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Passive, Active, and Hybrid Solutions for Aircraft Interior Noise Problems

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Introduction

Today's aircraft industry is placing increasing emphasis on creating a comfortable environment for passengers and crew. There are many potential treatments for reducing noise and vibration in aircraft. One of the keys for effectively implementing these is to understand the benefits and limitations of each type of treatment.

Noise and vibration treatments can be separated into two categories, passive and active. Passive treatments include Rubber-To-Metal (RTM) mounts, Fluidlastic® mounts, Fluidlastic® Torque Restraint (FTR) mounting systems, Tuned Vibration Absorbers (TVA), and a range of cabin wall/interior treatments. Active treatments, which require controller electronics, consist of three main types:

- Active Isolation Control (AIC) systems introduce actuators into mounts to prevent vibration from being transmitted into the structure to reduce cabin noise and vibration (1). The AIC system commands actuators to minimize the vibration and noise signals from accelerometers or microphones.
- Active Noise Control (ANC) systems use loudspeakers and microphones in the cabin to reduce interior noise as measured by the microphones (2).
- Active Structural Control (ASC) systems encompass a wide range of solutions, including placing actuators near sources or on structures that radiate noise (3). Typically, an ASC system will use microphones as sensors, but accelerometers can also be used.

As will be discussed, the best comprehensive solution to aircraft interior noise problems will be "hybrid" in nature, optimally combining active and passive technology.

Active Isolation Control (AIC) and Passive Mounting Systems

All mounting systems need to accomplish two basic functions: constraining motion and providing vibration isolation. "Constraining motion" refers to limiting the relative motion between two structures. For example, an engine mounting system must limit the relative motion between the engine and the airframe structure created by thrust, "g" loads, weight, and torque. "Providing vibration isolation" involves minimizing the transmission of vibration from one structure to another. For an engine mounting system, the goal is to reduce the forces transmitted into the structure relative to rigidly connecting the engine to the structure. To provide the first basic function, the mounting system needs to be stiff to minimize motion. In order to minimize transmitted vibration, however, the mounting system needs to be dynamically soft.

The Fluidlastic® Torque Restraint (FTR) system, as shown in Figure 1, is the state-of-the-art in passive mounting systems for turboprop engines (4). FTR combines elastomer and fluid. Fluid inertia is used to enhance vibration isolation by creating forces that tend to counteract the vibratory forces transmitted vertically through the elastomer. The overall effect is that the vertical dynamic stiffness at the vibration frequency can be significantly less than the static stiffness. (Fluidlastic® mounts used on turbofan engines also exhibit this dynamic behavior). Further, the fluid in an FTR system reacts propeller torque loads, minimizing the roll motion of the engine. This weight efficient system further enhances vibration isolation by eliminating other connections which are typical of torque tubes used in many aircraft today.

AIC systems utilize active mounts (1) with integrated actuators. These systems are the ultimate solution for constraining motion and providing vibration isolation. Active mounts can have virtually zero dynamic stiffness at the vibration frequencies, and yet the static stiffness can be quite high (1). Figure 2 shows an early prototype of an active mount. The actuator is used to create dynamic pressure within the fluid to cancel the transmitted force through the elastomer. Additionally, active mounts can be used to create forces which directly control noise sensed by microphones in the cabin. In this way, the actuator forces can compensate for flanking paths, such as bleed airlines, linkages, fuel lines, and hydraulic lines.

Figure 3 shows a graph that provides insight into the selection of AIC or passive mounting systems. This figure is based on two simplifying assumptions. The first is that the engine behaves like a velocity source, meaning that engine vibration is unaffected by the dynamic stiffness of the airframe or mounting system. Generally, the dynamic stiffness of the engine is significantly higher than the combined dynamic stiffness of the mounting system and the airframe (1). The second assumption is that cabin noise and vibration is structure-borne. Testing shows that the vibration transmitted through the mounting system often creates up to 90% of the cabin noise and vibration. In figure 3, the dB reduction in SPL (an vibration) relative to a hard mount is plotted versus the normalized mount stiffness, which is the ratio r of the dynamic stiffness of a passive mount to be roughly equivalent to the airframe dynamic stiffness. The simple analysis used to produce Figure 3 predicts that a normalized mount stiffness of r = 1.0 provides 6 dB reduction in cabin noise (or vibration) relative to a rigid mount (also known as a “hard mount”). With near zero dynamic stiffness at the engine vibration frequencies, AIC systems can perform significantly better than passive mounting systems.

