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# THE RSRA ACTIVE ISOLATION/ROTOR BALANCE SYSTEM

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## ABSTRACT

The Rotor Systems Research Aircraft (RSRA) developed by Sikorsky Aircraft under joint NASA/U.S. Army sponsorship includes provisions for the installation of an Active Transmission Isolation/Rotor Loads Balance System (AIBS). The purpose of this system is to allow aircraft operation, with an arbitrary rotor system, over a wide rotor speed range and maneuver envelope without vibration envelope restrictions, while simultaneously providing measurement of rotor system loads.

The history of the design and development of this system, culminating in its successful flight test evaluation in the Fall of 1977 is reviewed. Highlights of the design, ground test, and flight test are presented. The design highlights include the trade-offs required to provide desired vibration attenuation, adequate margins of mechanical and aeromechanical stability and acceptable handling qualities of the aircraft. Particular attention is focused on the ground resonance and rotor whirl stability characteristics, which were found to be driving factors in the system design.

Ground test highlights include the evaluation of the adequacy of the control compensation linkage and the results of the airframe/isolation system shake test. Problems encountered with the system resulting from mechanical friction are discussed and the vibration attenuation characteristics are presented. Highlights of the flight test program cover the evaluations of ground resonance, whirl mode stability, vibration attenuation, handling qualities, and the relative motions within the airframe/gearbox/isolator system over the maneuver envelope.

## 1. INTRODUCTION

The Rotor Systems Research Aircraft (RSRA) has been designed and developed by Sikorsky Aircraft during the past five years under joint sponsorship of NASA and the U.S. Army. Figure 1 is a photograph of the RSRA in its compound configuration. The purpose of the RSRA is to serve as a flying test bed for advanced rotor systems, ranging from 2-bladed teetering to multi-bladed hingeless, bearingless and articulated designs. The aircraft can be configured as a pure helicopter with rotor operating speeds of 90-110% $N_R$, a compound aircraft with auxiliary lift and propulsion and rotor operating speeds of 70-110% $N_R$, or as a pure fixed wing aircraft. In each mode of flight, the loads generated by all primary aerodynamic and propulsive components are measured by load measurement devices, typically commercial load cells. In this manner, the aircraft serves the function of a flying wind tunnel, with the advantage of being able to test maneuvering flight conditions. References 1-4 are suggested for additional background on the research capabilities of the RSRA.

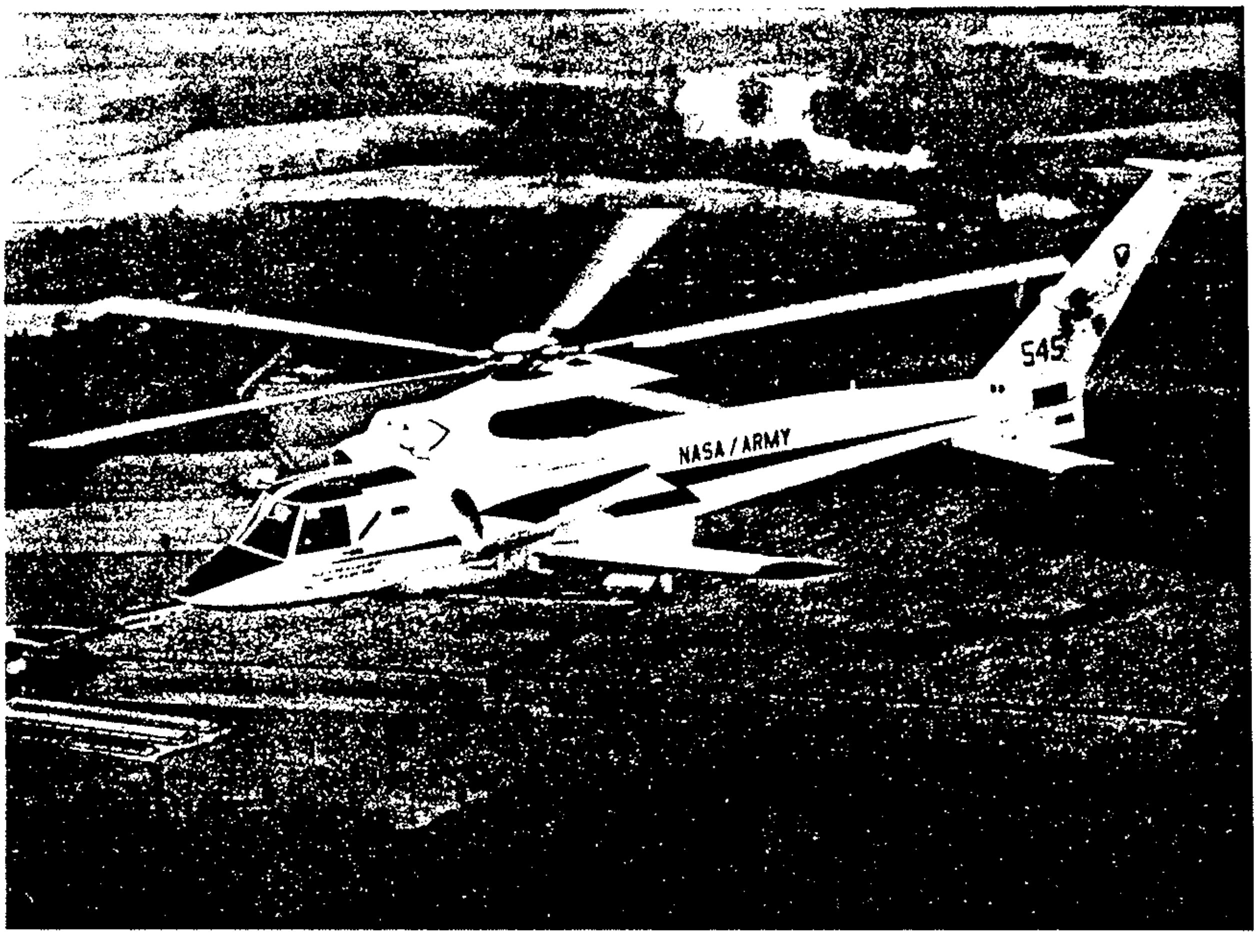



Figure 1. RSRA - Compound Configuration.

The combination of multiple aircraft flight configurations, the wide range of potential rotor excitation frequencies, and the primary rotor load measurement requirement complicated the task of providing an acceptable airframe vibration environment. Conventional approaches for controlling airframe vibration could not be realistically applied to this aircraft unless significant flight time and funds for each aircraft configuration, new rotor system, and rotor speed range were devoted to vibration control. This approach is not consistent with the design philosophy of the RSRA, which is to provide a safe, reliable, and relatively inexpensive rotor system test bed.

The design of the RSRA vibration control system was therefore initiated with the objective of providing a satisfactory aircraft vibration environment for any of the envisioned rotor systems, without compromising the research mission capability of the vehicle, and requiring minimal aircraft modifications for each new research mission.

The development of the RSRA active isolation system has progressed to the point where a 6 hour shakedown flight test program using the baseline S-61 rotor system has been completed. The RSRA was configured as a pure helicopter for this initial evaluation. This paper will discuss the important design and development activities which led to the successful demonstration of the active isolation system. Future activities which will mature the system so that it can efficiently serve its ubiquitous role for advanced research rotors are suggested in the concluding remarks.

## 2.0 DESIGN APPROACH AND CRITERIA

The approach to vibration control of the RSRA which was selected was a transmission isolation system. It was judged that this class of system had the most promise of providing satisfactory adaptability to all of the envisioned rotors since it operates on a resultant load at the transmission feet rather than specific rotor loads. The selection of transmission isolation necessitated the resolution of two basic potential problems prior to design initiation, control of the relative motion of the transmission and airframe, and accurate measurement of the loads generated by the rotor system. With a transmission isolation system the motions of the gearbox must be limited due to interfacing systems such as the engines and controls. It was envisioned that for some applications extremely "soft" transmission supports would be required for acceptable isolation. This led to the decision to use displacement feedback servo null hydropneumatic "active isolators" to recenter the transmissition under the influence of flight loads. This active feature allowed arbitrary selection of unit spring constants to achieve isolation while ensuring that system interface motions would always be acceptable.

With the selection of the active isolator units as the transmission support elements, the design of the complete transmission isolation system was initiated. In order to obtain a system which was sufficiently versatile, pre-design studies were performed on three different rotor systems. These rotor systems were selected to cover the major classes of rotors; articulated, hingeless (bearingless), and 2-bladed teetering. It was felt that if a system design was obtained which provided satisfactory performance for these rotors, then it would be capable of operation with almost any rotor system.

The design criteria for the active isolation system are summarized in Table I. The reader is referred to Reference 5 for an interim (i.e. prior to test evaluation of the system) assessment of the AIBS prepared by the NASA and U.S. Army personnel who worked very closely with Sikorsky during the design and development of the system. The paper offers an excellent review of the design and analysis of the system.

Table 1: Active Isolation/Balance System Design Criteria

| | |
|---|---|
| Preliminary Design Rotor Systems | . Articulated (5 bladed, S-61 Rotor)<br>. Hingless (4 bladed, Westland WG-13)<br>. 2-bladed teetering (Bell AAH) |
| Safety | . Fail-safe for hydraulic or mechanical failures |
| Isolation | . Vibrations attenuated by $\geq$ 70% for all rotors |
| Load Measurement | . Minimum time (< 3 sec) without load measurement in maneuvers due to isolator bottoming<br>. Accuracy equivalent to the baseline RSRA load cell system |
| Stability | . Isolator servo-mechanical system stable<br>. A/C stable in ground/air resonance<br>. A/C aeroelastically stable |
| System Interfaces | . Motions within T-58 and tail rotor drive shaft coupling constraints<br>. No control system coupling with transmission motions<br>. Engine vibrations within manufactures specification |
| Handling Qualities | . A/C amplitude and phase response changes to pilot input acceptable<br>. SAS/isolator interactions acceptable |
| Isolator Parameters | . Isolator parameters readily adaptable with minimal hardware changes |

## 3.0 DESCRIPTION OF SYSTEM

The primary elements in the isolation system are hydropneumatic, servo controlled actuator units. A schematic of the unit is shown in Figure 2. To interject some reality, a photograph of the lateral active isolator installed in the aircraft is shown in Figure 3.

