TWENTY-FIRST EUROPEAN ROTORCRAFT FORUM

Paper No. III.5

ELASTOMERS + FLUIDS + ELECTRONICS = IMPROVED COMFORT AND RELIABILITY FOR AIRCRAFT

J. L. Potter, D. P. McGuire, E. L. Brubaker
LORD CORPORATION
ERIE, PENNSYLVANIA, USA

August 30 - September 1, 1995
SAINT-PETERSBURG, RUSSIA

Paper nr.: III.5

Elastomers + Fluids + Electronics = Improved Comfort and Reliability for Aircraft.

J.L. Potter; D.P. McGuire; E.L. Brubaker

TWENTY FIRST EUROPEAN ROTORCRAFT FORUM
August 30 - September 1, 1995 Saint-Petersburg, Russia

ELASTOMERS + FLUIDS + ELECTRONICS = IMPROVED COMFORT AND RELIABILITY FOR AIRCRAFT

J. L Potter, International Technical Director
D. P. McGuire, Sr. Staff Engineer
E. L. Brubaker, Engineering Specialist

Lord Corporation
Erie, Pennsylvania, USA

Abstract

Engineers have continued to strive for lower vibration levels to improve structural and sub-system reliability and enhance the comfort levels of the passengers and crew in all types of aircraft for years. Passengers and crews in corporate and EMS helicopters and fixed wing aircraft have become more demanding in expecting low vibration and low noise levels within the cabin.

In the current world of reduced defense spending and smaller commercial markets, intense competition has increased the value of product differentiation. Differentiation in the form of lower D.O.C. (Direct Operating Costs), improved R & M (Reliability and Maintainability), and low vibration and noise levels will be a key to success in future markets. Helicopters and tilt rotors will be competing with the fixed wing aircraft for some of the same target markets.

In vibration isolation systems, damping is desirable to control system response at resonance, but it deteriorates performance in the isolation region. The ideal vibration isolator is one in which the dynamic to static stiffness is < 1:1 to reduce the static motion between the vibrating source and the structure while minimizing the transmitted vibration during isolation. Traditional passive devices cannot meet this objective. The introduction of a hermetically sealed fluid within a passive elastomeric isolator can produce a passive device which has a dynamic to static stiffness characteristic of < 1:1.

Electronically controlled actuators or valving can be easily added to passive elastomeric/fluid devices to allow external control. The isolator can "adapt" slowly or respond instantaneously in real time to a vibrating system such that the effective dynamic stiffness will approach zero. This results in the lowest possible transmitted vibration, while maintaining the desired high static stiffness.

The rapid evolution of DSP (Digital Signal Processing) chips has made active cancellation of noise and/or vibration practical and affordable. ANC (active noise control), ASC (active structural control) and AIC (active isolation control) have been developed and flight tested to demonstrate the benefits of this new active technology for controlling vibration and noise.

Traditional energy dissipation devices such as hydraulic or friction dampers, while excellent for controlling resonant conditions are subject to rapid degradation due to wear and environmental exposure. Dampers using high performance silicone elastomers with loss factors up to 0.70 (equivalent C/Cc = 0.35) have been utilized in modern helicopters. Recent developments employing viscous fluids, hermetically sealed within an elastomeric cavity have enhanced the performance of traditional elastomeric dampers.

MR (magnetorheological) fluids which change physical properties when exposed to a magnetic field can be used to create controllable dampers, brakes, isolators, clutches or valves.

The basic theory and performance of elastomeric, fluid/elastomeric, MR devices and fully active, low power consumption, vibration control systems is reviewed with laboratory and flight test results.

Introduction

The need to reduce vibration levels in the helicopter (as well as in fixed wing aircraft) has been understood since the early introduction of this valuable mode of transportation. Vibration reduction is necessary for insuring flight control/stability, improving the life and reliability of sub-systems and components, and improving passenger and crew comfort.

Engineers recognized the benefits of employing isolation systems to address the aforementioned needs since the introduction of engine suspensions for propeller powered fixed wing aircraft (to reduce vibration induced by the prop and reciprocating engines). Early helicopters (i.e., Bell Model 47, Hiller UH-12, etc.) also employed isolators to reduce the vibration from the engines and the pylon.

These early aircraft applications employed the use of elastomeric ("rubber") materials to provide the required flexibility to isolate the unwanted disturbances. Elastomeric materials were selected over metallic springs for many of the following reasons:

- Inherent damping due to hysteresis.
- Designs that were lighter and more compact.
- Long service life with minimal, visual, on-condition inspection and replacement criteria.
- Non-catastrophic failure mode due to very slow crack propagation characteristics.
- Ability to incorporate stiffness changes within the same isolator package quickly.
- Multi-directional isolators.

The need for the isolation of aircraft vibration continues today for the same reasons as in the past. Isolation systems have become more sophisticated to increase performance as well as handle the greater size, payload, range, speed and operator demands to improve passenger/crew comfort. While the introduction of turbine engines reduced vibration from reciprocating engines, the aforementioned changes (size, payload, speed, etc.), and demands by the users for lower vibration levels and noise (interior and exterior) continues. Lower vibration and noise levels have come to be expected by users and are being legislated by various governmental agencies to address health and safety issues.

Significant progress in reducing vibration and noise has been achieved recently in the fixed wing aircraft market through excellent passive and active devices in combination with passive products. Vibration levels are very low and interior noise is approaching a comfortable level of approximately 70-75 dBA.

Helicopters have made similar progress in reducing vibration from main and tail rotors, but interior noise levels, primarily from gearboxes and main/tail rotor interactions, have been generally unchanged, except for special passive interior treatments that are space and weight consuming and offer little improvement at low frequency (< 250 Hz). Very high (> 600 Hz) tones are also prevalent in these interiors.

Significant improvements in R & M (Reliability and Maintainability) as well in D.O.C. (Direct Operating Costs) have been achieved for helicopters through the introduction of elastomeric technology for main and tail rotor bearings and dampers, landing gears, shaft dampers, pylon isolation, and miscellaneous isolators for sensitive avionics, pumps, fans, etc.

Additional refinements in lowering vibration and noise as well as further reductions in D.O.C. are being pursued. Bearingless rotors, composite structures, and sophisticated electronics as well as enhanced vibration & noise and new damper technology is being developed and introduced to support the helicopter needs. A review of the building blocks to achieve the latest technologies follows.

Vibration/Noise Control Basics

Figure 1 demonstrates the effect of adding damping to an isolation system. Damping is a necessity to control system resonances, but it sacrifices isolation at higher frequencies. Traditional passive elastomeric isolators exhibit those characteristics in isolation systems. The amount of hysteresis damping in the elastomeric parts is a physical property of the basic polymer and the specific compounding ingredients. The hysteresis damping for an elastomeric product is represented by the ratio of the damping modulus (G") divided by the dynamic elastic modulus (G').

Figure 1. TRANSMISSIBILITY vs FREQUENCY RATIO for a DAMPED VIBRATION SYSTEM

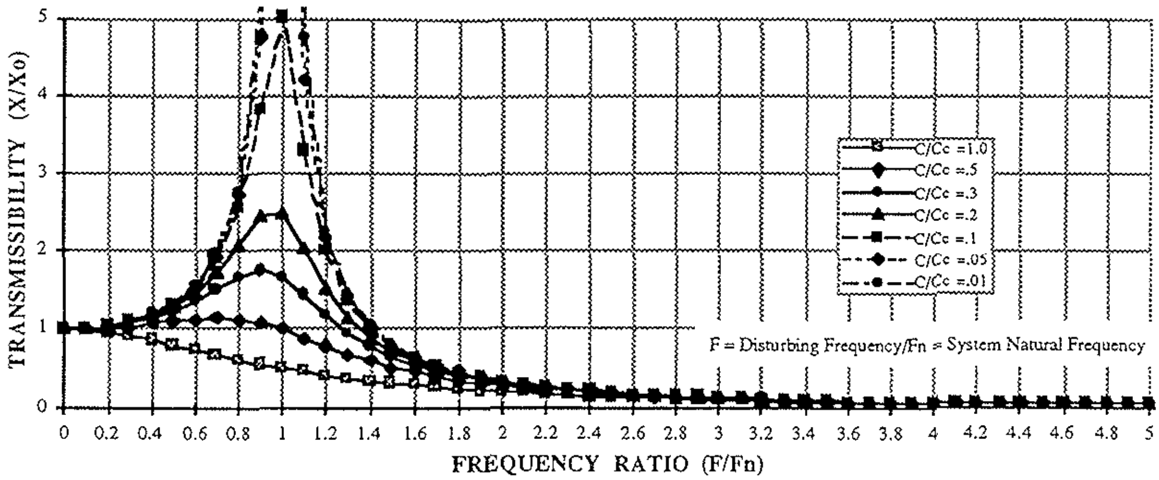
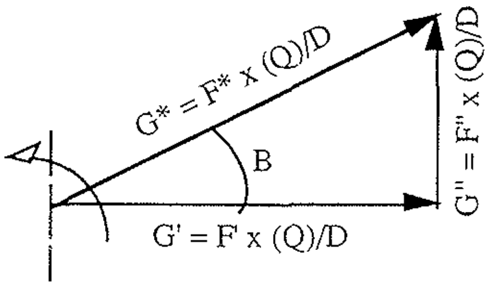


Figure 2 depicts these components. The G'/G" or K'/K" ratio is commonly called the loss factor or tan delta. The equivalent C/C_c (or system damping ratio). for an elastomeric part is:

Elastomeric $C/C_c = 0.5 \times (G'/G'')$ where; C = system damping and C_c = system critical damping

Figure 2. RELATIONSHIP BETWEEN ELASTOMERIC MATERIALS MODULI



$G^* = [G'^2 + G''^2]^{0.5}$

Since stiffness (K) is proportional to moduli (G);

$K^* = [K'^2 + K''^2]^{0.5}$

Where ,

1. F' & F" are rotating vectors, one in phase with the deformation (D) and the other 90 degrees out of phase.
2. Q - Factor depending on size/shape.