Each transmission path must be considered in selecting the optimal active or passive technology. To fully make this decision, the designer must have a knowledge of the static and dynamic stiffness properties of the airframe and engine, and engine vibration levels in all directions at each mounting point. Also, and possibly more difficult to acquire, an understanding is required of the dynamics between airframe acceleration at the mounting points and cabin noise. If the coupling for a given path is weak, AIC may not be needed. Admittedly, aircraft designers rarely know all of this information, even for existing aircraft. For aircraft being designed, this understanding can be derived from data for existing aircraft.

In general, AIC systems will be hybrid, including active and passive components. As an example, in many turbofan installations actuators may be included in the front mounts and be oriented in the radial and tangential directions relative to the engine coordinate system. The radial and tangential directions will include elastomer to reduce the force requirement of the actuators. Typically, the aft mounts and the fore/aft direction of all the mounts will use passive RTM technology. Hybrid AIC systems have been flight-tested and have reduced noise by 20 dB in the cabin (5). In general, these systems reduce the noise globally throughout the cabin.

Active Noise Control (ANC) and Interior Treatments

ANC systems utilize loudspeakers inside the cabin to create a secondary noise field which cancels the primary field due to the engines or propellers (6). For an ANC system to create global reductions, one of two criteria must be met. Firstly, the acoustic response must be lightly damped and possess low modal density in the frequency range where the noise must be reduced. When this occurs, a few actuators can be used to reduce noise at all points throughout the cabin. Secondly, speakers can be placed within a ¼ wavelength of discrete sources. Unfortunately, neither of these criteria can normally be met in aircraft. Depending on the size of the cabin, the transition from sparse to dense modal response typically occurs at a frequency less than 50 Hz. Since most aircraft sources such as turbofan engines or propellers produce noise at frequencies above 50 Hz, global noise reduction will not be possible using the first criteria. Further, since the sources are distributed rather than discrete, the second criteria can rarely be used.

If global noise reduction cannot be achieved, then local control can be utilized. Local control involves creating zones of quiet around the error microphones. The size of the zone of quiet is related to frequency being controlled. In general, the radius of the sphere of quiet, will be roughly one-tenth the wavelength of the sound. At 200 Hz, the radius of the sphere of quiet is 6 inches (0.15 meters). It is possible to enlarge the zone of quiet by a number of techniques including using multiple microphones. However, if the frequency is 2,000 Hz, the sphere of quiet would be too small to be practical. While ANC has its limitations, it can be very effective for controlling low-frequency noise in turboprop aircraft. A production ANC system for the Beech King Air provides up to 12 dB spatially averaged reduction in the propeller-induced noise, producing dramatic subjective improvements in passenger and crew comfort (2).

In addition to ANC, a variety of passive interior treatments are used in today's aircraft. Usually integrated into the cabin wall, these treatments include acoustic insulating materials behind the trim, acoustic absorption material on the inside of the trim, and constrained layer damping on the inside of the aircraft skin. Also, elastomeric mounts can be used to reduce noise transmitted through trim attachment points, luggage racks, and seating. Due to size and weight constraints, these passive treatments generally work well only at frequencies above 1000 Hz. In the case of propeller-induced noise, passive acoustic treatments (e.g., constrained layer damping and acoustic damping) provide virtually no noise attenuation.