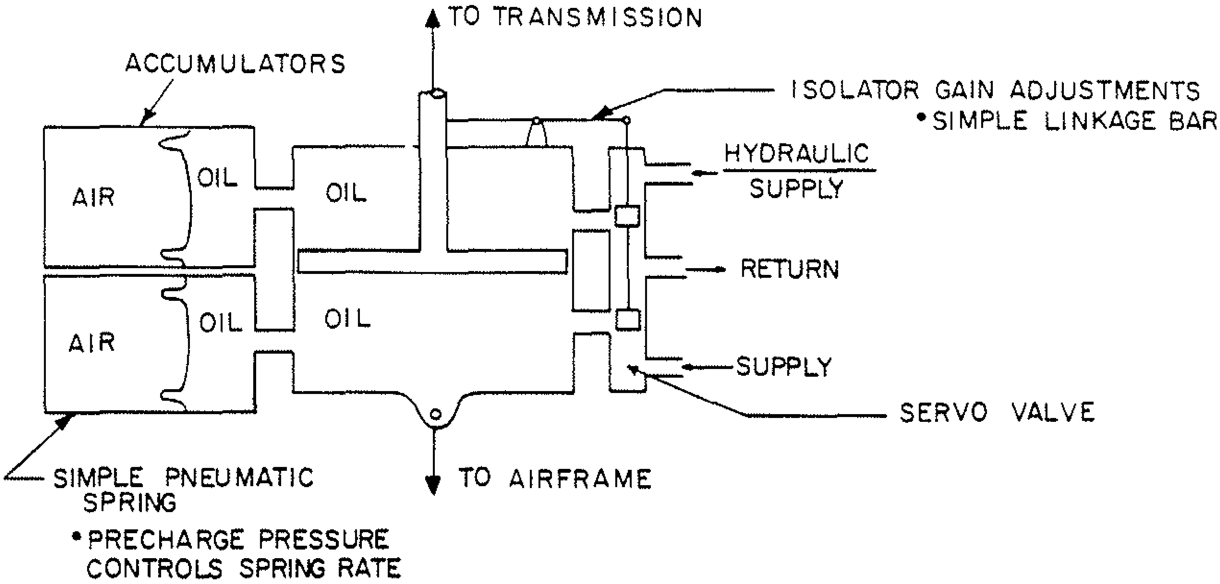



Figure 2. Schematic of Hydropneumatic Active Isolator.

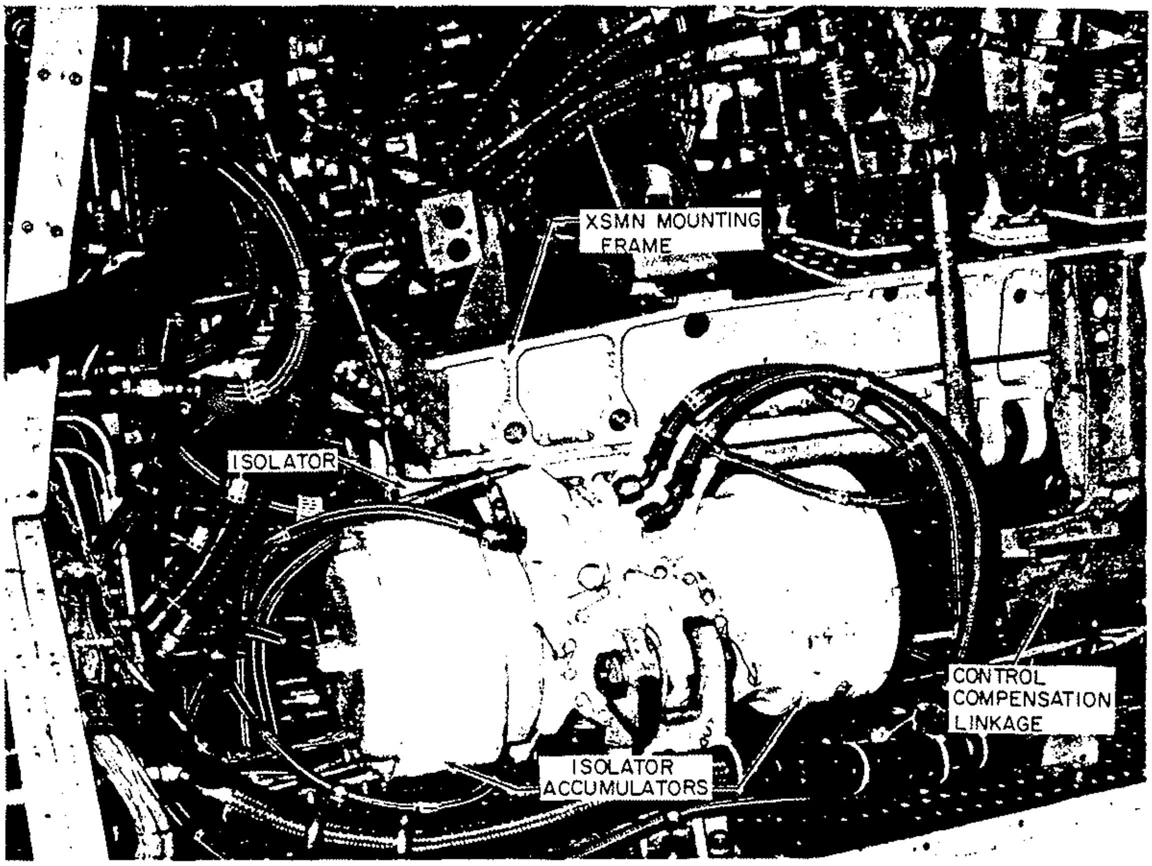



Figure 3. Right Rear Lateral Active Isolator Installed in RSRA.

The unit is basically a hydraulic piston reacting against captured air chambers with a relatively low gain mechanical displacement feedback servo valve. The captured air bulk modulus provides a spring restoring force with piston displacement. Also when the piston displaces, the servo valve feeds hydraulic fluid into the piston chamber in the direction of motion, compressing the air and creating a restoring force on the piston 90 degrees out of phase with the piston displacement. The net result is that for static or transient loads on the isolator the displacement servo feature keeps the unit centered in mid-stroke, while for high frequency (N/rev) motion the unit acts as a air spring, as insufficient fluid flow thru the servo occurs to creat appreciable forces. The load measurement requirement on the unit is satisfied through measurement of the differential pressure across the piston, which in conjunction with the piston area defines the load being reacted by the unit. These features, in addition to the easy adjustability of the spring rate and servo gain inherent in the design, provided the flexibility desired to allow large changes in the isolator dynamic characteristics which are likely to be required by rotor systems of different designs.

The hardware associated with the active isolation system consists of the primary structural support of the main transmission and the interface hardware between the gearbox and the drive system and controls. A schematic of the structural gearbox support is shown in Figure 4. For comparison the baseline RSRA load cell transmission support system is shown in Figure 5. The structural support of the gearbox consists of 4 inplane isolator units, four vertical load cells and an anti-torque linkage. The structural system will "fail-isolate" and thus is also "fail-safe". The two lateral isolators and two longitudinal isolators are redundant, the lateral units are redundant with the anti-torque link and a failure of a single vertical load cell can be tolerated.

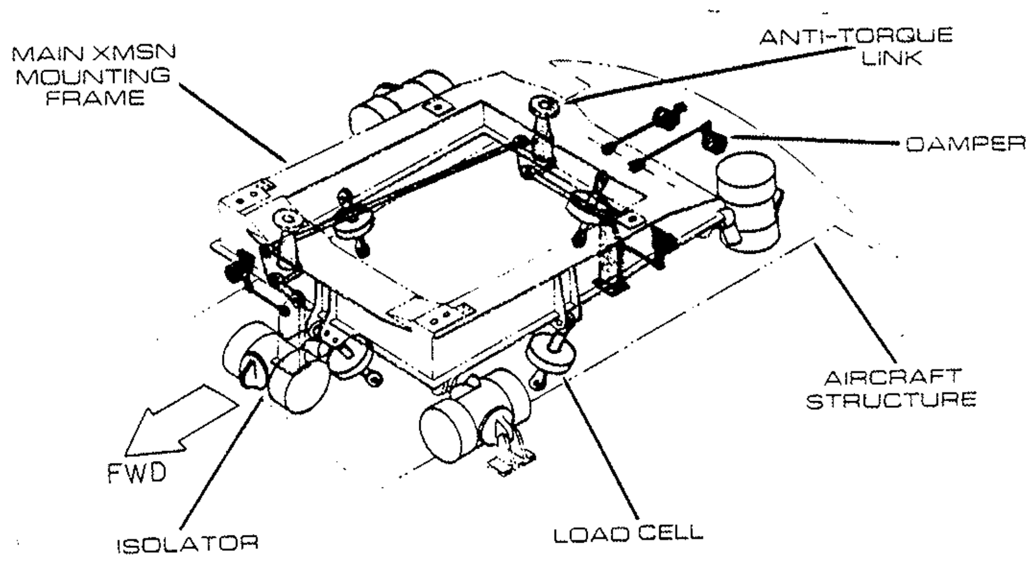



Figure 4. RSRA Transmission Active Isolation Rotor Balance System.