G (K) = Static Modulus (Stiffness)
G* (K*) = Dynamic Complex Modulus (Stiffness)
G' (K') = Dynamic Elastic Modulus (Stiffness)
G" (K") = Dynamic Damping Modulus (Stiffness)
Loss Factor (Tan Delta) = G"/G' (Tan B)

Conventional Passive Solutions

Elastomer Characteristics

Typical elastomers can be formulated to exhibit loss factors at room temperature (22°C/72°F) in the range of 0.05 to 0.70 depending on the base polymer and specific ingredients. Figures 3a and 3b exhibit the response of typical elastomers to amplitude and frequency. In designing systems or products with elastomers, it is important to understand that the response is affected by cycling amplitude, frequency and temperature. It is different based on the polymer type (i.e., natural rubber versus silicone) and the specific formulation. Ambient temperature affects the stiffness of an elastomeric product, but cycling reduces the stiffness until it approaches the room temperature value. Figure 4 demonstrates this phenomena for an elastomeric bearing. Various elastomers respond with different specific stiffening factors, but the trend of lowering the stiffness with cycling always occurs. Metallic springs, while generally unaffected by amplitude, frequency and temperature, exhibit very little damping. This is ideal in the isolation range, but totally inadequate in controlling system resonance. Metallic springs provide lower energy storage density and will not be as space/weight efficient as an elastomeric part designed for the identical requirements.

Figure 3a. ELASTOMER RESPONSE vs FREQUENCY

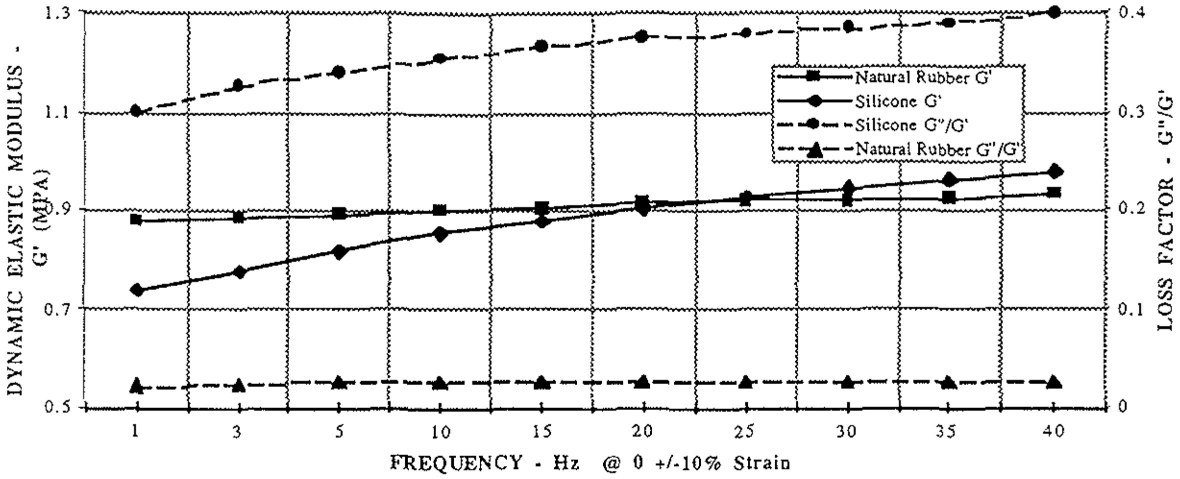


Figure 3b. TYPICAL ELASTOMER RESPONSE vs DYNAMIC AMPLITUDE

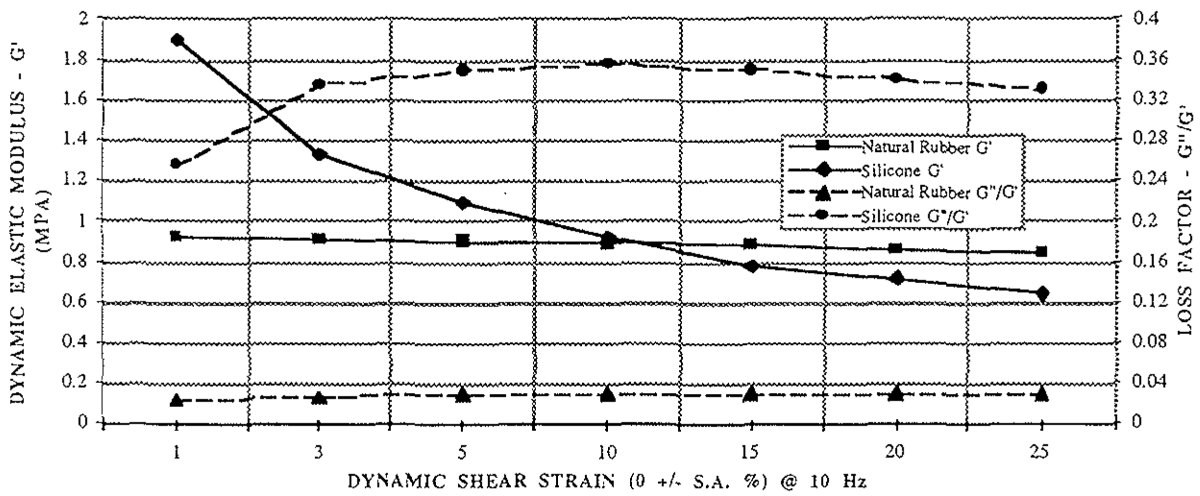
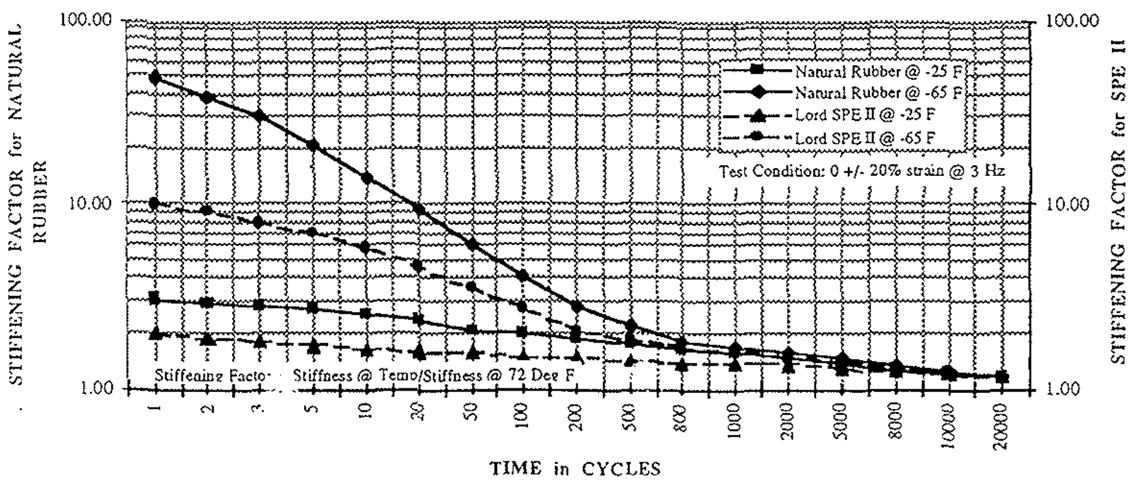


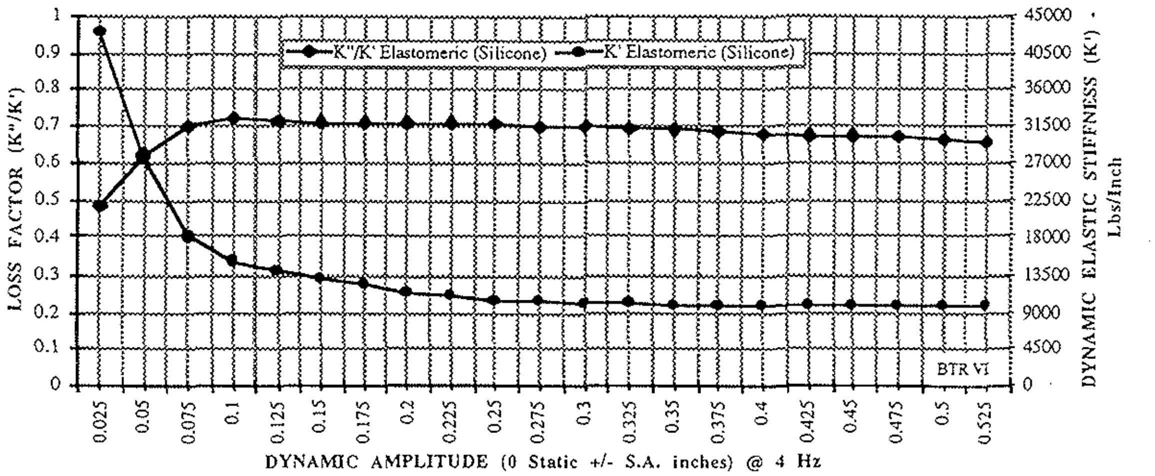
***Figure 4.* CYCLING IMPACT on *LOW TEMPERATURE STIFFENING* of a RADIAL ELASTOMERIC BEARING**



Elastomeric Dampers [1,2]
The elastomeric damper response, shown in Figure 5, can result in inadequate damping and high structural loads at low amplitudes, thus possibly leading to undesirable rotor-pylon system limit oscillation conditions in hover of a soft in-plane rotor. Elastomeric dampers have been in successful production (service lives in excess of 4000 hours) for over 25 years, since introduction on the Aerospatiale SA-341 Gazelle, but the above phenomena, plus a desire to improve the stiffness (K' and K") linearity versus amplitude has been sought.