Active Structural Control (ASC) and Passive Tuned Vibration Absorbers (TVA)

TVA (3) and ASC (7) systems control structural vibration and consequently noise in the cabin. Tuned vibration absorbers work by increasing the localized impedance of the structure. This is accomplished by using a tuned resonant mass and spring (elastomeric stiffness). While this resonant behavior is used to greatly reduce the weight of the TVA, it generally limits the performance of the TVA to a narrow range of engine speeds and necessitates a second set of TVAs if noise reduction is desired at other frequencies (such as the harmonics of the tone). Further, TVAs can be used to increase the overall damping in the structure, particularly when the structure is lightly damped. ASC systems represent a very wide range of solution possibilities, including placing actuators on the aircraft cabin wall or in dominant vibration transmission paths (3). The curve plotted in Figure 3 can also be used as a simple tool to predict the performance of TVAs and ASC when the acoustics are strongly coupled to structural vibration. In this case, r is the ratio of the structural impedance divided by the passive impedance of the TVA or actively created impedance of the ASC actuator. Note that as a rough rule of thumb, the impedance of the TVA or ASC system must be approximately that of the impedance of the structure (r=1.0) to achieve a 6 dB reduction. Since the actuators in an ASC system have a force producing element, ASC can impart significantly more impedance over a wide frequency range with less weight relative to TVAs. In comparison to ANC, ASC and TVAs can be conveniently packaged behind the existing trim.

In cases where the acoustic response is strongly coupled to vibration, TVAs are being used in production aircraft to provide significant noise and vibration reduction (7). Unfortunately for some aircraft, the acoustic response may not always be strongly coupled to the structural vibration, limiting the benefit of TVAs and eliminating the usefulness of the curve in Figure 3 as a predictive tool. This situation occurs when the dominant interior acoustic modes are spatially different (at the fuselage walls) from the dominant structural modes (3). For example, consider a case where the disturbance frequency matches an acoustic resonance. The modes dominating the structural vibration can be differently shaped than those dominating the acoustics. However, it is the structural motion that spatially couples to the resonant acoustic mode that drives the noise, and thus it is this motion that must be controlled. When this is the case, simply controlling the vibration (as would be accomplished with TVAs) will not significantly reduce interior noise. An ASC system with microphones can overcome this limitation by adaptively reducing structural motion that radiates noise into the cabin. This will reduce cabin noise, but control spillover into non-radiating motion may increase vibration. Intelligent placement strategies and other schemes may limit this phenomena to provide reduced noise and vibration for the passengers and crew.

In addition to the behavior discussed above, the placement of actuators/TVAs with respect to the noise source is another factor that largely affects the performance of a TVA or ASC system. In situations where the source of cabin noise is well defined and localized, good global noise reductions are possible with few actuators or TVAs placed near the source (within ¼ wavelength) to “block” energy from propagating into the cabin. This strategy can be used instead of AIC on commercial jets. This results in global reductions in noise levels with a few actuators, even at high frequencies. When the ASC actuators or passive TVAs cannot be placed near the source, truly global reductions are more difficult to achieve, especially when the structure and acoustics are not directly coupled. In any situation, an ASC system can provide localized noise reductions. This has been demonstrated in turboprop aircraft to be very effective, providing good noise reductions (an average of 10 dB) near the passenger head locations. Table 1 summarizes application issues for TVAs and ASC.

Hybrid Systems/Total Aircraft Solutions

An effective and comprehensive noise and vibration strategy for a given aircraft can only be arrived at logically if the benefits and limitations of each technology are assessed, and if the cost, weight, and performance goals are defined. While treatment technology has advanced rapidly, the aerospace community must become more sophisticated in how it evaluates noise and vibration. As an example, the aircraft industry generally uses dBA. Unfortunately, dBA is just one of many important measures. For example, dBA can be very misleading in determining the benefits of any treatment in loud, low frequency environments, because dBA tends to discount low-frequency noise (8). As proof of this statement, passengers prefer the acoustic environment of commercial jets to commuter turboprops, even in cases where both aircraft have the same dBA levels. This is because the perceived noise in turboprop aircraft is heavily dominated by low frequency noise (frequencies that are lower than jets and are further attenuated by the A-weighting scale). Moreover, the effects of vibration are often as important to passenger comfort as noise. Today, sophisticated aircraft acoustic teams use an array of measurements including dBA, dBC, tonal emergence, speech interference level, and g's of vibration.