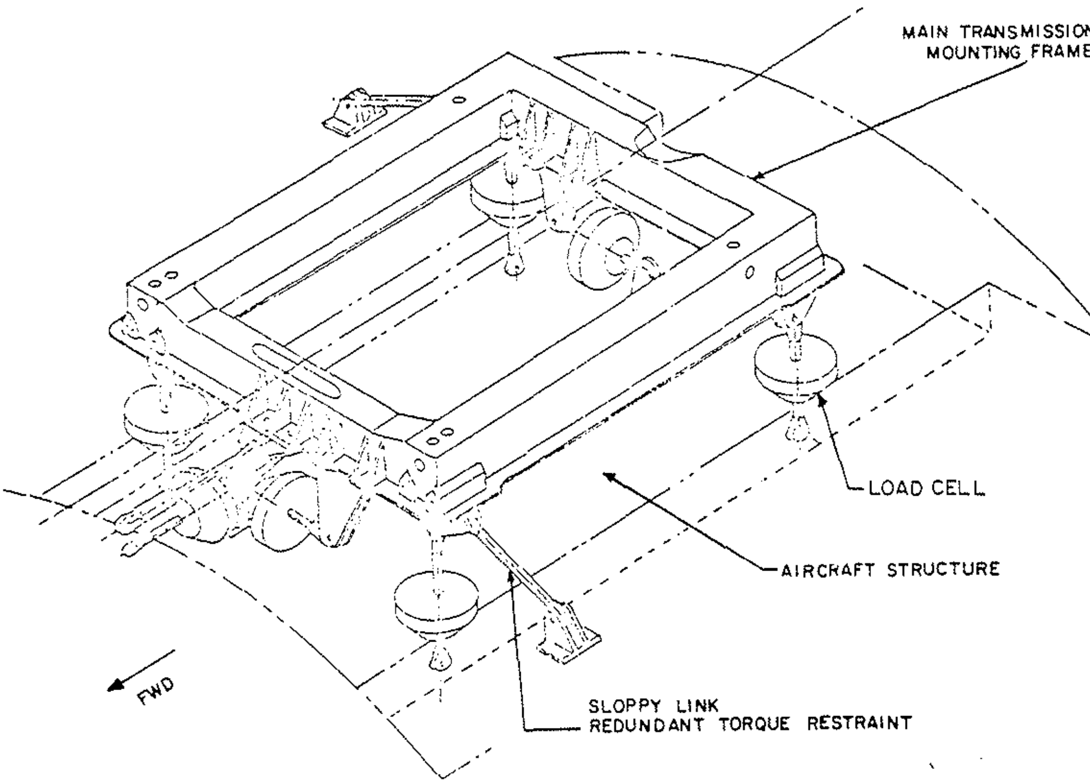



Figure 5. Baseline RSRA Load Cell Transmission Support System.

The geometric configuration is arranged to maximize load measurement accuracy. For example, the redundant fore-aft (longitudinal) isolator does not normally play an "active" role in the support of gearbox. This unit is designed with an electrically operated "bypass" valve which prevents it from carrying steady loads unless actuated by pilot command, or by an automatic safety monitoring system. The safety monitoring system automatically engages the aft isolator in the event of either a hydraulic or structural failure of the forward isolator.

The remainder of the isolation system consists of drive and control system interface hardware plus provisions for auxiliary dampers (if required for system stability). The control compensation linkage consists of a walking beam arrangement which nulls control inputs which otherwise would be generated by relative motion between the transmission and airframe.

The T-58-GE-5 engines and the tail rotor drive shaft interfaces with the transmission were also modified to accomodate anticipated isolator motions. The engines are mounted to the airframe at their forward end through a N-strut support which provides vertical and lateral restraint, but which allows the engine to yaw and pitch about this point and translate to a limited degree (± 0.5 inches) in the fore-aft direction. The aft support of the engine is connected to the transmission housing through a Zurn crown spline coupling which allows pitch and yaw motions of the drive shaft at the high speed transmission input. The tail rotor drive shaft (TRDS) modification includes a shaft spline coupling to permit fore-aft motion of the shaft and Thomas pack couplings for the pitch and yaw misalignment of the shaft at the transmission output and first airframe support bearing. These couplings for the engines and TRDS are designed to accomodate continuous full isolator motion plus elastic deformation of the airframe and gearbox support systems.

## 4.0 ANALYSIS

An extensive series of analyses were conducted to support the design of the active isolator. The general flow of the analyses is shown in Table II. Iterations on the design and analysis are implicit. The analyses focused primarily on forced response and stability. Relatively simple models were used initially to aid in the preliminary definition of the isolation system concept. These were followed by more sophisticated analyses as the design was refined. Table III summarizes the analyses which were used to design the RSRA active isolator.

Table II: Flow of Analysis

Select configuration which meets design criteria
Define required isolator spring rates
Confirm isolation
Select damping
Size accumulators
Select servo gain
Confirm isolator servo-mechanical stability
Evaluate transient response
Analyze system stability
Determine effect of airframe flexibility on isolation
Evaluate handling qualities

Table III: Analyses Used for AIBS Design

| ANALYSIS | MODEL | PURPOSE |
|---|---|---|
| Rigid Body Forced Response | Spring-damper isolators, rigid body A/F, gearbox and engine, rotor head forces. | Preliminary engine and airframe vibration. |
| Servo Stability | Full isolator force-displacement transfer function, rigid body A/F, gearbox, 2 engines, eigenvalue analysis. | Verify stability of isolation system as a servo-mechanical system. |
| Transient Response | Same as servo stability analysis, applied rotorhead forces, time history solution. | Evaluation of system load factor and maneuver load measurement capability. |
| Rotor Stability Analysis | Perturbational rotor aeroelastic equations, rigid body A/F & gearbox, landing gear properties, isolator force displacement transfer functions. | Aeroelastic and mechanical stability of coupled rotor/airframe/isolator system. |
| Digital Flight Simulation | Fully coupled rotor/controls/isolators/fuselage, steady and transient flight. | Verify A/C handling qualities and SAS/isolator compatibility. Evaluate control system/isolator coupling. |
| NASTRAN | Coupled isolation system and airframe. | Elastic airframe dynamic characteristics and vibration, relative motions at critical interfaces. |

The phenomena which had the most influence on the design of the isolation system were mechanical stability and inflight whirl mode stability. The introduction of the low generalized mass transmission modes associated with the isolators markedly increased the coupling between the rotor and fuselage and decreased stability margins. The active feature of the isolators also provided an energy source which was manefisted as negative damping in the modes of the system. The design approach for stability was to provide sufficient isolator stiffness so as to adequately separate the rotor and fixed system modal frequencies and thus reduce the damping required for stability. Since isolator stiffness could only be adjusted within limits because of the isolation requirements the focus positions of the load cells were used to adjust the generalized masses of the transmission modes which also affected damping required for stability (i.e. a higher generalized mass reduces damping requirements).

Examples of the analyses results are shown in Figures 6 to 11. Figure 6 illustrates the ground resonance stability of the system. It is a root locus plot of the modes of the system as a function of rotor speed at 80% airborne for the design isolator stiffness, damping and servo gain characteristics. 80% airborne is predicted to be the most critical condition for mechanical stability. It is seen that the advancing lag mode becomes unstable at approximately 125% $N_R$. Significant modal coupling is noted among the fixed system and rotor modes despite what might be considered comfortable frequency separation for conventional rotor/fuselage systems.

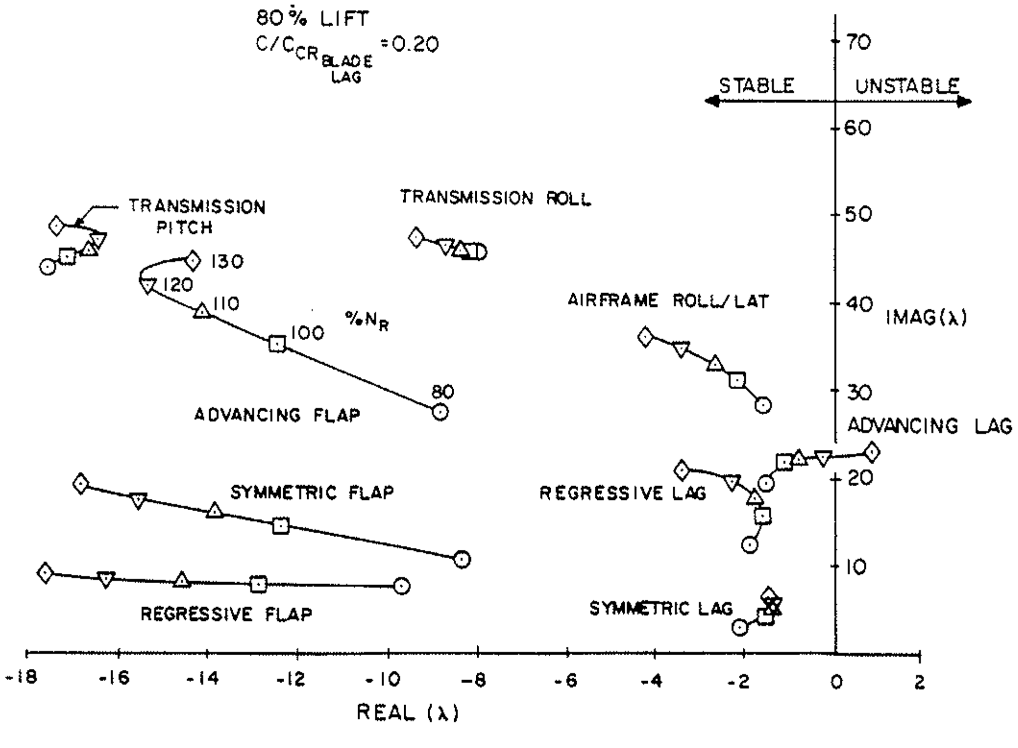



Figure 6. RSRA/AIBS Ground Resonance Stability.

Figure 7 presents a similar root locus plot for the system in flight. Thrust levels are at 1.5 g's. All modes are stable, due primarily to the absence of significant coupling between rotor and fixed system modes as was evident in the ground resonance analysis results.

Since the characteristic frequencies of the stability augmentation system (SAS) are within the range of isolator and rotor frequencies, the potential for SAS/rotor/isolator coupling was considered high. The analysis which was used to evaluate the influence of the isolator on the handling qualities of the aircraft was the Sikorsky GENHEL program appropriately modified to model the isolators. GENHEL is a flight simulation program (maneuvers and level flight) which has an excellent representation of the fully coupled rotor, fuselage and control system. As a result of the analysis of the SAS/isolator interaction, the only significant modification to the SAS was the introduction of a 1.3 Hz second order filter in the roll channel to stabilize a lightly damped oscillation at 4 Hz, which is the rotor lag forward whirl mode frequency.

