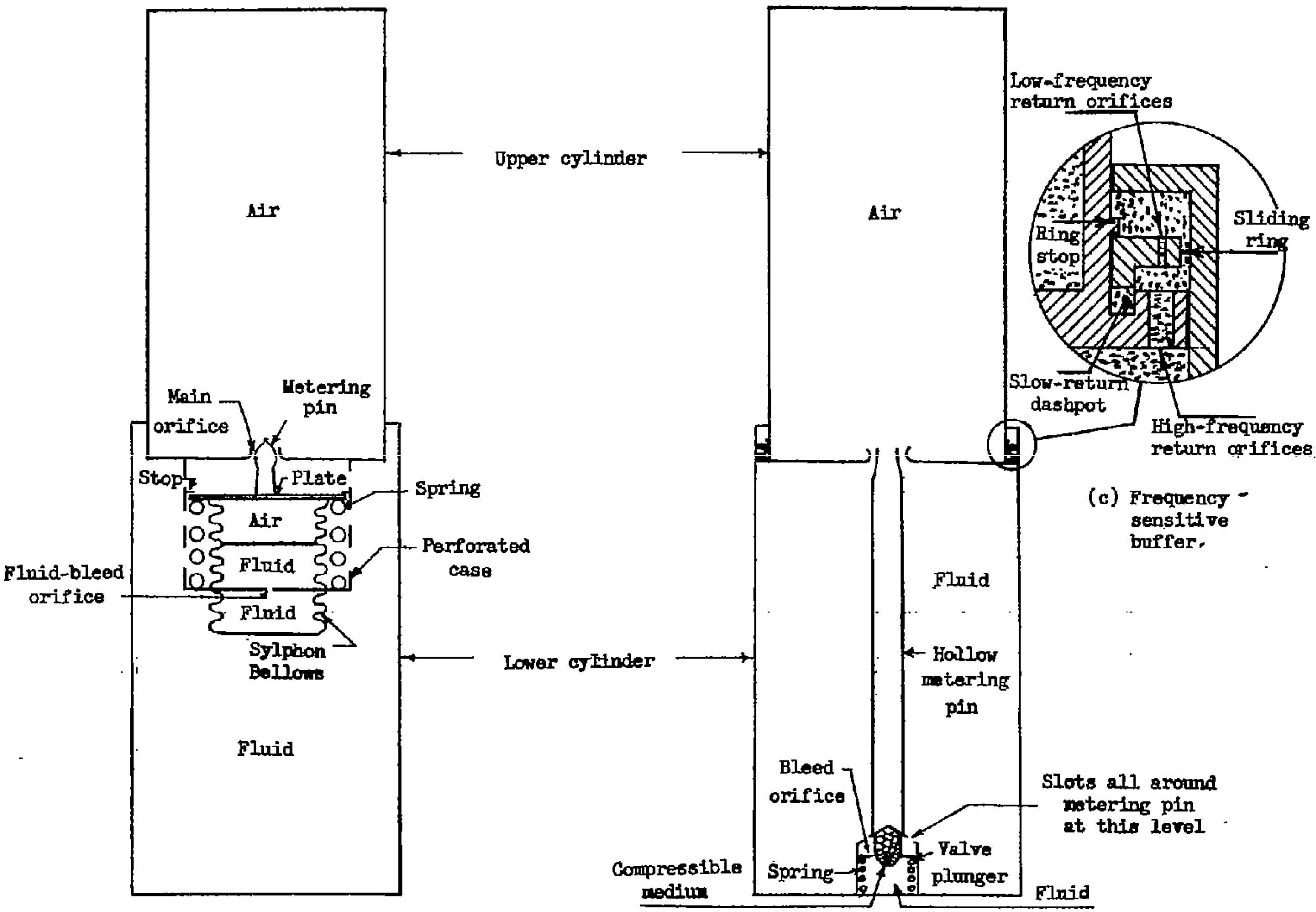
(b) Low-pass control cylinder.

(c) High-low-pass control cylinder.

(d) Metering valve for intermediate-pass strut.

(e) High-pass control cylinder.

Figure 3.- Band-pass shock-strut configurations for various frequency ranges.



(a) Frequency sensitive.

(b) Combined displacement and frequency-sensitive type.

Figure 4.- Alternate forms of low-pass shock strut.

