C-5A Main Landing Gear Bogie Pitching Control

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The C-5A six-wheel main landing gear bogie, as the result of a high flotation requirement, poses a problem for designing a wheel braking torque compensating mechanism which stabilizes bogie pitching during braking. For ground operation, the bogie is also required to pitch ±12° with respect to the shock strut. During retraction of the main gear, however, the bogie is required to be at a right angle with the shock strut for the first 60% of the gear travel and then rotate about the pitch pivot with a defined pattern for 85°. To meet these requirements, avoiding weight penalty and complexity, a single braking torque link is used; and the bogie pitching control for on ground and in air operation is simplified to a two-stage pneumatic centering spring cartridge with the utilization of the torque compensating mechanism and a guiding track in the wheel well.

Nomenclature

B = front brakes anchoring force, lb
E = effectiveness of braking torque compensation
F_1 = ground drag force by braking at a front wheel, lb
F_2 = ground drag force by braking at a rear wheel, lb
P = resultant force at the front axle produced by the front wheels drag and the front brakes anchoring force, lb
T_1 = applied braking torque at a front wheel, lb-in.
T_2 = applied braking torque at a rear wheel, lb-in.
W = total vertical load on gear, lb
W_1, W_2 = vertical load on a front and rear wheel, respectively, lb
c,d,h,s = dimensions as shown in Fig. 6, in.
r_1, r_2 = front and rear tire rolling radius, respectively, in.
k_1, k_2 = front and rear tire vertical spring rate, respectively, lb/in.
k_3 = bogie beam V bending spring rate, lb/in. structure
μ_1, μ_2 = front and rear tire-ground coefficient of friction respectively
$(\ )_0$ = initial static condition

Introduction

THE C-5A is not only the heaviest and largest airplane to date but is also required to operate from rough and unpaved airfields. In addition to the high ground flotation capabilities, the landing gear is designed to perform other functions which are not conventionally required of a landing gear. These extra functions include kneeling, crosswind positioning, inflight tire pressure reduction, and integral jacking for changing main landing gear tires. Kneeling lowers the fuselage while the airplane is parked, so that the cargo floor is at truck bed height for pallet loading/unloading from either end of the airplane. Other kneeling modes also allow drive-on of wheeled payloads from the ground at either end. For taxiing, taking off and landing, the fuselage is raised and maintained at the normal height from the ground for proper clearance. Crosswind positioning provides the capability to roll down the runway with a crab angle up to 20° to either side. The inflight tire pressure reduction further enhances the ground flotation capability. The integral jacking, for changing of main landing gear wheels, tires, or brakes is a part of the simplified maintenance approach which specifies a certain elapsed time.

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The high flotation requirement calls for a total of 28 wheels for the landing gears which are equipped with the same size 49 × 17 type VII tires. The nose gear has four wheels and each of the four main gears has six. The wheel arrangement is shown in Fig. 1a. Figure 1b and 1c show the wheels relative to the C-5A airframe at landing gear down and up positions, respectively. As for the other functional requirements, each demands additional hardware and control equipment which occupy a considerable amount of precious space and require additional operational clearances. All these design requirements impose some degree of difficulty to provide a retraction mechanism and particularly present some problems for the main landing gear bogie pitch position control.

Design Requirements

The C-5A main landing gear assembly is shown in Fig. 2. Figure 3 shows an assembly without the rolling stock, electric and hydraulic line installations for clarity. The bogie assembly is connected to the lower end of the shock strut by a pitch pivot and a roll pivot. Figure 4a shows schematically the views of a main landing gear at the extended and retracted positions. In order to store the wheels in the assigned space with minimum interruption of the airframe structural integrity, the bogie is, for the retraction operation, first rotated 90° with respect to the vertical centerline of the shock strut, orientating the leading pair of wheels toward the inboard direction of the fuselage. Then the strut is rotated inboard and up about its T-shape crosshead trunnions to bring the whole gear assembly under the cargo floor. Again, for the consideration of maximum fuselage structural integrity, the bogie beam angle with respect to the shock strut centerline is required to maintain a certain relationship with the shock strut rotation angle as shown in Fig. 4b. The same relationship is required for the extension operation.