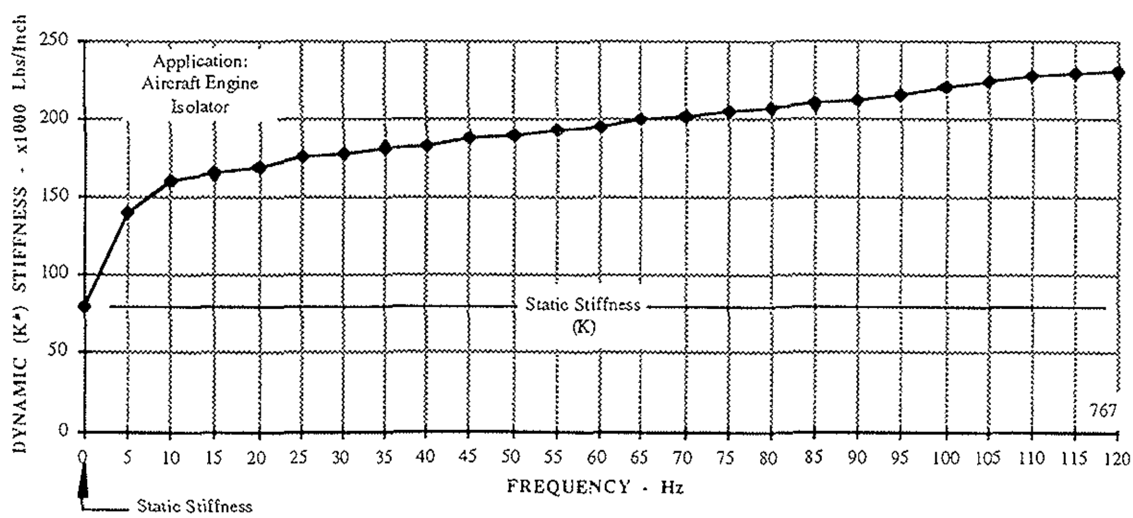
In order to achieve adequate damping for ground and/or air resonance at the highest amplitudes, the normal condition structural loads become higher due to the non-linearities.

Figure 5. TYPICAL CONVENTIONAL ELASTOMERIC DAMPER RESPONSE vs DYNAMIC AMPLITUDE



Elastomeric Isolators
Figure 6 demonstrates a typical elastomeric isolator response versus frequency. Note the dynamic to static ratio (K*/K) is greater than 1.0 - this is always true for a conventional passive elastomeric product and must be taken into account in the system design. The "ideal" device for isolation systems would be where the G*/G or K*/K ratio is less than 1.0, to limit static deflection, while improving dynamic isolation.

Figure 6. CONVENTIONAL ELASTOMERIC ISOLATOR FREQUENCY RESPONSE



Vibration Absorbers
Tuned vibration absorbers (TVA) have been around the aircraft industry for many years with varying degrees of success. TVA's can provide substantial reduction in vibration levels for fixed

frequency or very narrow band disturbances. Most absorbers have used metallic springs. While they are very effective, over a very narrow operating frequency, they can be a maintenance problem with bearings, etc. An elastomeric TVA using special elastomers can be an effective approach to reduce vibration on fuselage structures. Figures 7a-7c show the installation schematic and performance benefits of elastomeric TVA's installed on a fuselage. Figure 8 shows some typical elastomeric TVA's. Elastomeric TVA's are "tuned" at the factory in production. "Field tuning" adjustment capability can be provided; for design optimization during installation development. They offer long, maintenance free life over a broad operating temperature range.

Figure 7a. TYPICAL FIXED WING AIRCRAFT FUSELAGE SECTION WITH TVA's INSTALLED

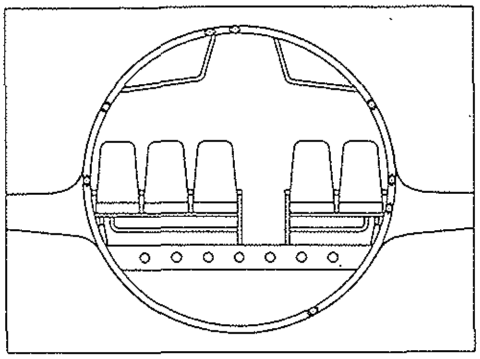


Figure 7b. TYPICAL FIXED WING FUSELAGE WITHOUT TVA's

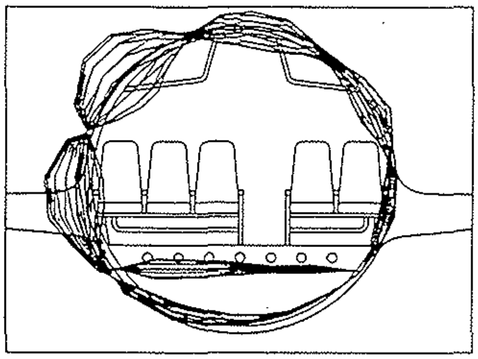


Figure 7c. FIXED WING AIRCRAFT FUSELAGE SECTION WITH BENEFIT OF TVA's

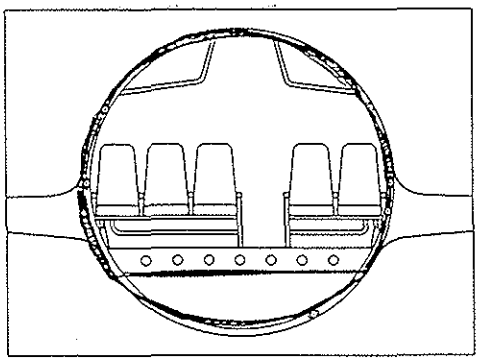
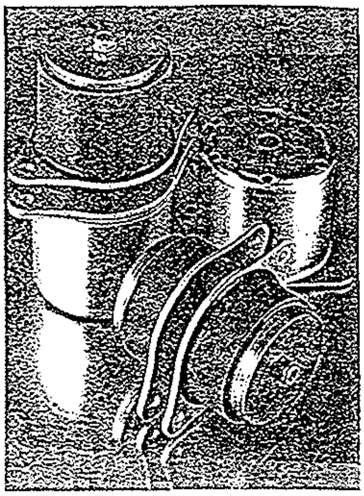


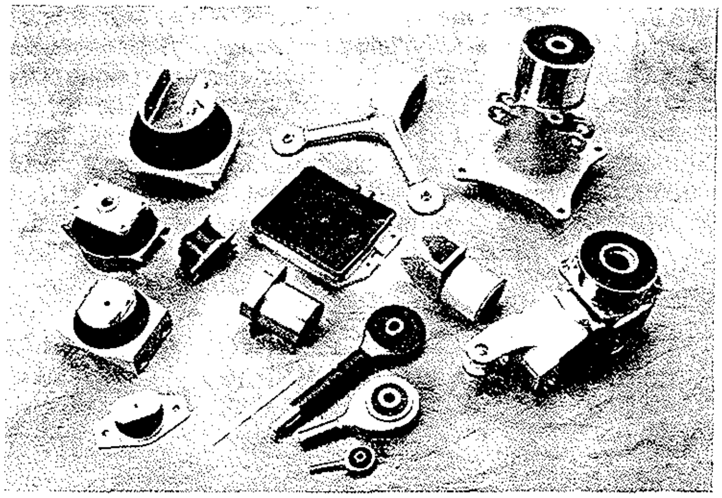
Figure 8. PHOTO OF TYPICAL LORD SILICONE TVA's



Elastomeric Bearings/Pylon Isolators

Elastomeric bearings [3, 4, 5, 6 & 7] have been utilized in helicopter rotor and pylon isolation systems since their introduction into the Bell AH-1 main rotor control system in the early 1970's. Today every major helicopter manufacturer in the world utilizes these high tech elastomeric products to improve R & M and D.O.C. Elastomeric bearings have greatly simplified rotor design by reducing the complexity and the number of individual parts (by a factor of 10 or more compared to metallic bearing systems). Elastomeric bearing technology has contributed to the helicopter's growth. Today's bearingless rotors employ elastomeric pivots/snubbers, dampers and pitch link bearings to provide enhanced performance and R & M for key elements of these advanced rotors. Pylon isolation systems of the past, present and future have utilized the inherent advantages offered by elastomeric technology. Figure 9 is a photo of some typical elastomeric bearings and pylon isolators.

Figure 9. TYPICAL CONVENTIONAL ELASTOMERIC BEARINGS and PYLON INSOLATORS



The introduction and continued technical development of conventional passive elastomeric products and systems for helicopters, tilt rotors, and fixed wing aircraft has been evolutionary. Improvements in design/analysis tools (such as finite element analyses) as well as new, special performance elastomeric materials have been developed to meet customer needs. New manufacturing methods and inspection techniques have also been introduced to insure reliable, cost-effective products.

These conventional passive products have greatly contributed to the military and commercial aerospace/defense success relative to reducing vibration, noise, providing damping and motion accommodation. This success will continue, but the helicopter manufacturer and the industry's customers have demanded even better performance and cost effectiveness in solving the noise and vibration and reliability (D.O.C.) issues facing future markets.

Elastomer + Fluid Technology

While the conventional passive elastomeric products have worked well for many years, the need for performance enhancements has been addressed with the introduction of hermetically sealed fluid chambers inside the conventional passive product. This new class of elastomeric product is still a passive device, since no external control is exercised over the product's static or dynamic response. The use of the sealed fluid's mass and viscosity relative to the product's mechanical configuration and the operational environment (applied vibratory excitation or motion), alter the products response, compared to the identical product without the internal fluid cavity. Inadvertent fluid loss would relegate the product's performance back to that of a conventional elastomeric device.