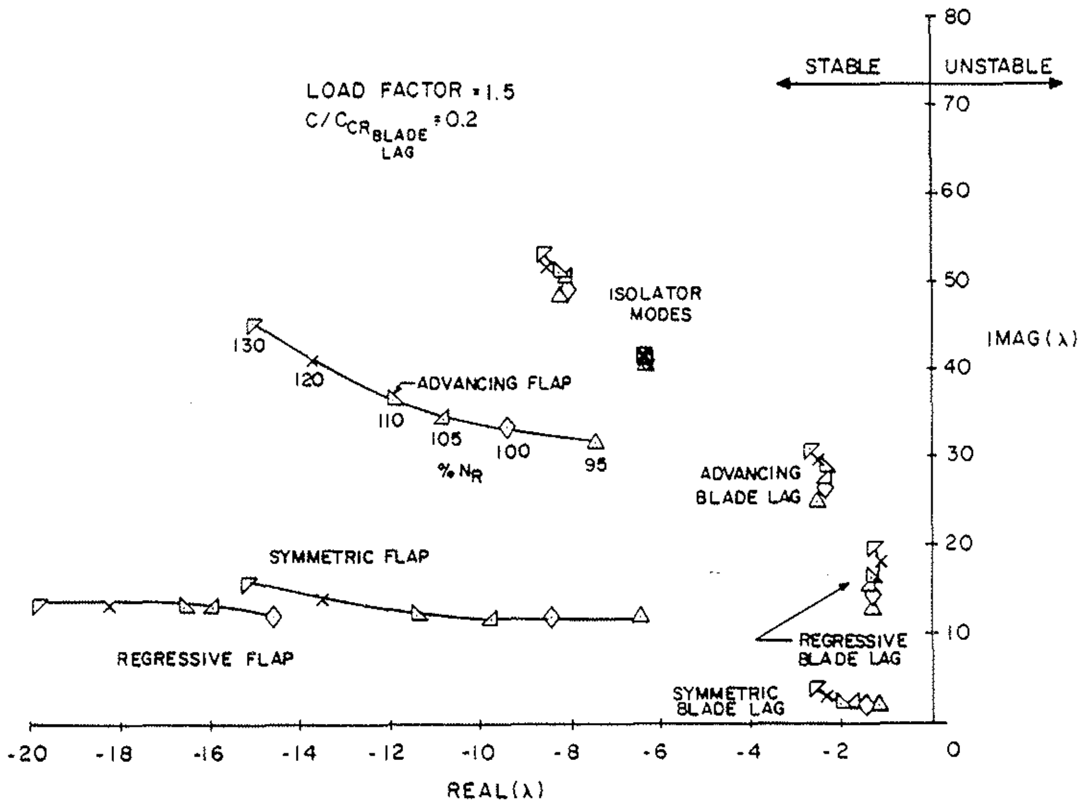



Figure 7. RSRA/AIBS Inflight Whirl Mode Stability.

The effect of the active isolation system on the response of the RSRA to control inputs is illustrated in Figure 8. The curves presented are for the final SAS and isolator configurations. The conditions of isolator active and isolator locked are compared. The frequency response plot shows that there is no loss of amplitude and very little shift in phase due to the presence of the isolator within the pilots operating bandwidth. Therefore it is unlikely that the pilot will detect any delay in A/C response due to the travel of the isolator. A slight reduction in the frequency and damping of the coupled advancing rotor lag mode is noted. The frequency is high enough however, so as not to affect PIO tendencies and the modal damping level is sufficient to provide satisfactory stability margins.

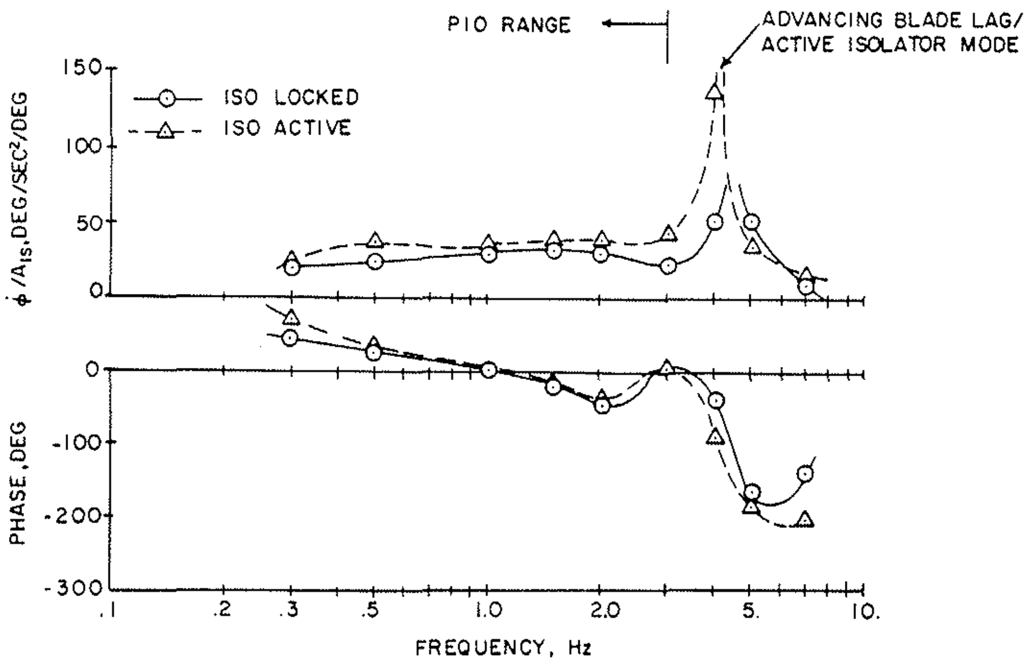



Figure 8. Effect of Active Isolator on RSRA Handling Qualities .

A NASTRAN dynamic analysis of the RSRA with the active isolator installed was performed to evaluate the effectiveness of the isolation system in reducing vibration and to assess relative motion at critical interfaces. Figure 9 illustrates the transmission pitch mode detuning achieved with the isolators. The pilot response to a longitudinal hub shear load is plotted for frequencies ranging from 0 → 20 Hz. The transmission pitch mode frequency at 13 Hz with the isolator locked is shifted to the design value of ~ 8.5 Hz by proper selection of the isolator stiffness.

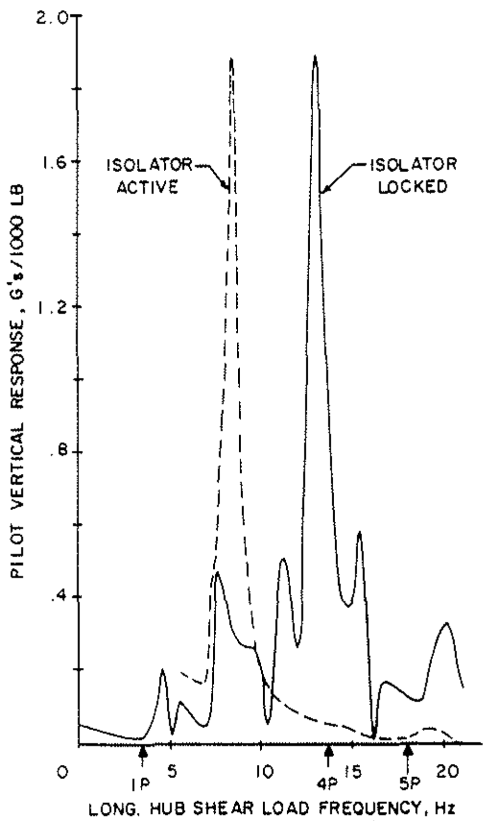



Figure 9. Predicted Transmission Mode Detuning by Active Isolator.

Figure 10 compares all modes of the RSRA with the isolator locked and active. The only significant changes in frequencies occur in the transmission pitch and roll modes.

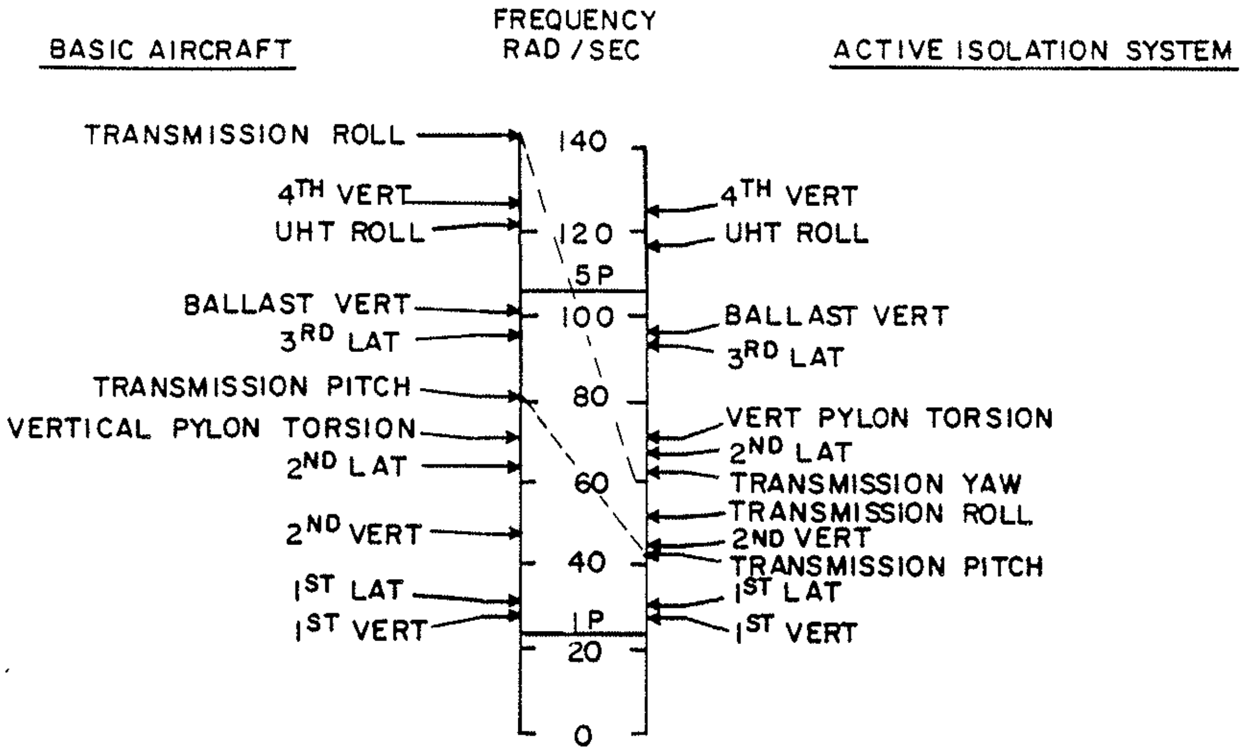
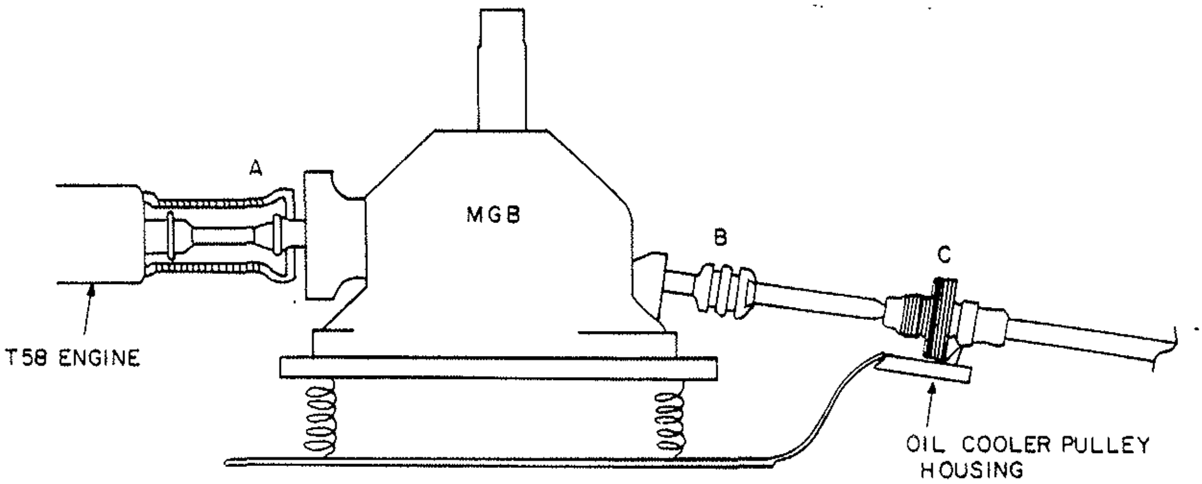