Once performance goals are set, the relative benefits of each treatment must be considered. Figure 4 shows general guidelines for applying various active and passive solutions on the basis of frequency. In general, passive systems work best at high frequencies and active systems work best at low frequencies. In cases where active systems can be applied near the source, performance at frequencies in excess of 400 Hz is possible and may provide solutions that are more weight effective than passive treatments. Passive RTM and Fluidlastic® solutions can provide vibration and noise benefits over an extremely wide frequency range.

When considering an active system, other factors, as shown in Table 2, must also be considered. ANC systems have an advantage that minimal or no prior knowledge is needed about the sources and paths, since cancellation is provided directly to the passengers and crew. Generally, AIC and ASC system require more of a prior knowledge in the form of test data or assumptions based on experience. While AIC systems typically use fewer actuators than ASC systems, the AIC actuators need to provide more force, limiting the choices of applicable devices. Also, AIC may require a redesign of the mounting system to accommodate the actuators. This makes AIC more difficult to demonstrate, but the weight and performance advantages of AIC are often worth the effort.

The implications of Figure 4, Table 2 and cost, lead to the notion of a total aircraft solution. As an example of this concept, Figure 5 shows the state-of-the-art turboprop aircraft solution. The figure shows and AIC system integrated with an RTM to provide a hybrid solution at the front of the engine mounting system. Assuming that the aft part of the engine does not transmit significant vibration, RTM mounts may possibly be the best alternative. TVAs may be located on other flanking paths including the fire wall and bleed airlines. In the cabin, passive interior treatments will be needed to control boundary layer noise above 1000 Hz. RTM mounts suspend auxiliary power units and attach luggage racks and interior trim. For low frequency induced noise created by propellers, ASC on the frames between the propellers will often provide the best solution. Finally, an ANC system in the cockpit reduces crew fatigue. This figure demonstrates just one of the many potential combinations of technologies to address the total noise and vibration problems of aircraft.

Conclusions

The technical demands of creating comfortable aircraft will require a range of solutions and products. The advent of active systems provides aircraft designers with cost effective and weight efficient solutions for many noise problems that are low frequency in nature. Either as an integrated system, or as separate but complimentary systems, passive and active technologies will be combined to create the best overall hybrid solutions to meet the demands of the aerospace industry.

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Table 1. Guidelines in Applying TVAs and ASC Systems

	Structural-Acoustics Dynamics	
Source	**Coupled**	**Uncoupled**
Well defined and localized	• ASC provides very good global reduction with few actuators. • A few TVAs can work well.	• ASC provides ver good global reduction with few actuators with some tradeoff between noise and vibration. • TVAs provide some reduction.
Not well defined or distributed	• ASC provides reductions. A larger number of actuators may be required. Reductions may be localized. • TVA system can work, but a large number of TVAs will be required.	• ASC provides good localized reductions. Large number of actuators may be required. Vibration local to the actuators may increase. • TVA system may provide limited performance.

Table 2. Advantages of AIC, ANC, and ASC

Active Isolation Control (AIC)	Active Noise Control (ANC)	Active Structural Control (ASC)
• Global reduction of noise and vibration. • Good low frequency performance. • Good high frequency performance. • Easy to install. • Low weight.	• Local noise control. • Solution independent of sources or paths. • Easiest to demonstrate. • Does not affect structure. • Opportunity to retrofit.	• Can control both noise and vibration. • Easy to demonstrate. • Minor impact on structure/trim. • Good low frequency performance. • Good high frequency performance with path identification. • Easy to retrofit.