Generally the following characteristics apply to fluid containing passive isolators or dampers compared to conventional passive:

- Fluids are non-toxic/non-flammable/ non-corrosive.
- Fluids are contained within the elastomer-to-metal bonded product.
- No sliding seals are used.
- Elastomer - fluid compatibility is excellent.
- Dynamic performance is enhanced (dynamic/static stiffness is < 1.0 for isolators; damper loss factors can be higher - i.e., 0.4 to 1.6).
- Product cost slightly (10 to 50%) higher.
- Isolator service lives equal to or greater than traditional passive.
- Deterioration is gradual; benign failure modes.
- Dampers are smaller/lighter and offer increased service life for comparable performance requirements.

Elastomeric/Fluid Isolators

The inclusion of the fluid into an isolator provides some unique performance characteristics not achievable with the conventional passive isolators [8, 9]. Figure 10 shows some typical helicopter and fixed wing aircraft elastomer and fluid isolators (known at Lord as Fluidlastic®). The mass of the fluid, being "pumped" through an orifice (inertia track) creates forces within the isolator which reduce the isolator's dynamic stiffness in a particular frequency range (known as the "notch frequency"), while not affecting the static stiffness. This phenomena creates the "ideal isolator" referred to earlier. The isolator's dynamic to static (K*/K) stiffness will be less than 1.0 in the region of the notch frequency - this minimizes the static deflection of the isolated mass, while providing for improved isolation in the region of the notch. The notch frequency normally coincides with the disturbing frequency. Figure 11 provides a typical stiffness comparison between a conventional passive and a fluid containing isolator. The resulting isolation in the region of the notch frequency would be dramatically improved. System tests of Fluidlastic® tuned isolators have demonstrated over 97% isolation. Figure 12 provides simplified concepts of the conventional passive, orifice damped and Fluidlastic® isolators and relative stiffness and loss factor comparisons.

Figure 10. TYPICAL FLUIDLASTIC® ISOLATORS for HELICOPTER and FIXED WING AIRCRAFT

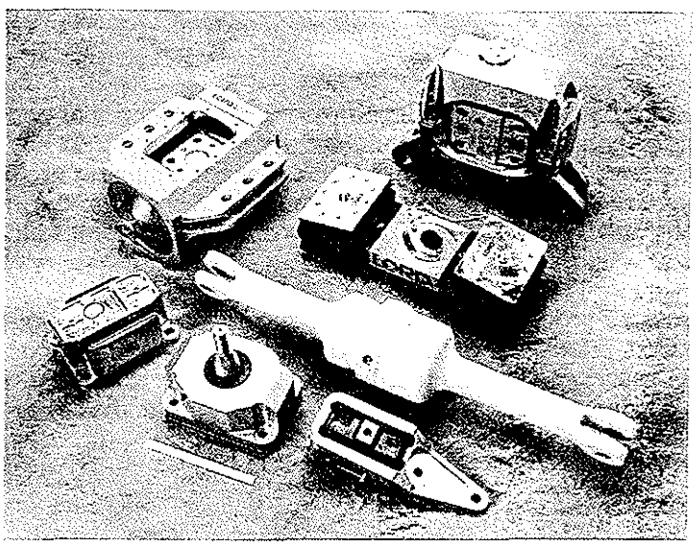


Figure 11. CONVENTIONAL ELASTOMERIC vs FLUIDLASTIC® ISOLATOR FREQUENCY RESPONSE

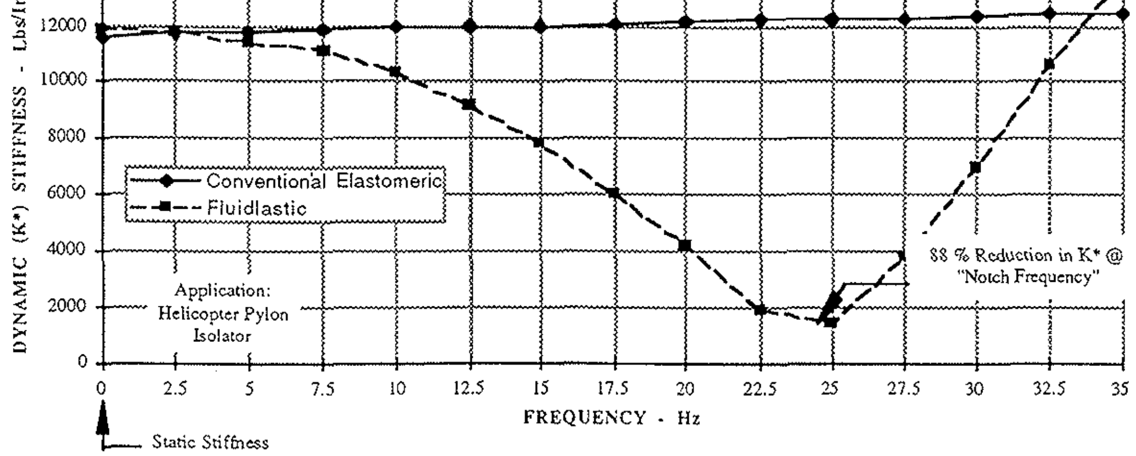
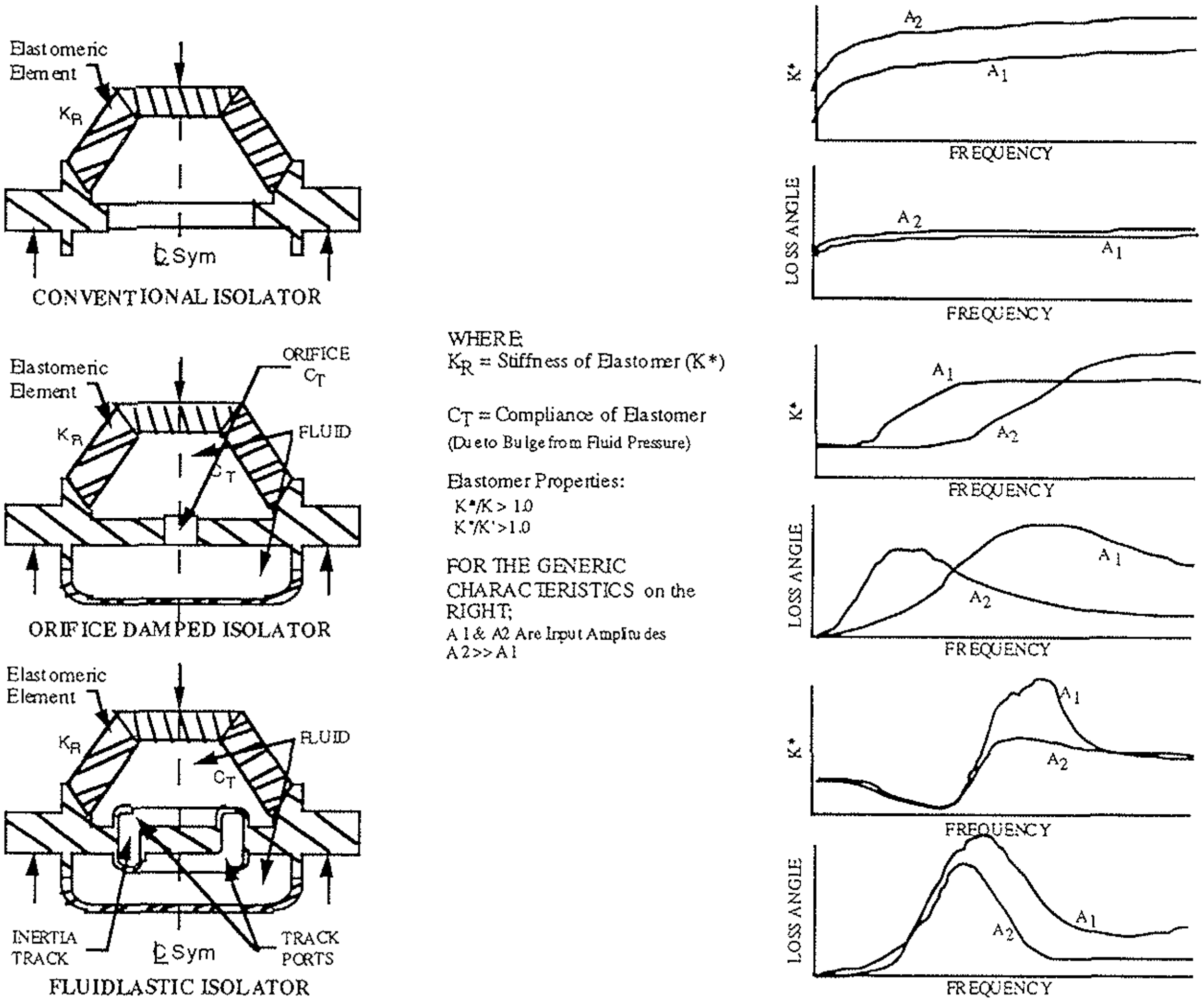


Figure 12. SIMPLIFIED SCHEMATIC COMPARISONS of PASSIVE vs ORIFICED DAMPED vs FLUIDLASTIC® ISOLATORS



Elastomeric/Fluid Dampers

The elastomeric rotor dampers used for many years have used special formulated silicone elastomers to achieve loss factors (K'/K") of up to 0.70 in the normal operating range. A desire to increase the loss factor and/or improve linearity (i.e., K' versus dynamic amplitude) has resulted in the development of patented fluid containing Fluidlastic® dampers [5], where no sliding surfaces are used, thus greatly improving life as the environment (i.e., sand/dust) does not affect the elastomer which hermetically seals the fluid. Damping from this elastomer/fluid device results from a sharing of the hysteresis damping of the elastomer and the fluid via orifice damping. Typical damper characteristics are shown in Figures 13a-13c. Improvements in linearity and increases in the loss factor (up to 1.5 are possible) can be noted. A concept drawing of the elastomer - fluid damper can be seen in Figure 14.