Figure 10. Effect of Active Isolator on RSRA Helicopter Airframe Mode Frequencies.

The results of the transmission/airframe angular misalignment analysis are summarized in Figure 11. The predicted angles are well within allowable limits.




| LOCATION | COUPLING | MAX. PREDICTED ANGLES | | ALLOWABLES | |
|---|---|---|---|---|---|
| | | STEADY | TRANSIENT | STEADY | TRANSIENT |
| A | CROWNED GEAR COUPLING | .5° | 1.3° | 2.0° | 3.25° |
| B | TRIPLE ELEMENT THOMAS | 1.2° | 1.7° | 2.25° | 3.0° |
| C | CROWNED GEAR COUPLING | .4° | .7° | .75° | 1.5° |

Figure 11. RSRA Transmission/Airframe Misalignments.

## 5.0 GROUND TESTS

A series of component and system ground tests were performed to establish that the RSRA with the Active Isolation System installed was safe to fly and functional. The component tests included both strength and functional experiments.

- Axial load fatigue test (isolator locked and active)
- Isolator pressure cycling fatigue test
- Isolator accumulator burst test
- Isolator static deflection test
- Isolator performance and acceptance tests
  - Accumulator bladder
  - Servo valve
  - Force-displacement transfer function
- Isolator damper tests

Based on the strength tests, the lives of the isolator components exceeded the life of the RSRA vehicle (600 Hrs) with the exception of the accumulator bladder which is replaced at 50 flight hour intervals. From a functional point of view the isolator performance tests were the most interesting since they defined the actual dynamic characteristics of the isolator which had heretofore been estimated. Typical results of the tests are shown in Figures 12 and 13 for the lateral isolator. The stiffness of the unit was measured to be very close to the design value and relatively invariant with frequency changes. The phase response of the system was greater than predicted. This would normally be a concern for an isolation system since the effectiveness of such systems are usually sensitive to damping. For the case of the RSRA active isolator however, an auxiliary damper was already a part of the design to insure adequate mechanical stability. The higher than predicted isolator damping thus became a positive factor since it permitted the elimination of the auxiliary dampers.

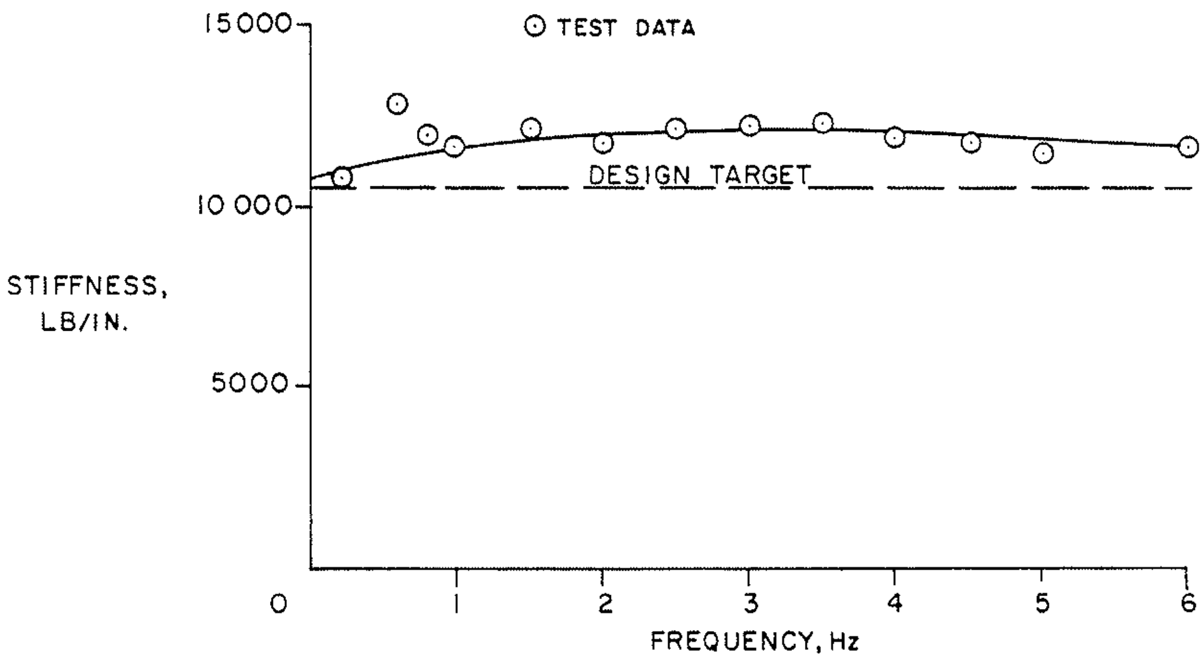



Figure 12. Lateral Isolator Effective Stiffness From Performance Test Results.

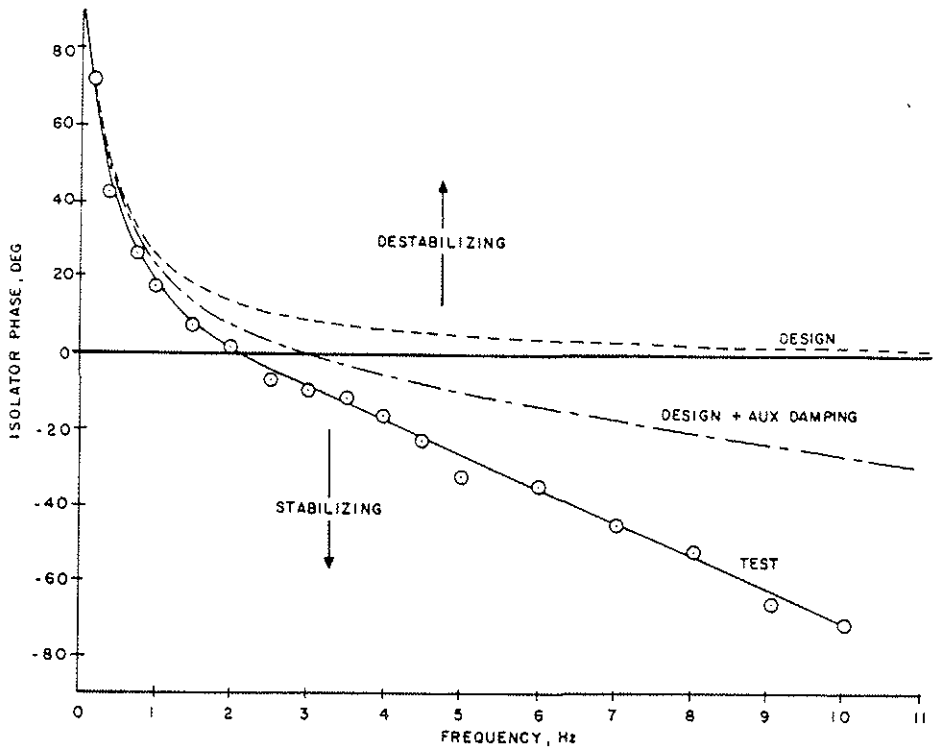



Figure 13. Lateral Isolator Phase Response Characteristics.

System tests which were peculiar to the active isolation system consisted of:

- Static deflection and control coupling tests
- Airframe mechanicial stability shake test
- Airframe shake test

The static deflection tests were conducted to define misalignments at critical interfaces under flight loads and to check the adequacy of the control compensation linkage. As noted earlier the function of the control compensation linkage is to decouple transmission motion from control input. Such coupling can lead to aeromechanical instability if the phase of the relative motions between the transmission and control input is incorrect. The results of the control system coupling evaluation showed the maximum coupled control motion due to transmission pitch motion to be equivalent to ~ $1/2^{o}$ of blade pitch. This degree of coupling is acceptable. The coupling with transmission roll was negligible. The phase of the coupling is favorable for stability producing a slight increase in the least stable system mode (i.e. coupled transmission/rotor lag) of approximately 1 ½% critical damping. It is noted that the controls/transmission coupling which exists is due primarily to friction loading of the control system rather than pure kinematic coupling.

The data acquired during the system static tests relative to misalignments at critical drive system couplings were sufficient to convince us that analytical predictions were valid. The difficulty in applying hub flight loads (moments and shears) simultaneously precluded direct measurement of misalignment angles.