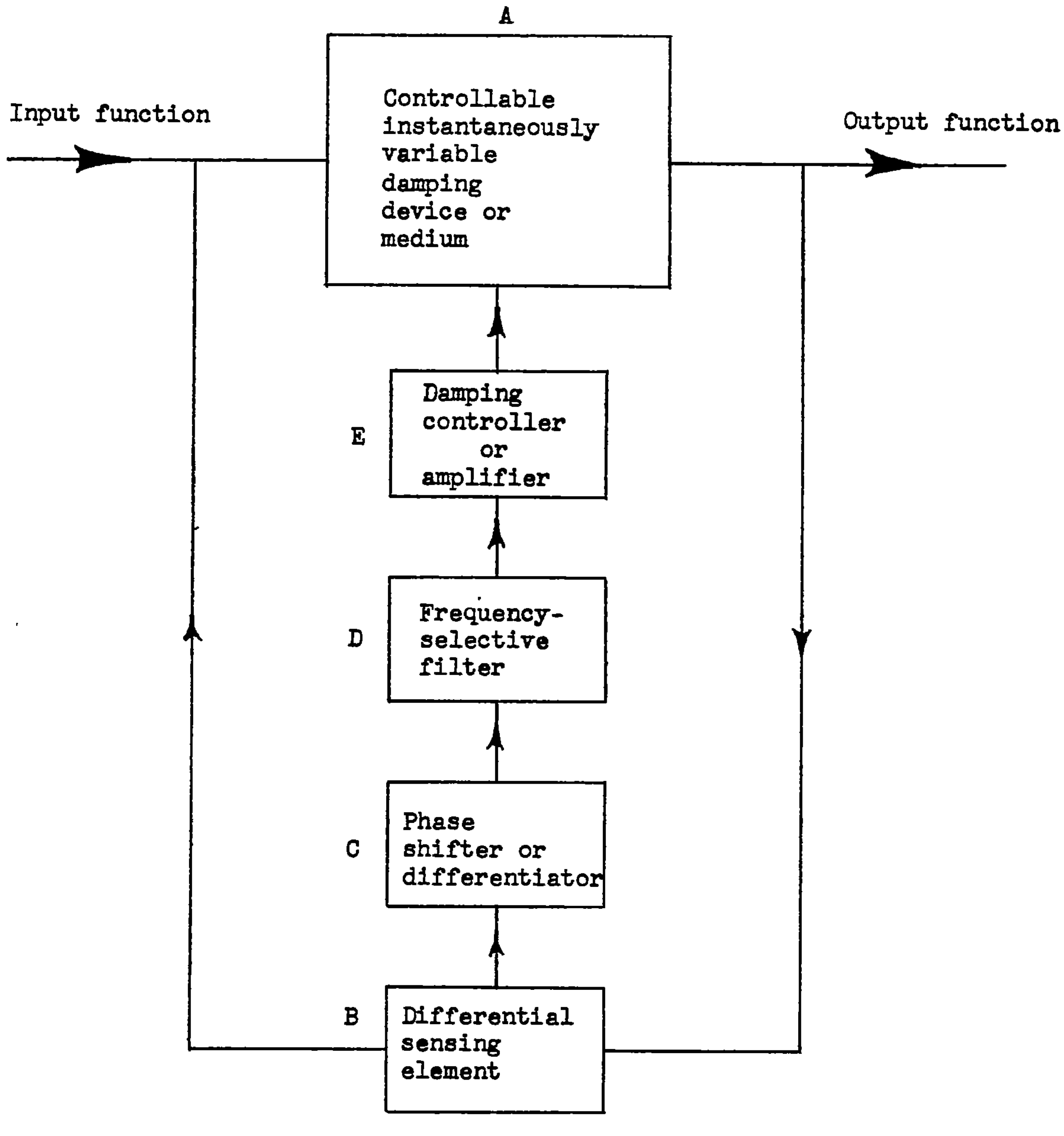


Figure 5.- Block diagram of band-pass shock absorber.