Figure 13a. TYPICAL FLUID/ELASTOMERIC vs CONVENTIONAL HYDRAULIC DAMPER RESPONSE vs FREQUENCY

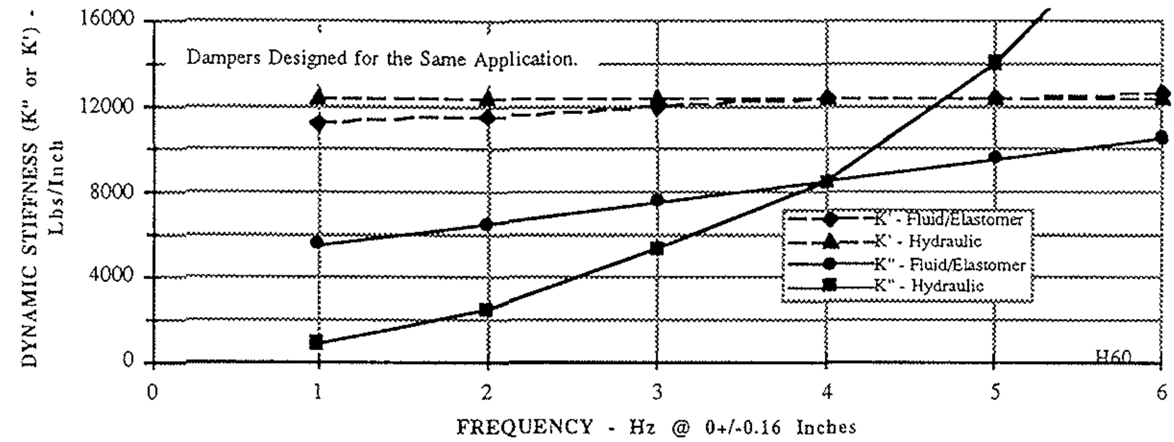


Figure 13b. TYPICAL FLUID/ELASTOMERIC DAMPER STIFFNESS vs FREQUENCY

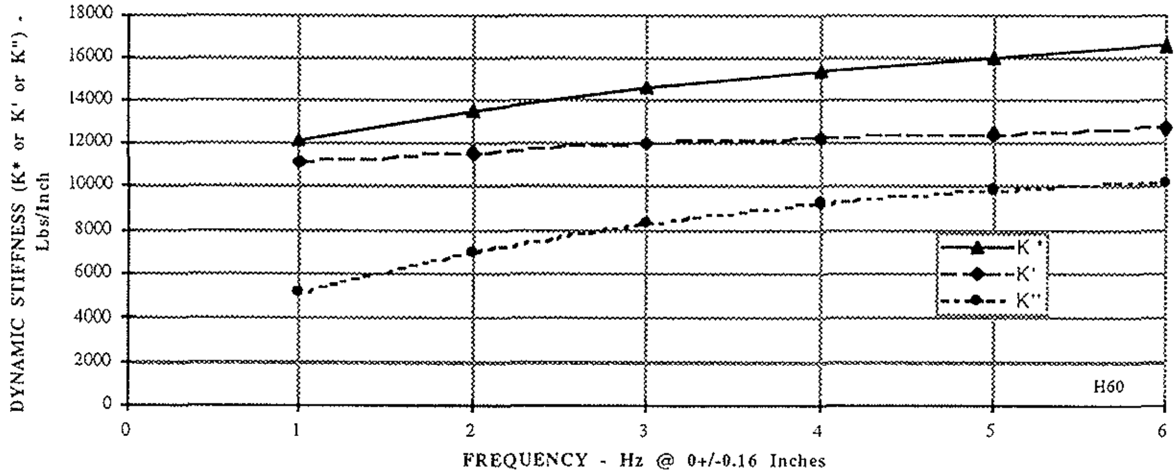


Figure 13c. FLUIDLASTIC® DAMPER STIFFENING @ LOW TEMPERATURE

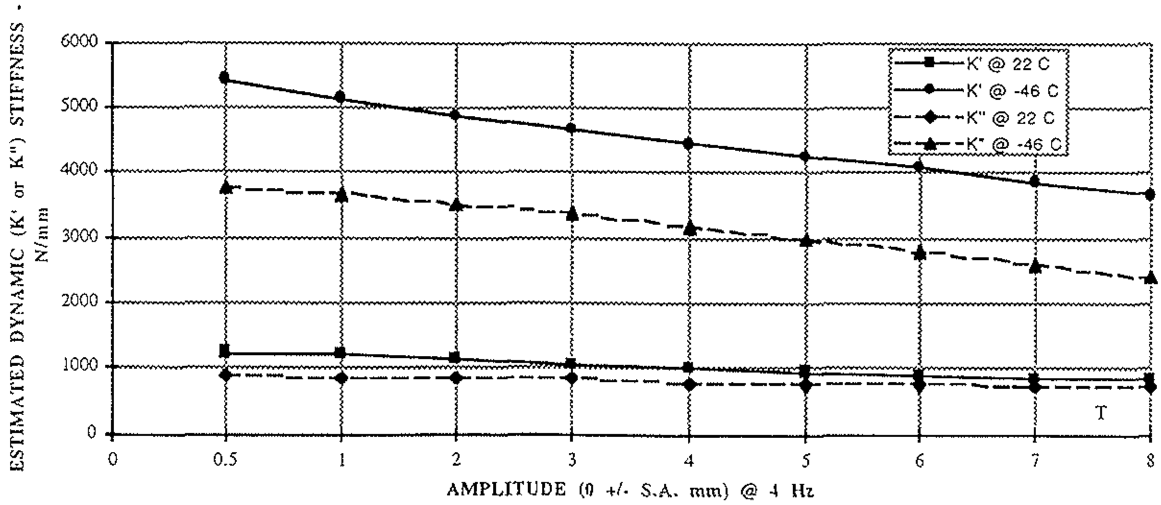
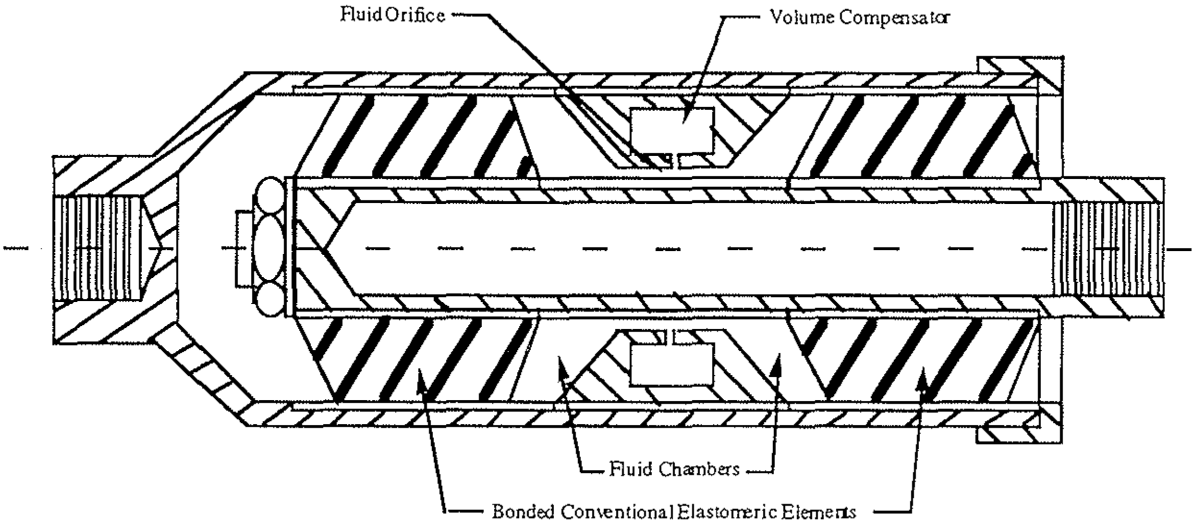


Figure 14. FLUID/ELASTOMERIC DAMPER CONCEPT
(Cylindrical Version Shown)



Elastomeric/Fluid Damper/Bearing

A unique elastomer pivot (bearing) combined with the elastomeric/fluid damper technology can be noted in Figure 15. This device [10] accommodates pitch and flapping motions as well as structural deflections due to centrifugal force while reacting pitch control forces and providing lead-lag damping for a bearingless, soft in-plane rotor. The one (1) piece construction and the use of the elastomer/fluid damping technology combined with an elastomeric bearing allows a very compact/ lightweight part in the main rotor (2 parts/blade are used). Figure 16, conceptually shows the installation of this damper.