During taxiing, taking-off and landing phases, the main gear bogie pitching angle is determined by the design tail down angle, the flat tire conditions and the allowance for negotiating bumps and rough surfaces. For the C-5A, 12° of bogie pitch is sufficient to accommodate all on-ground design conditions. It should be noted that the main gear bogie pitch position on ground really does not require "control" as such. The bogie is positioned by the attitude of the airplane with reference to the local ground surface while the wheels of that bogie are thus loaded. Tire bounce or bogie hopping, which is a dynamic phenomenon of the mechanical spring-mass system under disturbance, may take place if the disturbing frequency is close to the natural pitching frequency of the bogie assembly. Proper damping is perhaps the only control of the bogie in this case.

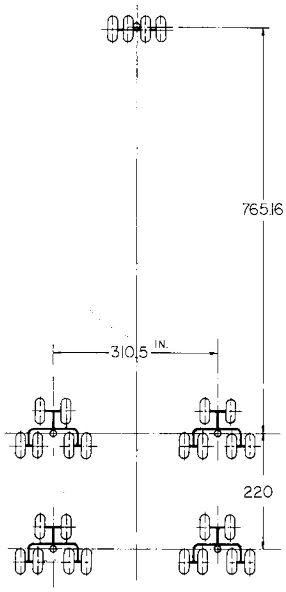

Fig. 1a C-5A landing gear wheel arrangement.

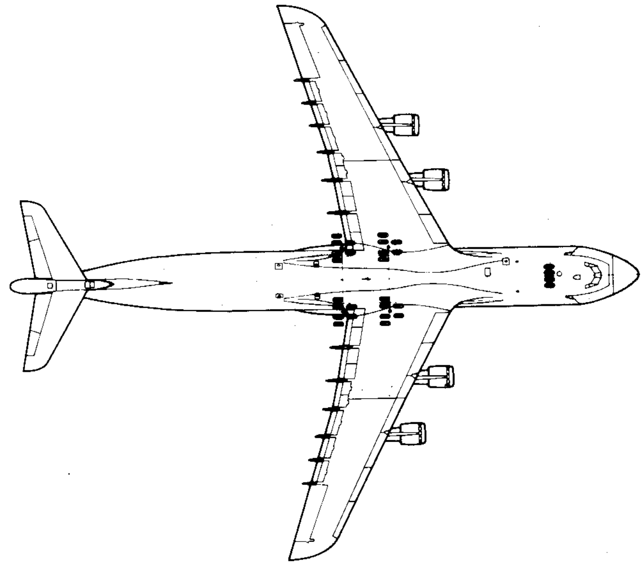

Fig. 1b C-5A landing gear at extended position.

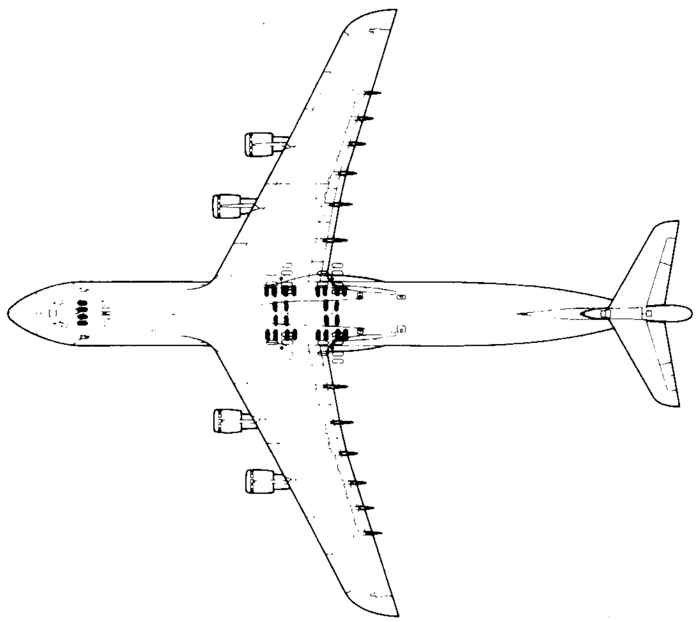

Fig. 1c C-5A landing gear at retracted position.