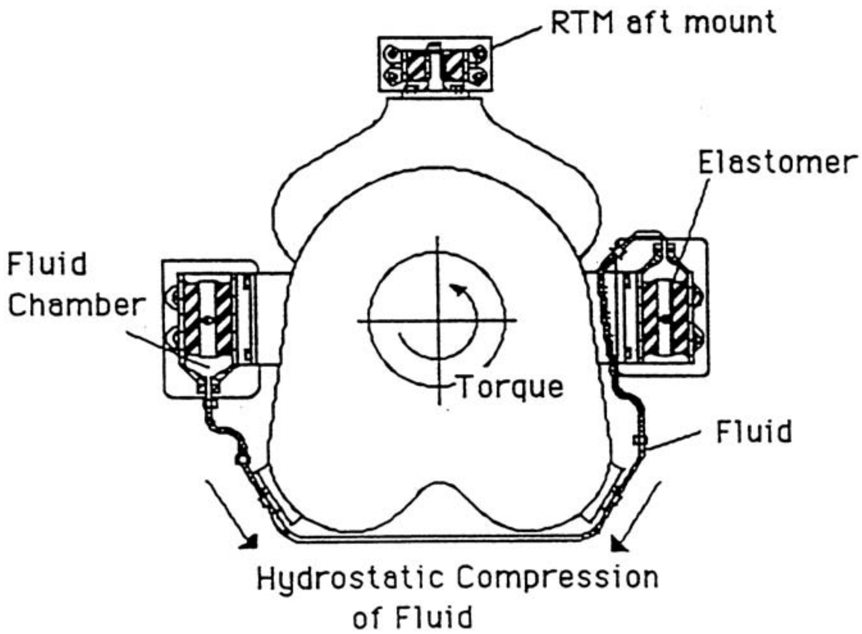

Figure 1. Fluid Torque Restraint System

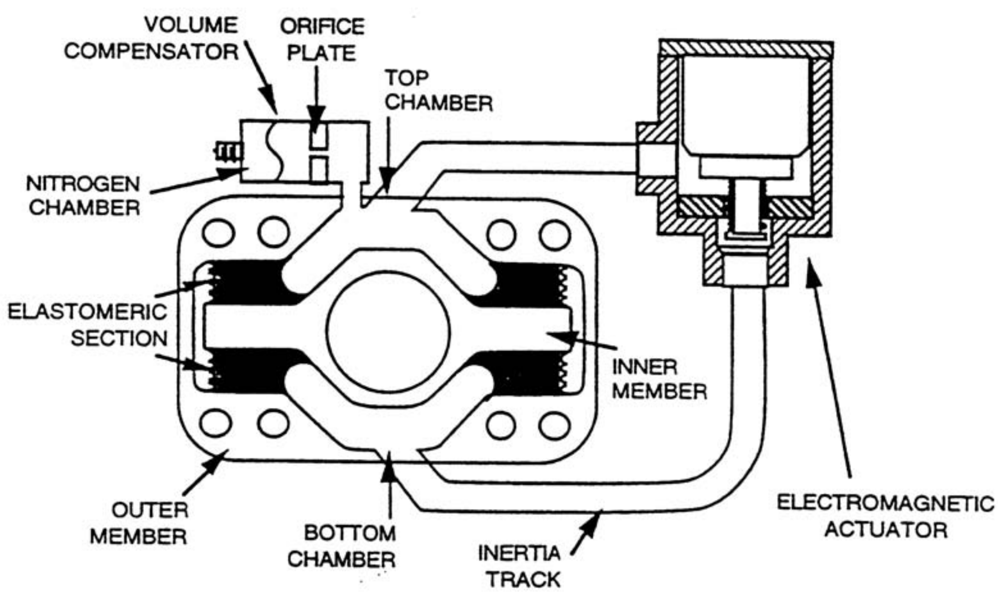

Figure 2. Early Active Mount