Figure 15. FLUIDLASTIC DAMPER/PIVOT for a NEW BEARINGLESS SOFT IN-PLANE ROTOR

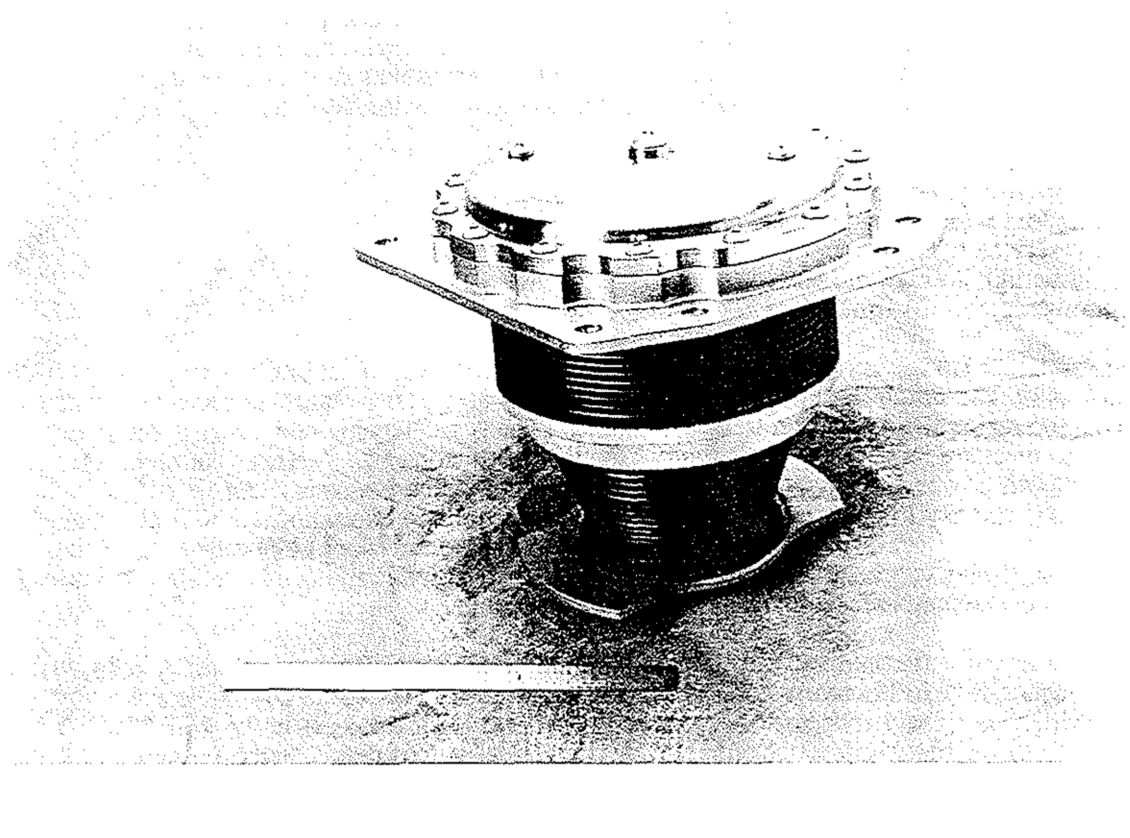
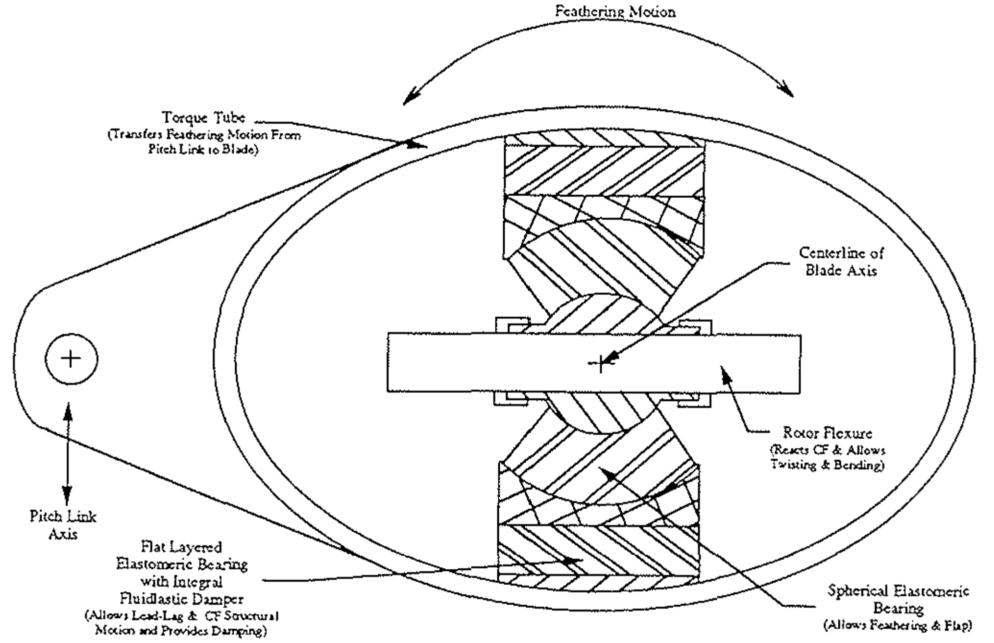


Figure 16. CONCEPT of an INTEGRATED FLUIDLASTIC® DAMPER/ELASTOMER PIVOT for a BEARINGLESS ROTOR



The proven elastomeric bearing technology, pioneered by Lord, coupled with the elastomer/fluid concept provides new opportunities for applying non-hydraulic dampers to fully articulated rotors, where conventional silicone elastomeric dampers were not practical due to the large motion requirements. Elastomeric/fluid damping can also be applied to landing gear and shaft dampers.

The elastomer/fluid combination has been demonstrated successfully as a means to improve the performance of isolators and dampers. These products are now in production on several new helicopter programs.

Semi-Active/Adaptive/Active Technology

Active systems have been introduced years ago to improve vibration and shock isolation for industrial [11, 12] and aerospace/aircraft applications [13, 14], with some success. While these early active systems are theoretically very good for vibration and shock attenuation, their commercialization has been limited due to some of the following reasons:

- Weight and size.
- Power (hydraulic and/or electrical) consumption.
- Complexity (actuators, valves, electronics).
- Low service life.
- Non-benign failure mode.
- Computer control limitations.

A semi-active/adaptive/active system (known at Lord as "NVX™" systems) can be simply defined as one in which the system output device (i.e., actuator, isolator, speaker) responds to sensors measuring the excitation to be attenuated. The typical system basically consists of at least sensors to measure input and output, output devices (actuators, isolators, speakers), an electronic controller and power supply. The differences between the semi-active, adaptive and active systems is primarily in the speed which the output responds to excitation inputs. The semi-active system could be an on or off type response, while the adaptive would be continuously changing its response slowly (over seconds - i.e., versus engine rpm) while the active (sometimes referred to as fully active) would respond in real time or milliseconds.

The introduction and commercialization of DSP (Digital Signal Processing) chips has contributed to the practicality of effectively employing active systems. The ability to handle the many complexities associated with sophisticated mathematical algorithms made the DSP chip mandatory in the electronic controller for medium to high frequency systems where tonal and broad band disturbances are to be attenuated.

For this discussion let's discuss three (3) approaches:

1. ANC - Active Noise Control
2. ASC - Active Structural Control
3. AIS - Active Isolation Control

Active Noise Control (ANC)
The ANC approach has been around for several years, where accelerometers and/or microphones are used as sensors and the actuators are loud speakers. ANC employs the principle of "anti-noise", where a noise of equal magnitude but opposite phase to the disturbing (input) is used to cancel the unwanted noise source. ANC can be very effective at reducing noise levels at low frequency (i.e., ≤ 250 Hz) in an enclosure such as a fuselage. ANC performance is very dependent on the acoustic dynamics within the enclosure — adding damping to a structure that is lightly damped with a low modal density can significantly reduce the interior noise. The addition of the required passive damping and soundproofing is many times impractical (bulky and heavy) due to the long wavelengths of the low frequency sound.

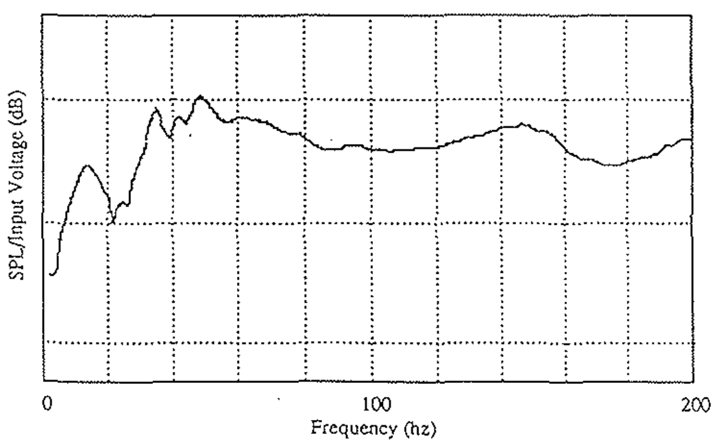
Passive treatments are generally more effective in reducing high frequency noise, where the acoustic modal density is high.

In order to determine the nature of the acoustical dynamics [15] of a typical light helicopter fuselage, microphones and speakers located in the cabin were used to measure frequency response functions (FRF). A typical FRF for a helicopter is shown in Figure 17. It can be noted that below 70 Hz, the acoustic response exhibits lightly damped modal behavior, while above 70 Hz, the sound field becomes more heavily damped. The transition between low and high modal overlap can be analytically determined by calculation of the Schroeder frequency [16, 17]. This frequency — a function of modal density and acoustic damping — can be approximated by :

$f_{Sch} = 2000 \times (T60/V)^{0.5}$ where T60 = reverberation time (seconds),
V = volume of the enclosure (cabin),
and a sound speed is assumed at 360m/sec.

For the light helicopter cabin evaluated, this calculated to be about 70-100 Hz. Since the cabin exhibited lightly damped acoustic behavior below the Schroeder frequency, an ANC system can be expected to provide global interior noise below this frequency.

Figure 17. TYPICAL FREQUENCY RESPONSE FUNCTION (FRF) BETWEEN A SPEAKER AND MICROPHONE IN A SMALL HELICOPTER INTERIOR



At higher frequencies, only localized noise reduction at the mic error sensors will be possible. As discussed in Reference [17], there are three basic guidelines which govern whether an ANC system will provide global (ideal solution) or local (small "spheres of quiet") interior noise reduction:

1. Global control of interior noise is possible in frequency ranges where the acoustics display lightly damped, low modal density.

2. Global interior noise control in sound fields above the Schroeder frequency (high modal density and overlap) can be achieved only when the speakers (actuators) are located within 1/4 wavelength of the sound in air from the source.

3. For cases where (1) and (2) do not apply, only localized noise reduction can be achieved at the mic error sensors. The "sphere of quiet" would have a diameter approximately 1/10th the wavelength of the sound in air. For example a 200 Hz noise would have a wavelength of approximately 170 cm (6.8 in.) — hence reduction in noise outside a sphere of, 170/20 ≈ 8.5 cm (3.4 in.) would be impossible.