Another dynamic condition which causes bogie pitching is the braking of the wheels. During braking, the frictional drag between the tires and the ground (which are developed to counteract the wheel braking torque) imposes turning moments to the bogie with respect to the pitch pivot causing the leading wheels to go down under increased vertical load, and the trailing wheels to go up due to decreased vertical load. The redistribution of load on the leading and trailing wheels of a bogie landing gear during braking invariably causes the bogie to pitch down if no attempt is made to compensate for the braking torque. This condition is illustrated in Fig. 5a and b. In a conventional twin-tandem bogie design, the problem is handily solved by anchoring the brakes to the shock strut with mechanical links as shown in Fig. 5c. The bogie pitching moment due to braking drags is counterbalanced by the moments of the forces induced in the compensating links. For the C-5A main landing gear bogie configuration, however, it is obvious that there is no simple way to incorporate braking torque compensating links for all the wheel brakes without paying excessive weight penalty and additional complexity. If the bogie pitching due to braking is left uncontrolled, the obvious effect is uneven wear of those tires and brakes installed on a single bogie assembly in addition to degradation of braking performance.

The design requirements of the C-5A main landing gear bogie pitching control can be summed up as follows: 1) maintain a defined angular relationship with the shock strut as a function of the retraction/extension travel of the strut. 2) Provide adequate damping to prevent bogie hopping (oscillating) under disturbances. 3) Maintain the bogie pitch attitude for even load distribution during braking of the wheels.

Design Analysis

Once the requirements are established, the design analysis is a matter of course. It appeared that one single hydraulic cylinder as the bogie pitch positioner with proper control could meet all the three requirements above. However, after many layouts and computations, the following problems became apparent: 1) a programed control of the bogie pitch actuator which positions the bogie angle with respect to the shock strut as a function of the strut position in retraction/extension travel would be highly complex and unreliable requiring a position signal input which would be difficult to mechanize. 2) Braking torque compensation by a bogie pitch actuator would require a hydraulic cylinder over $8\frac{1}{2}$ in. in diameter for a 3000 psi system. Hard points and space requirement would cause a large weight penalty. The real difficulty would be to provide input intelligence to differenti-

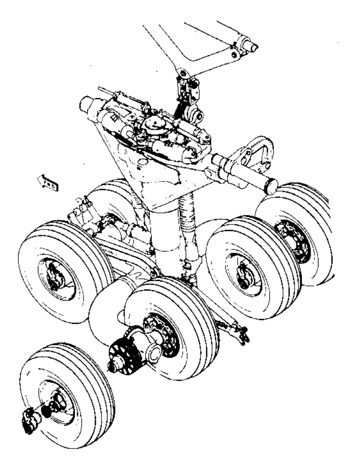

Fig. 2 C-5A main landing gear installation.

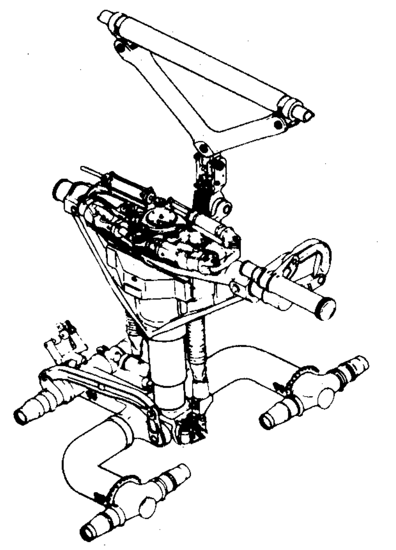

Fig. 3 C-5A main landing gear structure.