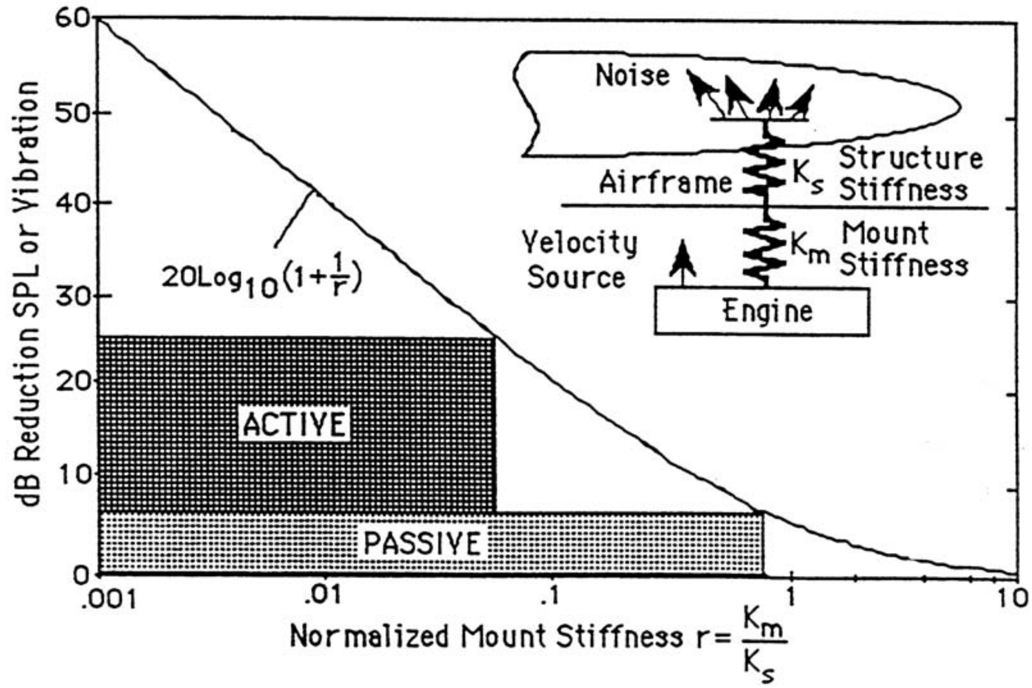

Figure 3. Simplified Prediction of Noise Reduction

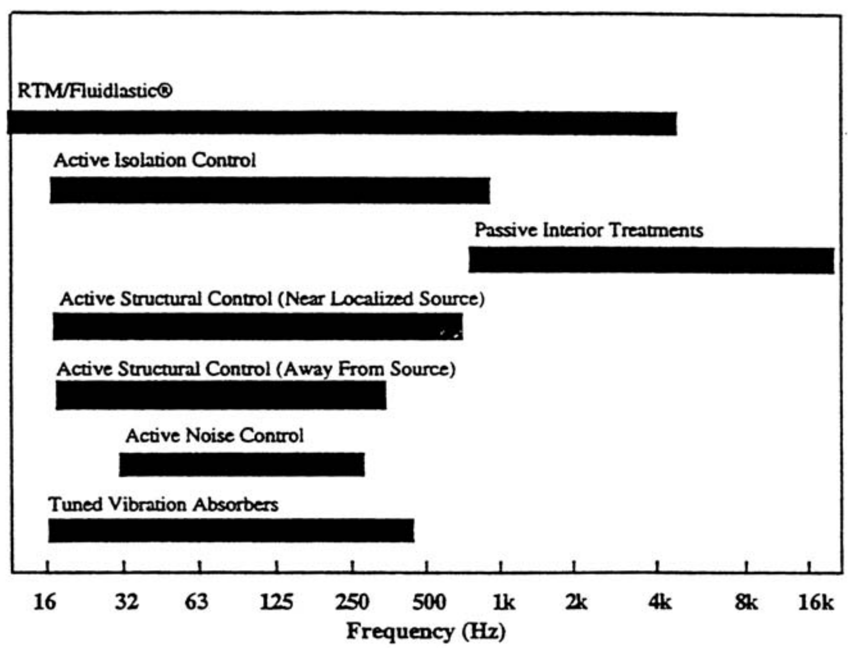

Figure 4. Applicable Frequency Range