This point (3) again provides a limit on the benefits of ANC for aircraft fuselages, depending on the FRF and the physical layout of the fuselage interior.

Laboratory [15] and subsequent flight testing of an ANC system inside a light helicopter demonstrated that interior noise (tones below ≈ 250 Hz) reductions of 7 to 13 dBA can be expected in the plane of the passenger's heads. Subjective improvement in interior sound quality was better than experimental measurements would indicate.

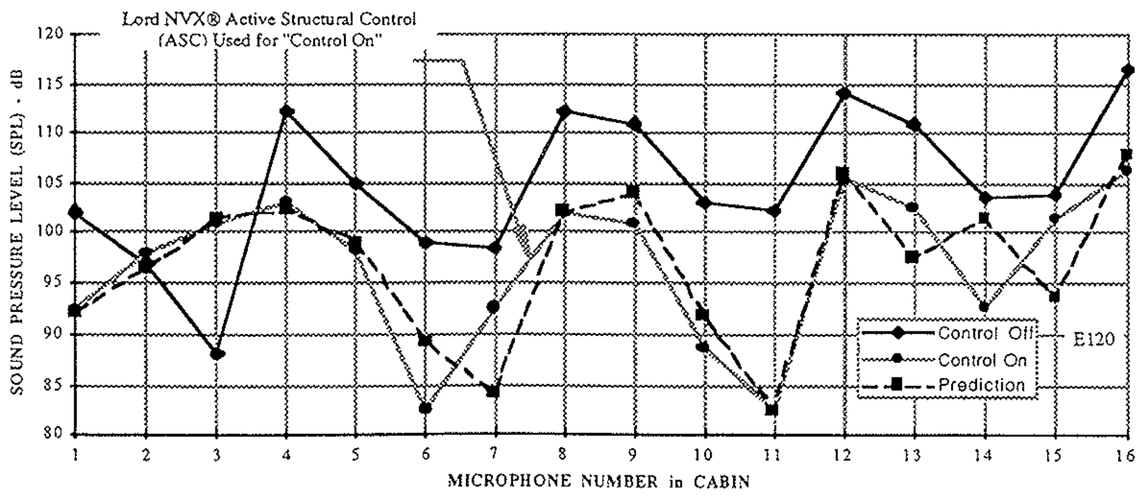
High frequency (i.e., gear noise) interior noise cannot be reduced by the ANC approach. The use of TVA's (Tuned Vibration Absorbers) and sound deadening materials can be employed but with weight and space penalties. Flight testing as a follow on to the Reference [15] work demonstrated the feasibility that once the sources and the noise transmission paths are understood, ANC in combination with ASC technology will probably be the lightest and most effective from a performance and cost viewpoint.

Active Structural Control (ASC)
The ASC approach is characterized by the placement of small, lightweight actuators (i.e., electromagnetic, piezo-ceramic, magnetostrictive, etc.) on the vibrating structure to produce a canceling force analogous to the ANC theory. The controller and power supplier can be identical to that used for ANC, while the sensors can be accelerometers and/or microphones.

ASC systems have been flight tested on fixed wing turboprops and fuselage mounted turbofan aircraft. Limited testing in helicopters has been completed with excellent results up to 650 Hz. Production of these ASC solutions has begun, with continued development of high frequency/high force output actuators continuing in the laboratory.

Depending on the specific application, the use of ASC systems, only, may provide the best performance, while others have used both ANC and ASC. In some cases elastomeric TVA's can also be used in conjunction with ASC. Figure 18 shows the benefits of an ASC/ANC system in a fixed wing turboprop aircraft. Substantial reductions in measured and subjective interior noise levels were realized.

Figure 18. TURBOPROP AIRCRAFT INTERIOR NOISE DURING FLIGHT



In order to effectively implement the benefits of an ASC in a helicopter, the noise paths must be identified and the appropriate actuators installed. A technical challenge here is the development of small, highly efficient (high ratio of output force to actuator weight) actuators capable of operating at frequencies of 500 to 5000 Hz. Controllers with MIMO (Multiple Input-Multiple Output) up to 48 channels are available to handle the expected multiple actuator/sensor locations.

Active Isolation Control (AIC)

AIC is an approach where an actively controlled isolator is located between the vibration (noise source) source and the structure (fuselage) to be isolated. In a fixed wing aircraft, the AIC could be the isolators between the engine and the structure, while in a helicopter the AIC isolators could be located between the main transmission and the fuselage.

Generally in the AIC approach, the isolator employs conventional passive or elastomer-fluid technology to react the normal static/maneuver loads, which is supplemented with actively controlled actuators located within or attached to the isolator. This approach eliminates the need for the actuators to react the static maneuver loads, thus reducing size and weight. In the unlikely event of a loss/failure of the active portion of the AIC, the conventional passive elastomeric isolator continues to function albeit with some decrease in isolation of the vibration/noise. Thus system failure is benign. Also, the dynamic force that the AIC actuators can produce is quite small, so controller malfunction cannot generate excessive dynamic forces in the structure.

Overall, the AIC approach may be the best, from a cost, size, weight, performance, compared to the ANC and/or ASC since the AIC isolator can "choke" off the undesirable vibration/noise at the source, rather than treating it, via ANC and/or ASC, after it enters the complex fuselage structure.

Initial production certification of AIC approach is expected in 1995 on a fixed wing aircraft. The AIC system reduces the undesirable vibration and substantially reduces interior noise levels.

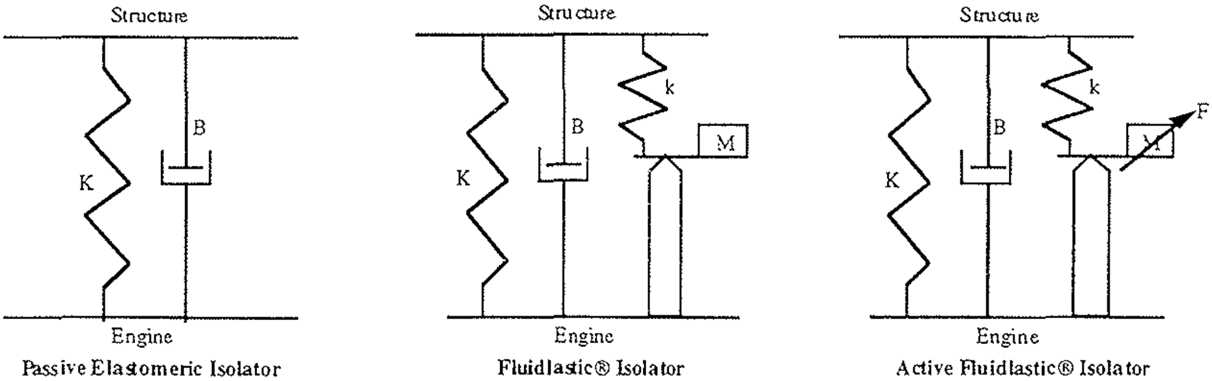
Active Fluid Isolation System (AFIS)

The concept introduced with the passive elastomer/fluid technology earlier, can be augmented to higher levels of performance by adding a small actuator (i.e., electromagnetic) in the fluid flow path. An appropriate controller and sensors are used to further reduce the effective dynamic stiffness and expand frequency range over which the very low dynamic stiffness is achieved.

This AFIS approach is applicable where a broader frequency range (i.e., 1/rev, N/rev, etc.) is to be isolated or isolation for a varying frequency is desirable.

The benefits of AFIS are demonstrated by comparing the various isolation concepts depicted in Figures 19a-19b

Figure 19a. MECHANICAL MODELS of PASSIVE vs FLUIDLASTIC® vs AFIS ISOLATORS



Where;

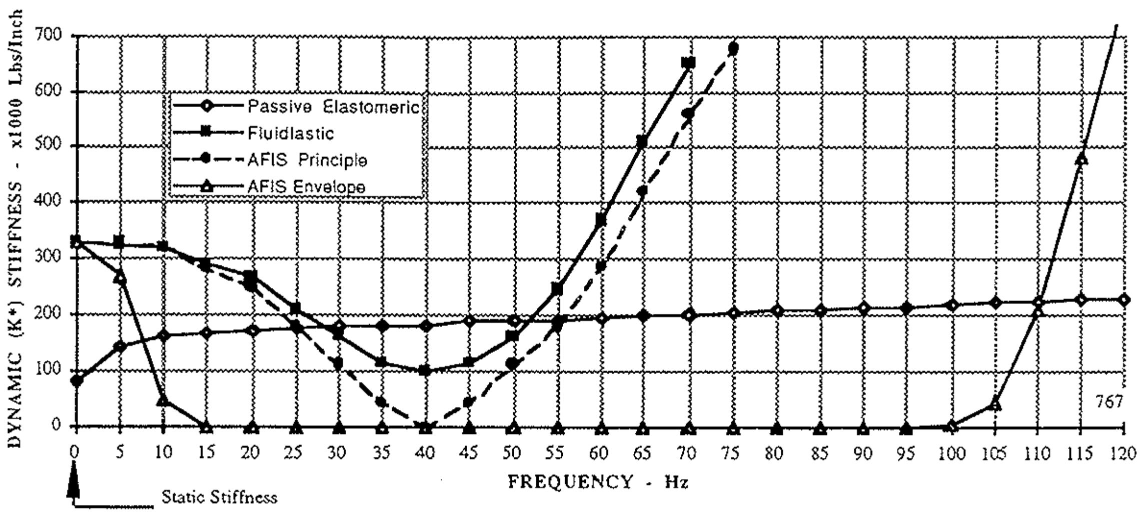
K = Dynamic Stiffness of Elastomer B = Hysteresis Damping (K"/K')

M = Fluid Mass k = Compliance of Elastomer Cavity

F = Computer Controlled Actuator Acting on Fluid Mass (M)

(Engine Isolator Assumed)

Figure 19b. COMPARISON of PASSIVE/FLUIDLASTIC®/ACTIVE ISOLATOR PERFORMANCE



AFIS isolators have been designed, built by Lord and tested to verify the concept. Results have demonstrated that significant reductions in the dynamic stiffness are obtained while maintaining the very high static stiffness desirable to minimize relative motion between a vibrating source (i.e., engine or pylon) and the structure (wing strut or airframe). Loss of the active portion of the AFIS results in the isolator performance reverting to that of a passive elastomer/fluid device or at the worst case scenario to that of a conventional passive elastomeric product.