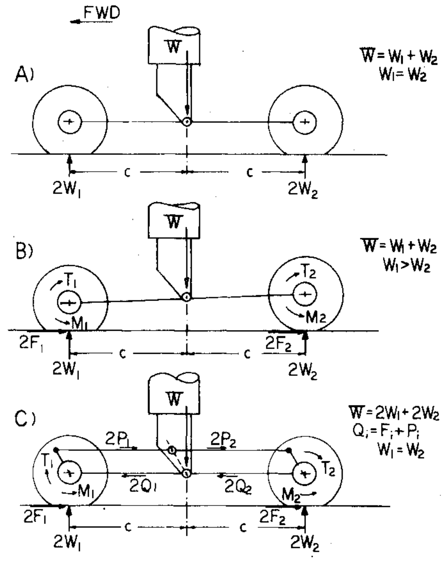

Fig. 5 Twin-tandem gear bogie pitching and stabilization during wheel braking.

ate without interference between the tendency for bogie pitch due to the airplane attitude change or ground surface roughness and that due to wheel braking.

There were other secondary problems too, such as hydraulic power requirements, installation checkout and maintainability for this integrated solution of using one single actuator to satisfy more than one functional requirement. The logical step for solutions is the separation of functions so that each deals with compatible requirements. The damping requirement, incidentally, is not a big problem. Almost any normal bogie pitch positioner design meeting the functional requirements together with the hysteresis of the tires would have sufficient damping in the mechanization to minimize undesirable oscillation if the range of the external disturbing frequencies does not cause resonance of bogie pitching.

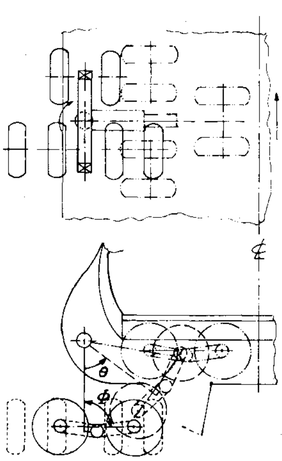

Fig. 4a C-5A main landing gear retraction sequence.

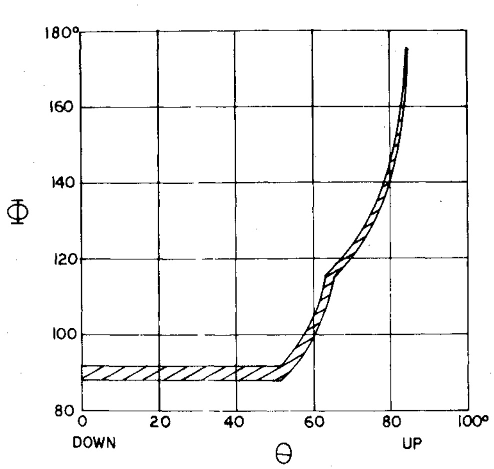

Fig. 4b C-5A main landing gear shock strut and bogie angles during retraction.

Even though the final design of the C-5 main landing gear bogie pitching control is, by principle, to meet the different functional requirements (namely, bogie pitch position control in air for gear retraction/extension operation and pitch stabilization on ground during wheel braking) by separate principal devices, the mechanization to solve the "in air" problem utilizes also the components that are designed primarily for solving the "on ground" problems. This approach saves considerable amount of space and hard points which mean weight. The combined mechanism has sufficient damping to meet the dynamic requirements.

Bogie Pitch Stabilization during Braking

Only one principal mechanical rod is used for each main landing gear bogie for pitch stabilization during braking of the six wheels. The arrangement is schematically shown in Fig. 6. The axle for the leading pair of wheels is assembled to the forward leg of the bogie beam and allowed to rotate about its own centerline with respect to the bogie beam structure. The two aft axles are integral parts of the trailing bogie legs. Six identical wheel and brake assemblies are installed on the three axles; and each brake is anchored to the axle in the same manner. The forward axle has a rigidly assembled crank arm which is linked by the torque compensating rod to the bogie pitch pin arm forming a four-bar linkage by the four points o, q, m, and n as shown in Fig. 6. The bogie pitch pin is splined to the shock strut piston, therefore the pitch pin arm is structurally grounded to the shock strut. It can be seen that when the bogie beam pitches up or down with respect to the shock strut, the forward axle rotates about its own axis with respect to the bogie beam.