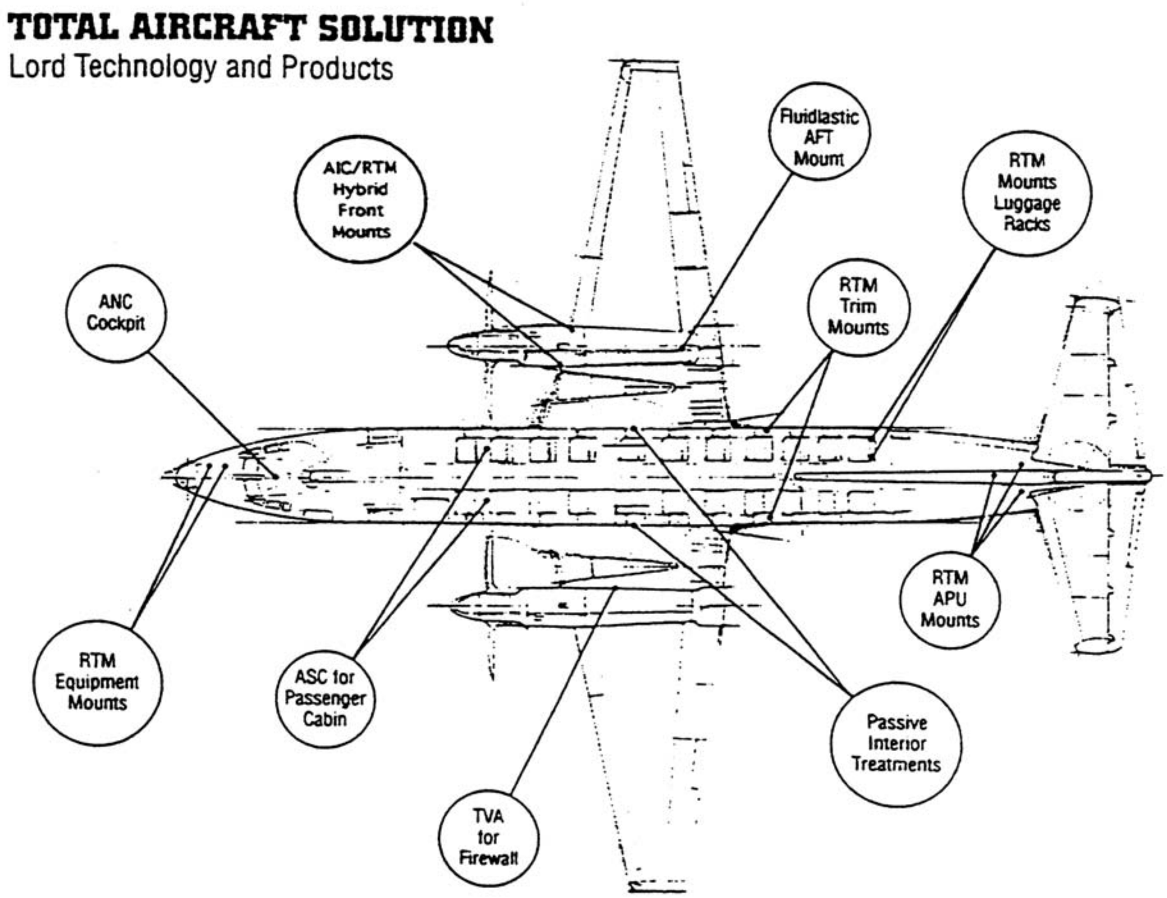

Figure 5. State-of-the-Art Turboprop Aircraft Solution

Paper presented at the Brazilian Acoustical Society Meeting, November 1995.