ANC/ASC/AIS/AFIS Summary

The introduction of active control into vibration and noise control has been impressive. New aircraft have been introduced into production using this capability. It should be noted that not all applications for reducing vibration and/or noise lend themselves to these more expensive systems. Excellent performance can still be achieved using conventional passive elastomeric approaches, while the passive elastomeric/fluid products offer an intermediate performance benefit. Cost-benefit analyses must be conducted to determine the optimum solution for the particular size helicopter (or fixed wing plane).

"Hybrid" systems, comprised of conventional passive elastomeric and/or passive elastomeric/fluid products coupled with the appropriate active system (ANC/ASC/AIS/AFIS) may be the optimum from a performance and cost standpoint.

The active systems discussed above have been designed to be compatible with aircraft electrical systems, EMI requirements, etc. Power consumption is quite low - 60 to 250 watts, while the size and weight of the controller, power supply, sensors, wiring, etc. is very compatible with the aircraft empty weight and available installation space.

Magnetorheological (MR) Technology

MR products (isolators, dampers, clutches, brakes, valves and positioning devices) contain fluids with micron sized polarizable particles, which thicken in the presence of an electronically controlled magnetic field, allowing continuous control of the devices' damping.

Low voltage and power, coupled with few or no moving parts translates into high reliability. Since the forces generated by a damper using MR fluid are nearly independent of velocity; substantial control authority can be realized at relatively low speeds. Figure 20 demonstrates this principle. Figure 21 shows the benefits of an MR product used in a damping system. With appropriate sensor and control electronics, the force versus velocity profile can be tailored to meet the system needs.

Figure 20. TYPICAL RHEONETIC® MR CONTROLLABLE DAMPER CHARACTERISTICS

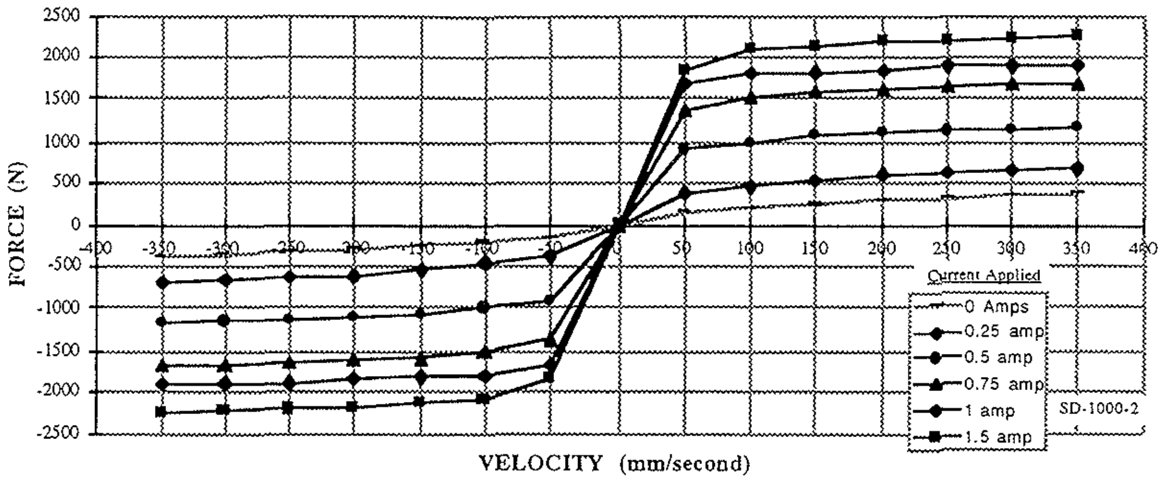
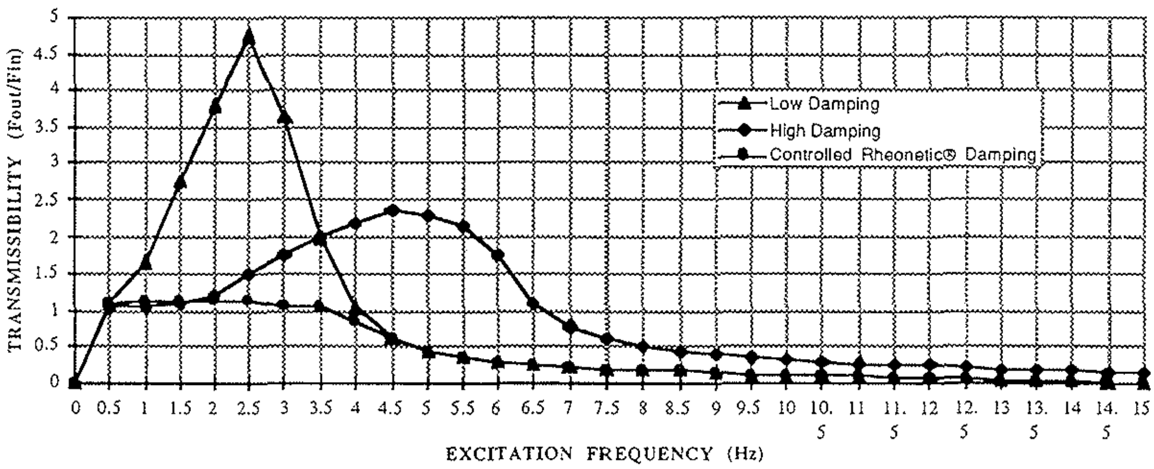


Figure 21. VIBRATION TRANSMITTED vs EXCITATION FREQUENCY for an ISOLATED SEAT



Linear or rotary action products can be designed using unique MR fluids to provide broad temperature performance. Initial Lord production Rheonetic™ applications have been in the industrial markets for vehicle seat suspension, exercise equipment, vibration isolators and positioning applications. Aerospace/aircraft applications being investigated include controllable, "smart" dampers for landing gears, shafting and various isolators.

Conclusion

The evolutionary technical development of unique products for the reduction of undesirable vibration, noise and shock using elastomeric materials, non-toxic fluids and electronic controls independently or in combination with each other has been briefly reviewed.

While this review introduces the various options available to engineers for reducing helicopter (and fixed wing aircraft) vibration, noise and energy control, the final solution for each application must be accepted from a technical and market perspective. The need for product differentiation is an important aspect in today's globally competitive market, but affordability must also be considered.

Helicopter users expect high reliability and low maintenance, while comfort demands of low vibration and noise are increasing, especially as helicopters, certain fixed wing aircraft, and future tilt rotors will be competing for some of the same markets, but D.O.C. must be reduced simultaneously. The new vibration and noise control technologies reviewed in this paper can contribute significantly toward meeting these objectives.

References:

1. Potter, J. L., Improving Reliability and Eliminating Maintenance with Elastomeric Dampers for Rotor Systems, Lord Library #LL-2120.

2. McGuire, D. P., The Application of Elastomeric Lead-Lag Dampers to Helicopter Rotors, Lord Library #LL-2133.

3. Potter, J. L., The Elastomeric Bearing: What It Can Do for You, Lord Library #LL-2125.

4. Herbst, P. T., Natural Rubber as a Bearing Material for Rotary Winged Aircraft Applications, Lord Library #LL-2126.

5. Schmidt, W. E., Design, Testing and Performance of Elastomeric Bearings, Lord Library #LL-2129.

6. Potter, J. L., Recent Advancements in Elastomeric Products for Improving Helicopter Reliability and Maintainability, Lord Library #LL-6500.

7. Staples, F. E.; Jones, P. J.; and Schmidt, W. E., Elastomeric Rod End Bearings: A Solution for Improving Reliability and Maintainability, Lord Library #LL-6501.

8. Flower, W. C., Understanding Hydraulic Mounts for Improved Vehicle Noise, Vibration and Ride Qualities, Lord Library #LL-2166.

9. Lord Mechanical Products, "Fluidlastic® Mounts - The New Generation of Elastomeric Mounts", Lord Brochure #PB-7417d.

10. McGuire, D. P., Fluidlastic® Dampers and Isolators for Vibration Control in Helicopters, American Helicopter Society Forum (1994), Lord Library #LL-6502..

11. Krasnicki, E. J., Comparisons of Analytical and Experimental Results for a Semi-Active Vibration Isolator, Lord Library #LL-2139.

12. Krasnicki, E. J., The Experimental Performance of an "On-Off" Active Damper, Lord Library #LL-2140.

13. Miller, L. R. and Ahmadian, M., Active Mounts - Future Technological Trends, Lord Library #LL-6002.

14. Swanson, D. A. and Miller, L. R., Design and Effectiveness - Evaluation of an Active Isolation System for a Commercial Jet Aircraft, Lord Library #LL-6003.

15. Jolly, M. R.; Norris, M. A.; Rossetti, D. J.; Potter, J. L.; Warner, J. V.,; and Delfosse, K. F., A Demonstration of Active Control for Helicopter Cabin Noise Reduction, 20th European Rotorcraft Forum (1994).

16. Nelson, P. A. and Elliot, S. J., Active Control of Sound, Academic Press (1992).

17. Schroeder, M. R. and Kruttruff, K. H., "On Frequency Response Curves in Rooms. Comparison of Experimental, Theoretical and Monte Carlo Results for the Average Frequency Spacing Between Maxima", J. Acoustics. Soc. Am. 34, 125-135, 1962.