It should be noted that the fully modulated anti-skid system for the six wheels of each main landing gear is divided into three independent circuits. Each circuit controls a pair of wheels symmetrical to the X axis as shown in Fig. 6. Each wheel has a skid detector, and either detector of the pair that senses the higher skid signal initiates the modulation of the braking pressure to the paired brakes, thereby minimizing the tendency to cause a yaw moment about the shock strut axis due to uneven ground drag on the paired wheels.

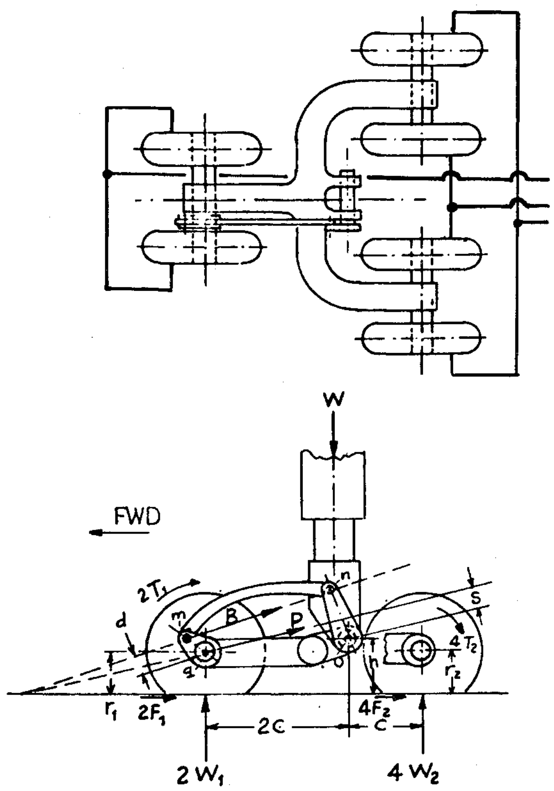

Fig. 6 C-5A main landing gear bogie configuration and braking torque compensation mechanism.

The function of the single torque compensating rod to stabilize the bogie assembly with six wheel brakes can be best explained by the following set of equations for static balance. For simplicity in analyzing the mechanism, it is assumed that the c.g. of the bogie assembly is at or very close to the pitch pivot. With the modulated anti-skid control, the prevailing braking condition is close to

$$T_1 = F_1r_1 \qquad T_2 = F_2r_2$$

When steady brakes are applied, neglecting bearing friction,

$$F_1 = \mu_1W_1 \tag{1}$$

$$F_2 = \mu_2W_2 \tag{2}$$

$$2W_1 + 4W_2 = \bar{W} \tag{3}$$

$$B = 2F_1r_1/d \tag{4}$$

$$Ps + 2\bar{W}_1(2c) = 4F_2h + 4W_2c \tag{6}$$

The ratio of W_1 and W_2 in Eq. (6) can be reduced to

$$\bar{W}_1/\bar{W}_2 = (2\mu_2h + 2c)/[\mu_1s(1 + r_1/d) + 2c] \tag{7}$$

The ratio of W_1/W_2 when the brakes are applied is the indication of the degree of torque compensation of this mechanical arrangement: $W_1/W_2 = 1$, full compensation; $W_1/W_2 > 1$, under compensation; $W_1/W_2 < 1$, over compensation. It should be pointed out that the quantities in Eq. (7) are variables except c which does not change appreciably under varying load. To evaluate the performance of the single rod braking torque compensation device, a parametric study was done with the following additional equations:

$$r_1 = r_0 - W_1/k_1 \tag{8}$$

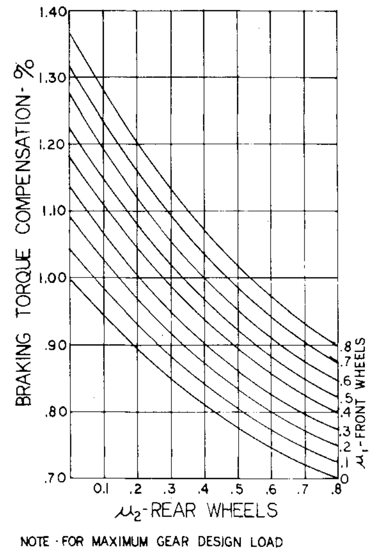

Fig. 7 C-5A main landing gear braking torque compensation versus ground conditions.