System shake tests were conducted to determine:

- Airframe modes on the ground and at partial airborne conditions for mechanical stability substantiation
- Airframe and engine modes and transmissibilities in flight with the isolation system functioning and locked out
- System frictional characteristics

The first thing that became apparent during the shake tests was that the friction in the system was higher than anticipated. Through a series of diagnostic tests, the sources of most of the friction were identified as the rod end bearings on the load cells and isolators and the bearings in the transmission torque restraint system. The rod end bearings were replaced by a similar design having a different Teflon liner and approximately 1/2 the breakout load. The effect of the friction in the bearings of the torque restraint was minimized by preloading the system so that it was approximately unloaded in level flight at cruise speed. The improvement in breakout loads in the longitudinal and lateral directions achieved with the low friction rod end bearings and the preload torque restrainst system is shown in Figure 14.

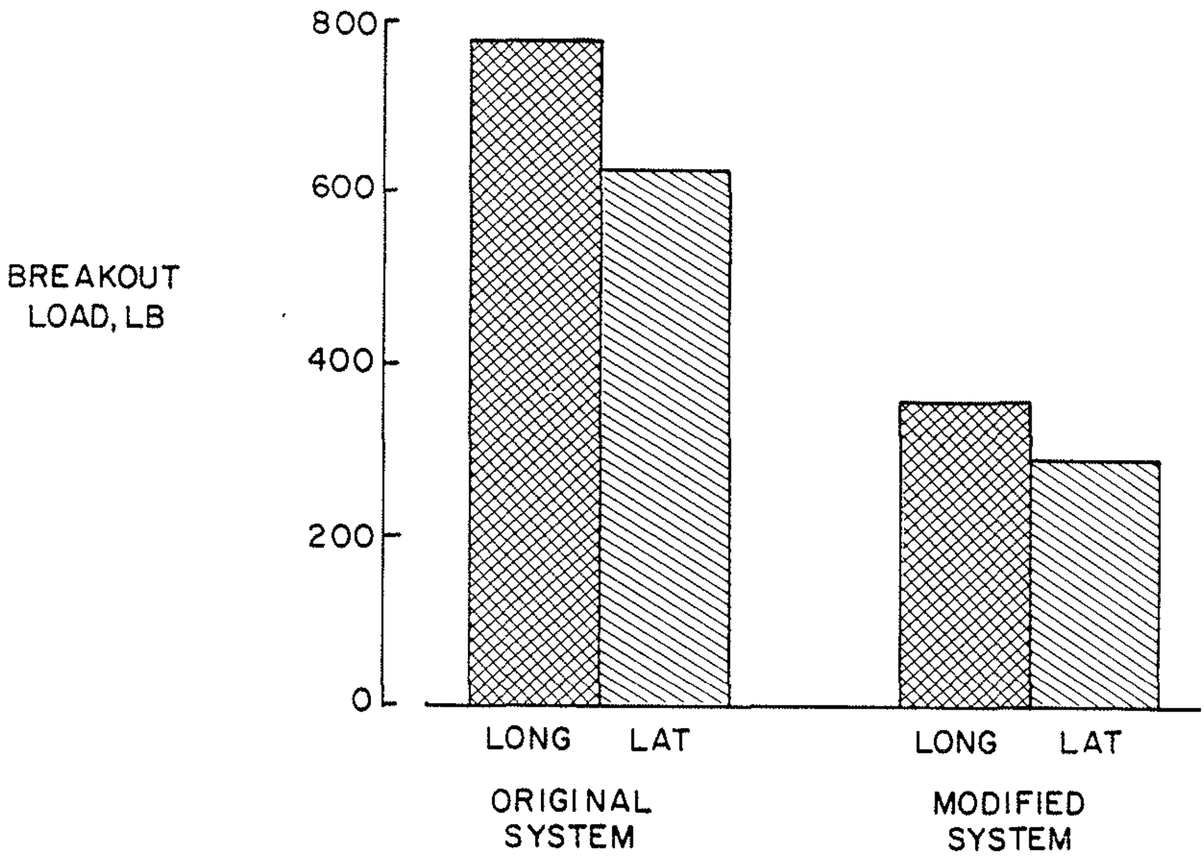



Figure 14. System Static Breakout Loads @ V = 120 kts Based on Component Test Results.

The airframe shake test was conducted using standard methods. The aircraft was suspended with a bungee system which produced a rigid body vertical translational mode frequency below 1 Hz. Hub longitudinal and lateral shear loads were applied with a unidirectional shaker. The aircraft was ballasted to a neutral cg at GW = 19600 lb. For the portion of the test devoted to mechanical stability, a frequency range of 1 → 6 Hz was investigated and the aircraft was supported on both its landing gear and the bungee system so as to simulate 0 → 80 percent airborne conditions. The airframe modes were determined in the frequency range of 5 → 35 Hz, which is 1.5/rev to 10/rev for the S-61 rotor system at 100% $N_R$. All tests were conducted with the isolator system both active and locked out. Applied force levels were varied because of the known friction levels in the system. It was intended to adjust the isolator stiffness and gain values as required to achieve satisfactory system characteristics (mechanical stability and isolation). As it turned out no adjustments were required.

Typical results from the airframe shake test are shown in Figures 15 and 16. The data presented give the pilot vertical response to lateral and longitudinal excitations at the rotorhead. Several observations can be made. First the transmission pitch mode @ ~ 14 Hz with the isolation system locked is detuned to about 9 Hz by the isolator. This frequency placement is acceptable though slightly higher than the design goal of 8.5/rev. The transmission roll mode, also @ 14 Hz with the isolator locked is only slightly detuned (to ~ 12 Hz) by the isolator. The isolator does introduce significant damping into the mode however, sufficient to reduce the transmissibility at the S-61 blade passage frequency (5/rev, 16.8 Hz) by a factor of 3. An as yet unexplained characteristic of the isolation system is an apparent high dynamic friction in the lateral direction which has prevented the achievement of the design transmission roll mode frequency. It is also noted from Figure 15 that the addition of the isolator has a negligible effect on the fundamental airframe bending mode.

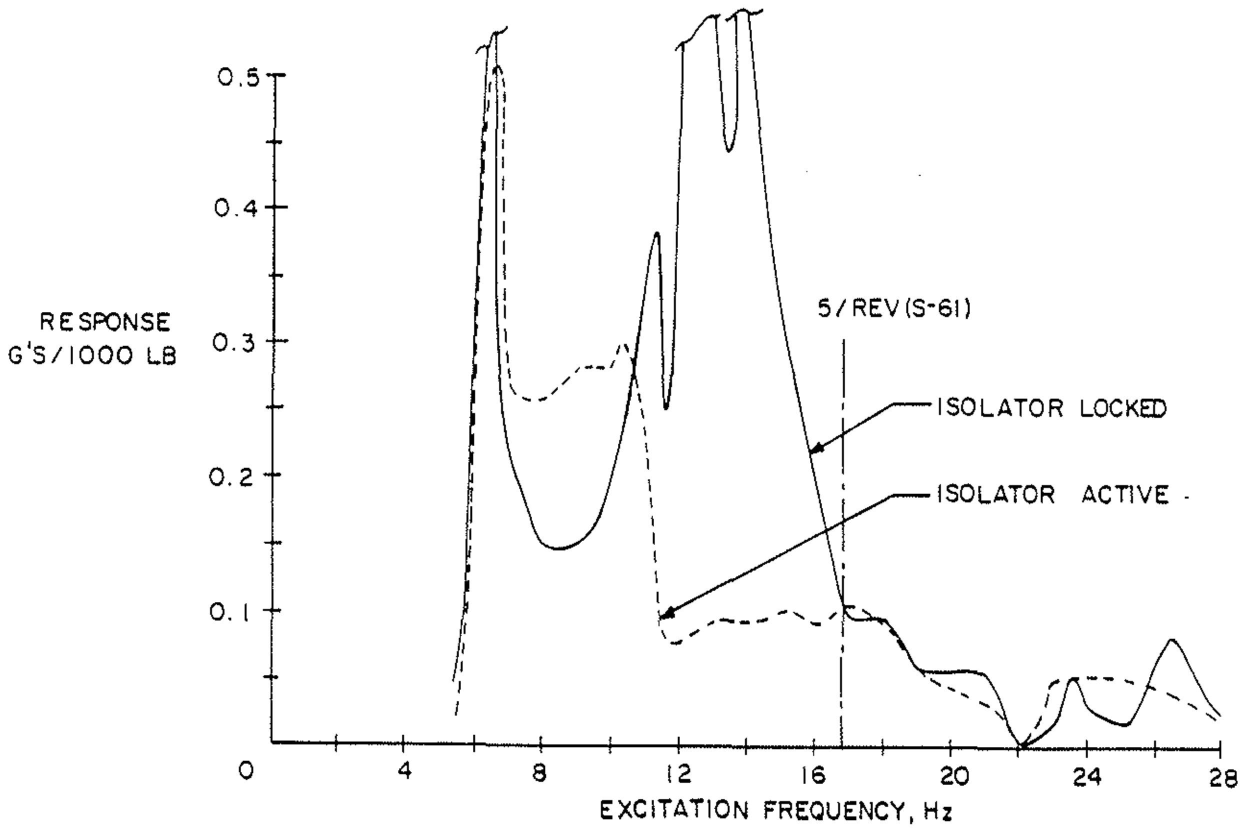



Figure 15. Pilot Vertical Response to MRH Longitudinal Excitation Force (RSRA Airframe Shake Test).