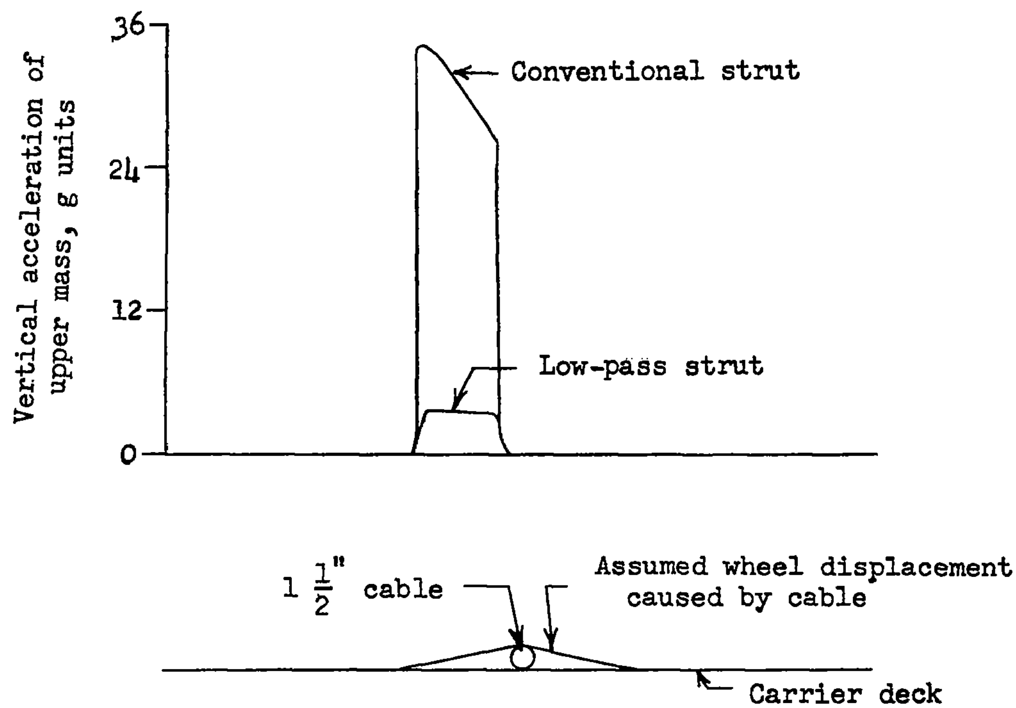


Figure 6.- Vertical-acceleration increment caused by passage over arresting-gear cable during hard landing on aircraft carrier. Tire bottomed; relative speed, 77 knots.

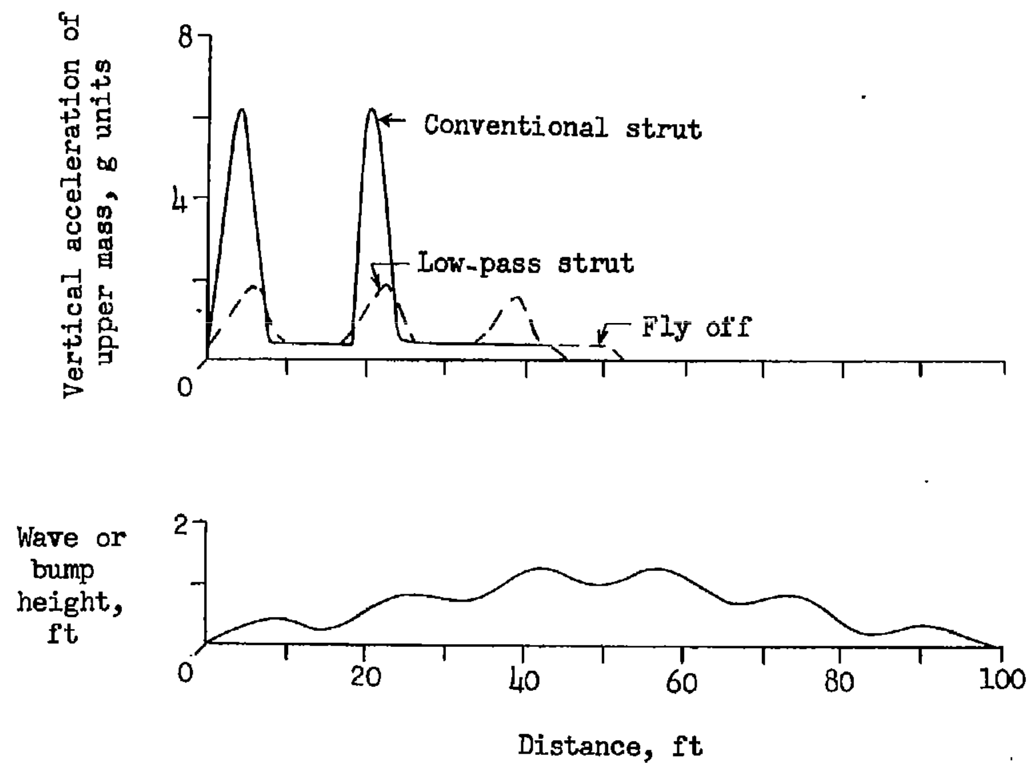


Figure 7.- Taxiing over a complex rough surface made up of superimposed wave trains. Aircraft speed, 120 knots.