$$r_2 = r_0 - W_2/k_2 \tag{9}$$

$$h = (r_1 + 2r_2)/3 - (\bar{W}/k_3 + 2) \tag{10}$$

$$d = d_0 - f(\bar{W}) \tag{11}$$

$$s = s_0 + f'(\bar{W}) \tag{12}$$

Figure 7 shows the plots of the parametric computer study with the gear assembly load of 199,800 lb and the tire-ground coefficient of friction varying from 0.1 to 0.8. Figure 8 shows the effectiveness, E, of this design. The term Effectiveness of Braking Torque Compensation is defined as the ratio of the total realized braking drag of the gear under a given set of ground conditions over the total braking drag under the same set of ground conditions if the same vertical gear load is evenly distributed among all the wheels (i.e., the braking torque is fully compensated).

$$E = 3(F_1 + 2F_2)/(\mu_1 + 2\mu_2)\bar{W} \tag{13}$$

From Fig. 8, it is seen that for the usual range of ground conditions, namely, the tire-ground coefficient of friction varying from 0.20 to 0.55, the minimum braking effectiveness of this braking torque compensating device is above 94% for the maximum design gross weight.

Bogie Pitch Control during Gear Retraction

The technique for stabilizing the bogie during wheel braking is to keep the forward wheel axle from rotating about its

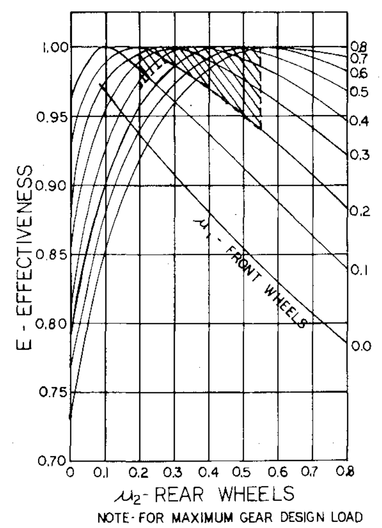

Fig. 8 Effectiveness of C-5A braking torque compensation.

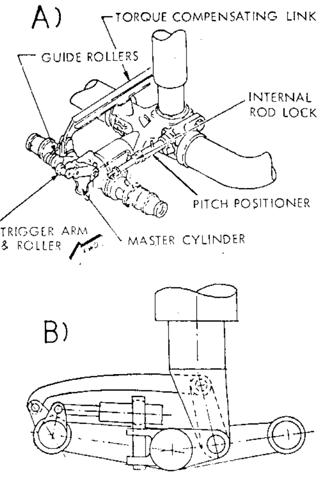

Fig. 9 C-5A main landing gear bogie pitch positioner mechanism and location.

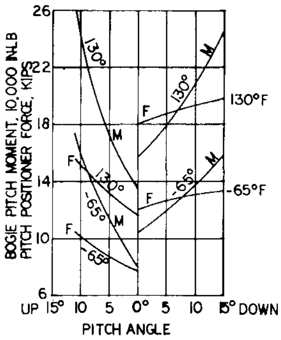

Fig. 10 C-5A main landing gear bogie pitch positioner forces and resistances to pitching moments.

own axis with respect to the bogie beam. In other words, when the bogie pitches up or down, the forward wheel axles rotates with respect to the bogie structure. For bogie pitch position control during gear retraction, therefore, the design is simplified to angular position control of the forward axle relative to the bogie beam thereby relieving the requirement for a hard point on the shock strut to anchor the bogie pitch actuator.

The bogie pitch position requirement with respect to the shock strut during gear retraction is shown in Fig. 4a and 4b. An obvious design is to engage the bogie to a track in the wheel well when the wheels approach the opening of the wheel well. Therefore, the bogie pitch "actuator" is reduced merely to a centering spring which assures the proper attitude of the bogie at the point of engagement/disengagement with the track. The centering spring, having sufficient travel to meet the bogie angular displacement in pitch down direction for gear retraction, is more than adequate for the design tail down condition of the airplane.