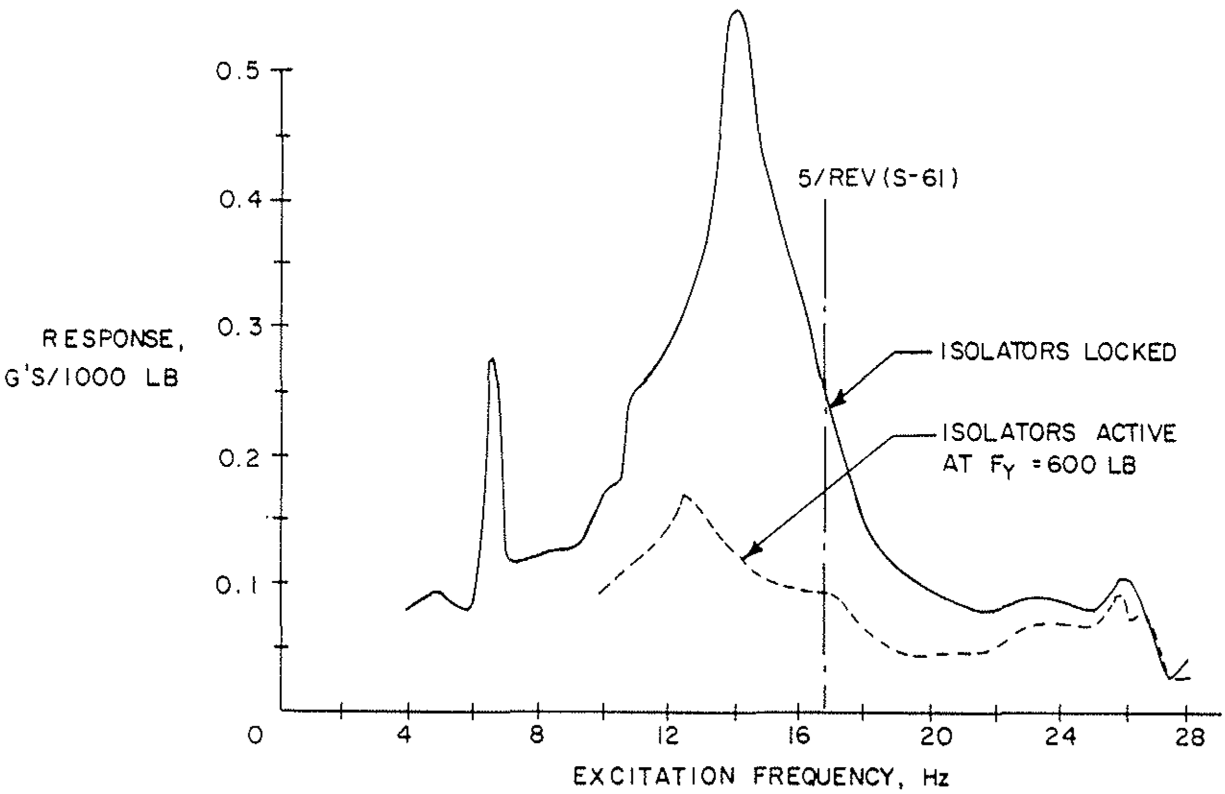



Figure 16. Evaluation Pilot Vertical Response to MRH Lateral Excitation Force (RSRA Shake Test).

The results of the ground resonance shake tests verified the predicted airframe roll/lateral mode characteristics with the isolation system locked. The friction levels with the isolator active, of course, improved the projection of the ground resonance stability margins.

## 6.0 FLIGHT TEST EVALUATION

The objectives of the flight test shakedown and evaluation of the RSRA with the active isolator were the following:

- Functional checkout of systems
- Verify aircraft dynamic stability
- Verify absence of detrimental system couplings
- Monitor critical parameters during envelope buildup
- Conduct limited AIBS vibration/load/motion survey
- Conduct limited T-58 powerplant stress/vibration survey
- Establish RTU vibration and temperature environment

The approach was to expand a flight envelope with isolation system locked equivalent to the envelope already established by RSRA aircraft No. 1 in its standard configuration. Following this, the isolator was activated and the flight envelope re-expanded. Primary emphasis during this initial shakedown flight program was focused on safety issues; mechanical stability, inflight whirl mode stability and structural response and loads. Full evaluation of the functional suitability of the isolator was beyond the scope of the program. There were however sufficient data acquired to determine, on a preliminary basis, the effectiveness of the active isolator in controlling vibration of the S-61 rotor system. Figure 17 summarizes the load factor/airspeed envelope which has been explored with the isolation system active in the RSRA configured as a helicopter.

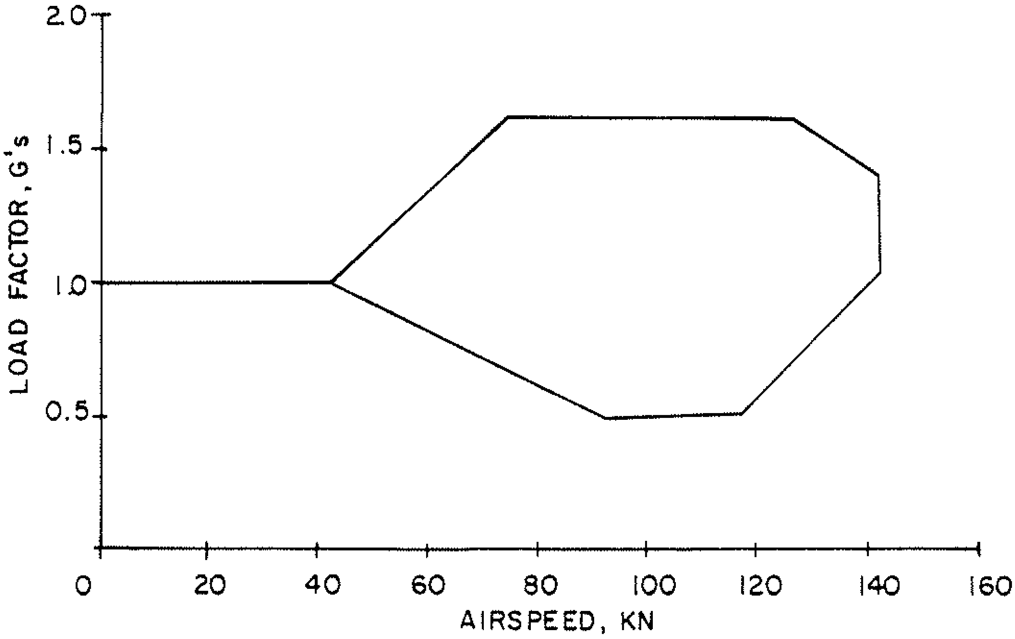



Figure 17. RSRA Load Factor/Airspeed Envelope with Active Isolator, Helicopter Configuration.

The ground resonance evaluation of the RSRA with the isolation system active substantiated that the system stability margins were adequate. A standard cyclic stick stir technique was used to excite the backward lag whirl mode of the rotor. Various rotor speeds and percent airborne conditions were tested. The least stable condition of those tested was 50% airborne at 104% $N_R$ which has a modal damping of 8.5% critical. Test data for this condition are shown in Figure 18. The damping level compares favorably with the predicted minimum damping values which are in the 5-10% critical range depending upon rotor speed, % airborne and lag damper motion.

During the initial hover tests, whirl mode stability of the system was checked with a stick stir technique similar to that used for ground resonance. Both advancing and regressing lag modes were excited. In all cases the damping levels were very satisfactory requiring less than 3 cycles for the induced oscillations to be completely eliminated. The predominant frequency detected in the fixed system during these tests was 1 1/4/rev which is the advancing lag mode frequency. Response at this frequency was also dominant during the analytical simulation work performed prior to flight test of the AIBS.

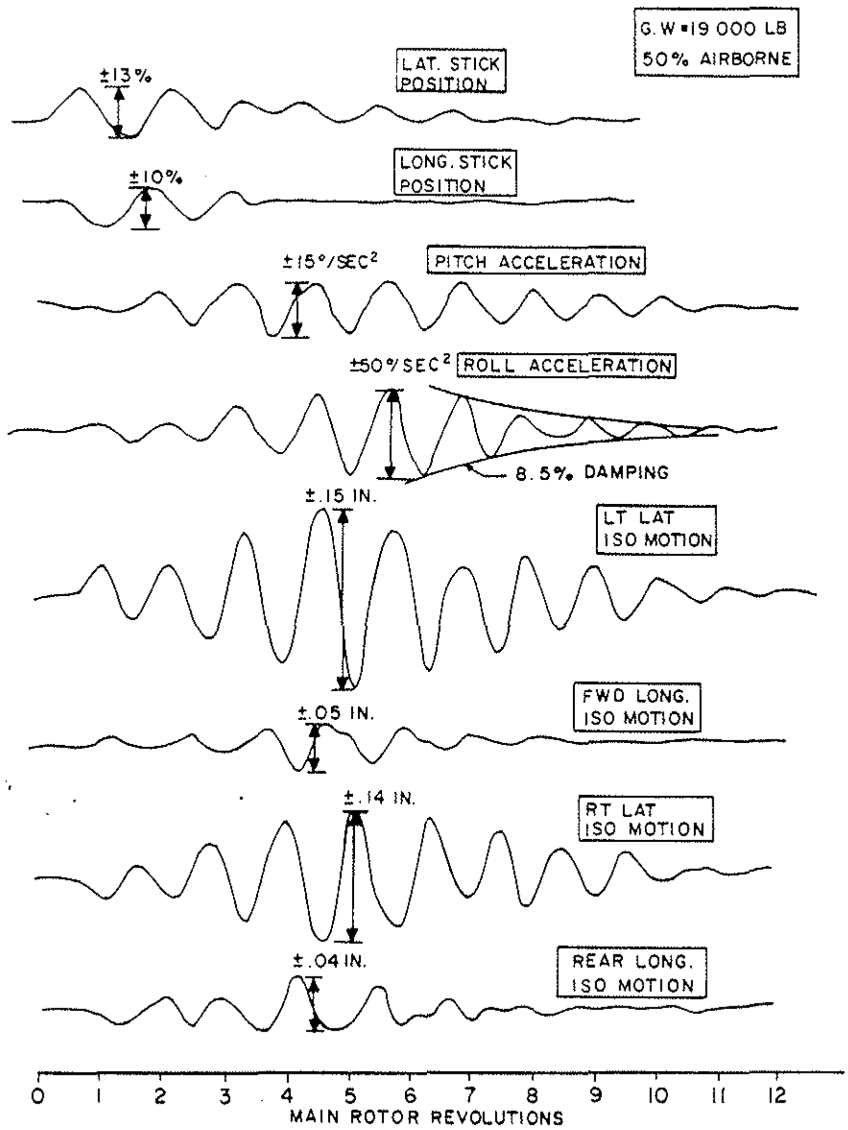



Figure 18. RSRA/AIBS Mechanical Stability Test Data.