In bogie pitch up direction, 12° travel provides adequate clearance for all design functions. However, the centering spring design presents a problem. The center of gravity of the bogie structure is not exactly at the pitch pivot point. The installed bogie assembly with rolling stock has a pitch down weight moment of approximately 20,000 in. lb. A mechanical centering spring cartridge providing the necessary stroke with high initial preload to counteract the weight moment under design g-loading condition would be prohibitively heavy. A pneumatic spring cartridge induces excessive loads to the hard points and the retracting mechanism at the higher limit of ambient temperature if the pneumatic pressure is charged at a level to insure adequate performance at the lower ambient temperature limit. The associated problem is the drastic increase of retraction power requirement for a moderate increase of resistance to rotate the bogie about the pitch pivot at the last portion of the retraction travel.

The solution of these problems again is found in separation of functions. The bogie pitch positioner is finally designed to operate in two stages: one, providing high resistance to bogie pitch with short strokes; two, relieving or reinstating the bogie pitch resistance at the point where the bogie engages or disengages, respectively, the guide track in the wheel well during retraction or extension of the gear.

Figure 9a shows the location of the bogie pitch positioner and the associated components as installed on the bogie assembly. Figure 9b shows a schematic view of the bogie pitch positioner which utilizes the brake torque compensating mechanism to achieve the bogie pitch position control. The positioner has a stroke of ±2.6 in. which allows the bogie to pitch up 12° by extension and pitch down more than 12° by compression. The forces and resistance to bogie pitch moments of the positioner in terms of bogie pitch angles are shown in Fig. 10 at the ambient temperature limits of −65° and 130°F.

The positioner is a pneumatic cylinder with a floating piston at each end, as shown in Fig. 11, and the charge is compressed by either extending or compressing the cylinder. The rod of the pneumatic cylinder is mechanically locked to the shell of an inner concentric pneumatic chamber. The internal mechanical lock of the rod is released by hydraulic pressure which is generated by a master cylinder on the leading end of the bogie beam as shown in Fig. 9a when the trigger roller and the arm is depressed as the guide roller enter into the wheel well track. The release of the rod lock allows a compressive stroke of 5.7 in. of the pitch positioner which in turn allows the bogie to be rotated to the gear-up-and-stored position as shown in Fig. 4, making an angular displacement equivalent to a "pitch-down" angle of more than 85°. The resisting force during the compressive stroke of the positioner when the rod lock is released is at about a constant level of 1200 lb which is sufficient to stabilize the travel of the bogie guide rollers in the track but depletes very little power from the retraction mechanism.

On lowering of the main gear, the bogie assembly regains its relative position with the shock strut at the point where its guide rollers leave the wheel well track. The pitch positioner rod lock re-engages at this point by spring action

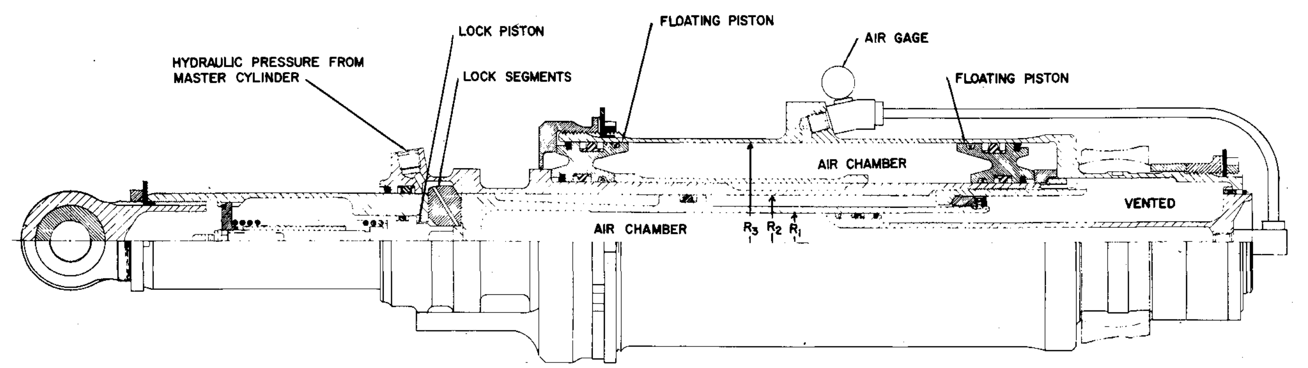

Fig. 11 C-5A main landing gear bogie pitch positioner design.

thereby returning the bogie pitch position control to the first stage operation of the pneumatic centering spring.

Conclusion

In the course of finding solutions for the C-5A main landing gear bogie pitching control problems, the following design techniques were applied.

Separation of functional requirements: Three major functions were defined, namely, bogie pitch angle pattern in gear retraction/extension, pitch angle range for on-ground operation, and pitching stabilization during application of wheel brakes. Damping to minimize oscillation was also identified. Design approaches were then selected with respect to the compatibility of the requirements. Two-stage operation of the pitch positioner is an application of this technique.

Re-evaluation of the objectives: When it was apparent that full compensation of the braking torque at all times could be achieved only at the expense of excessive weight and complexity by the conventional design approach, a re-evaluation of the design objectives showed that slight modification of the objectives would allow a much simpler and lighter design. Consequently, a single torque compensating rod is utilized to stabilize the C-5A main bogie which has six wheel brakes. The reduction of 0 to 6% braking effectiveness is hardly noticeable in the braking performance of the multiple brakes and yet the resultant mechanization is definitely simple and light occupying very little space.

Utilization of common components: The advantages are obvious. The bogie pitch positioner does not require an anchor point on the shock strut relieving a space congestion problem in that area. This is made possible by utilization of the braking torque compensating mechanism.

Utilization of environment: The bogie pitch positioner is designed as a self-contained unit. This is so by the utilization of a guide track in the wheel well to accomplish the bogie pitch position control in the retraction/extension operation. The track is also used to trigger the second stage operation of the positioner relieving excessive loads to the retraction mechanism and the associated structure.

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Requirements on Simulators Used in Handling Qualities Research

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A methodology has been developed for driving the visual display and motion systems of a large-amplitude and rotational 3-axis flight simulators to minimize the impact of the constraints of pilot subjectivity and task dependence. In explaining the drive technique, a simple model of the sensing mechanisms of the vestibular system is used. However, a way has not been found yet to take advantage of the vestibular system description to establish the dynamic performance required of the elements in the motion and visual display system. The success of the drive scheme depends on subjective observations of test pilots which allow filters used in the drives to be properly set in terms of gain and break frequency; the filter characteristics also are task-dependent. Experiments conducted on the simulators provide some assurance that the drive technique works within these constraints. The first of a series of experiments being conducted on the large-amplitude, 3-axis simulator to develop a rationale for motion and visual display drives for moving base simulators is discussed in which a comprehensive simulation of the Cornell T-33 inflight simulator has been mechanized. Flight experiments have been repeated on the simulator. Results of this work suggest that a mix of simulators be used to study the problems associated with fighter-bomber mission effectiveness and handling qualities.

Nomenclature

$G(\omega)$	= amplitude ratio
$<G(\omega)$	= phase angle
ω	= frequency
Z beam	= beam vertical displacement
$\dot{Z}$ beam	= beam vertical velocity
$\ddot{Z}$ beam	= beam vertical acceleration
K	= gain
τ	= time constant
S	= Laplace operator
ϕ	= bank angle
$\dot{V}_{co}$	= lateral acceleration
$\dot{U}_{co}$	= forward acceleration
m	= mass
θ	= pitch angle
N_Z	= vertical load factor
N_T	= lateral load factor
ζ	= damping ratio
ω_n	= natural frequency
$\|\phi/\beta\|$	= roll to sideslip ratio
N_p'	= yawing moment due to roll rate
δas	= aileron stick input
$N'_{\delta AS}/L'_{\delta AS}$	= yaw to roll ratio of lateral controls
$L'_{\delta AS}$	= rolling moment due to stick input
F_{AS}	= aileron stick force

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