As noted earlier a factor which greatly influenced the design of the active isolation system was relative motion at critical interfaces in the drive system. Specifically, misalignments at the main gearbox/ engine coupling, main gearbox/tail drive shaft coupling and the tail drive shaft/airframe coupling had to be controlled within steady state and transient limits in order to achieve satisfactory coupling lives. The effectiveness of the active feature of the isolator in recentering the transmission under flight loads is shown in Figure 19. The angular misalignment of the number 1 and number 2 engine drive shafts are shown versus airspeed and rotor speed for the isolation system active and locked. It is clear that the active feature of the isolators which recenter the system functions very well.

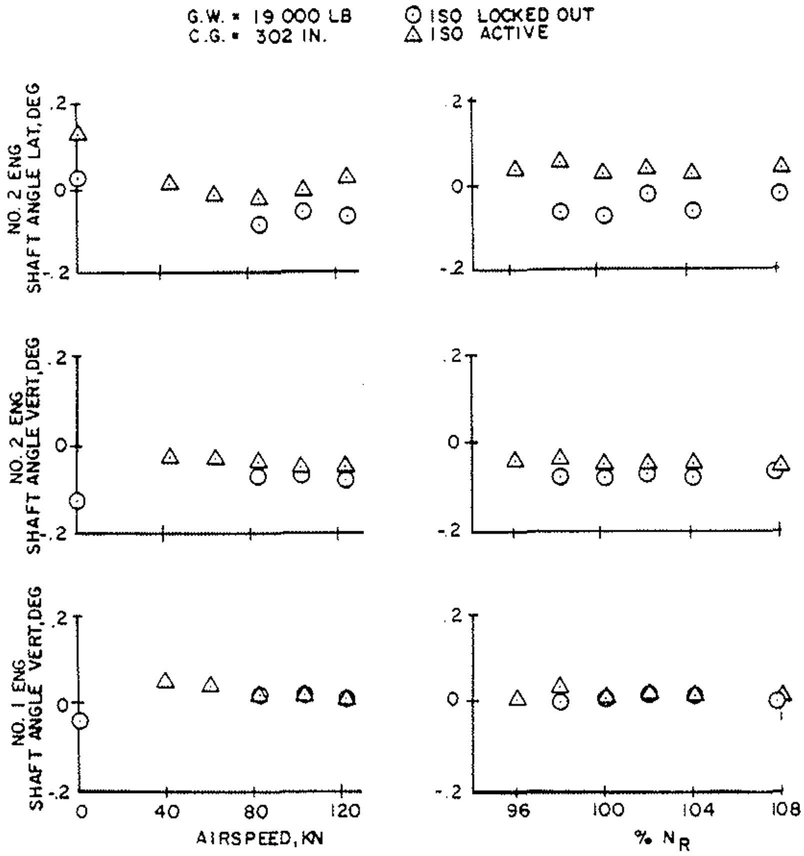



Figure 19. Engine Shaft Misalignments with Isolation System Active.

The active centering feature of the isolators is further illustrated in Figure 20. Time histories of isolator motions during a rapid lateral control reversal are shown. It can be seen that the isolators positions prior to initiation of the maneuver are in a centered position (zero displacement). This indicates that the servo feedback of the unit is exerting a positive control of the gearbox static displacement under flight load conditions. During the maneuver, which is a severe control input from both rate and amplitude standpoints, the lateral units are seen to displace to approximately 30% of their limits (maximum isolator travel is .21 in.), then return to their centered position after recovery from the maneuver. The combination of isolator stiffness and servo-gain have been selected such that for predicted transient maneuver load conditions of the a/c the units displace to positions which are less than the physical limits of the isolators. Due to the frequency dependancy of the isolator displacement feedback feature, the more rapid the maneuver, the larger the isolator displacement. The reversal presented in Figure 20 represents a severe control input. It can be seen that the isolator displacements for this condition remain well within allowable limits suggesting that both isolation and rotor load measurement will be retained during virtually all expected flight conditions which would be typically be tested in a normal research mission.

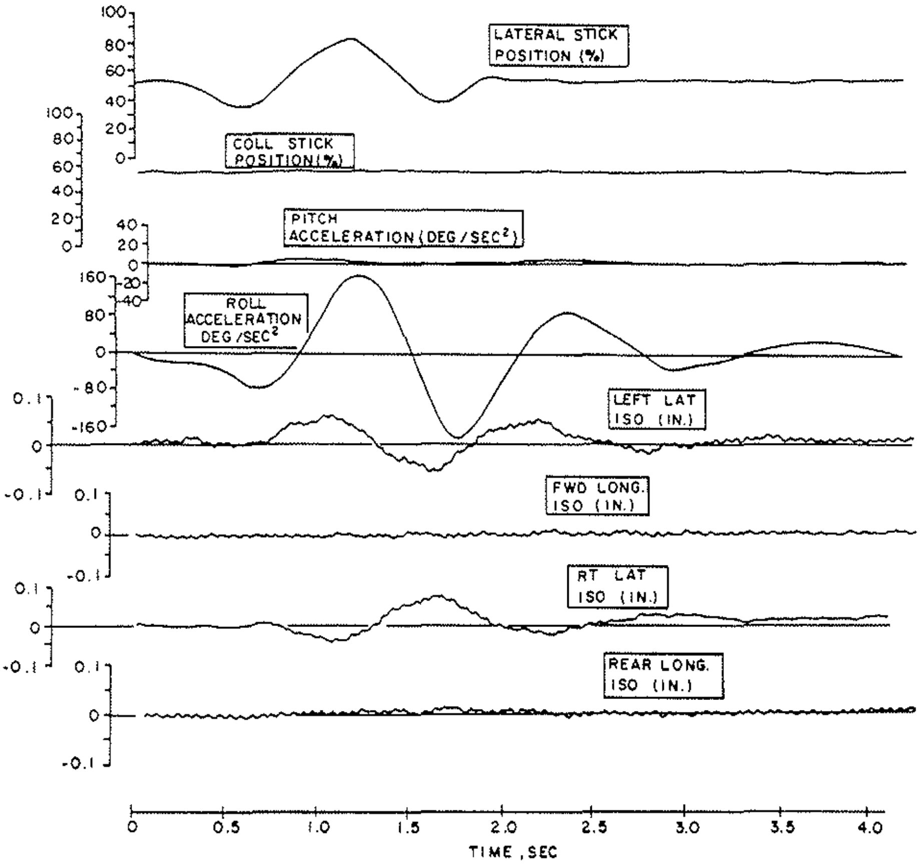



Figure 20. Illustration of Isolator Active Centering Feature During Maneuvering Flight.

Finally the performance of the RSRA active isolation system in controlling airframe vibration is shown in Figure 21. Cockpit vibration data are shown for configurations with the isolator both active and locked out. The curves show that the isolator is effective in reducing the pitch and roll response of the aircraft and has a negligible effect on the longitudinal and lateral vibration. This is as designed. It is also noted that the isolator does not function to attenuate vertical rotorhead forces which are a likely substantial cause of the residual vertical vibration in the cockpit.

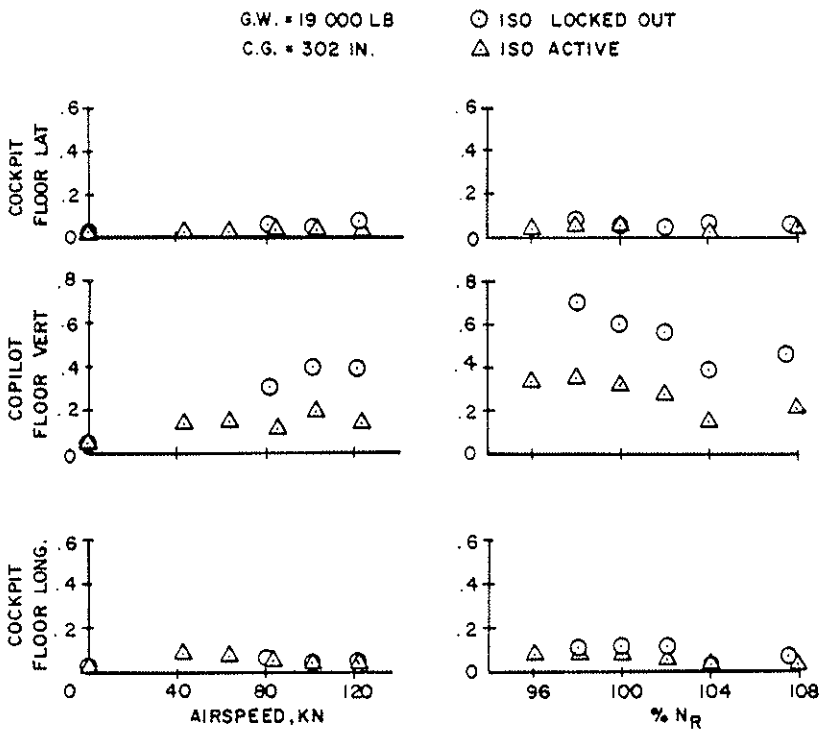



Figure 21. RSRA Vibration with Active Isolator.

## 7.0 CONCLUDING REMARKS

The development of the RSRA Active Isolation/Rotor Balance System has been a success. The requirements of the system were stringent and the hardware relatively complex. In most respects the system has functioned as designed. Available data suggest that the active feature of the isolators will be effective in retaining load measurement over a substantial part of, if not the complete, anticipated research maneuver envelope. The vibration reduction measured during the shakedown flight test program with the S-61 rotor is encouraging. The ability to easily tune the dynamic characteristics of the system for different applications is a strong positive result. The substantiated lives of the isolator components are more than adequate and safety issues appear to be well in hand.

What remains to be done in the near future is to enter in a maturity phase for the active isolation system. This is desireable prior to tests of advanced rotors on the system. This maturity should include the continued development and demonstration of the load measurement feature of the isolators, further work to reduce friction levels particularily in the lateral axis and parametric tests to optimize dynamic characteristics of the isolators to produce minimum vibration levels with the S-61 rotor.

In the future other research uses of the isolation system, perhaps not envisioned at its inception, would be to tune the rotor head impedances of the RSRA through isolator adjustments in order to study the effect of hub impedance on rotor vibratory loads and rotor absorber effectiveness. The tuneable isolators, of course, offer the opportunity to conduct a comprehensive study of the influence of the isolator characteristics on airframe vibration. Finally since the isolator units are active, they offer a unique opportunity to develop active feedback control technology.

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