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INTEGRATED FLOOR/FUEL ISOLATION SYSTEM FOR THE MODEL 234 COMMERCIAL CHINOOK

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ABSTRACT

A vibration isolation system is in development for the passenger cabin and the long-range fuel tanks of the Boeing commercial Chinook. The passenger floor is isolated from the airframe on a series of passive isolation units. The fuel tanks are isolated so that their dynamic mass is effectively nulled at all fuel levels, thereby avoiding any deleterious effect on airframe natural frequency placement. Analyses, component tests, and an aircraft shake test were conducted to prove the system. The aircraft test demonstrated that the floor isolation could lower the 0.15-g midcabin airframe vibration to an average of 0.05 g on the passenger floor. The fuel isolation was successful in maintaining an important airframe natural frequency within ±0.2 Hz of its normal 12.2-Hz value for any fuel level from 0 to 100 percent.

NOTATION

F	force (external) on airframe
I	IFIS bar inertia
K_A	airframe spring
K_I	IFIS spring
m_A	airframe mass
m_F	floor (or fuel) mass
m_I	IFIS bar mass
R	location of IFIS bar center of gravity
r	pivot separation on IFIS bar
Z_A	airframe displacement, absolute
Z_F	floor (or fuel) displacement, absolute
ω	forcing frequency
ω_A	floor IFIS tuned frequency
ω_F	fuel IFIS tuned frequency

INTRODUCTION

The prime mission of Boeing's Model 234 helicopter is to ferry personnel to and from offshore oil drilling platforms; therefore increased emphasis is placed on passenger comfort. The Model 234 (Figure 1) will have airliner passenger seats which are certainly conducive to comfort, but they cannot do the job alone. The basic vibration environment must be satisfactory.

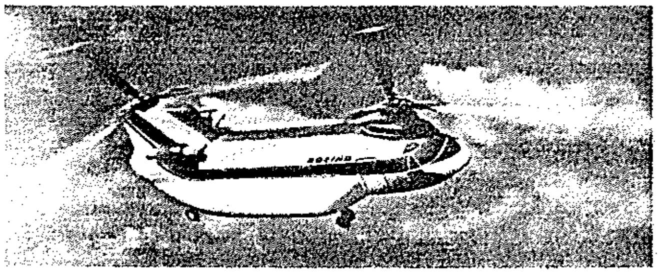

Figure 1. The Boeing Vertol Model 234 Commercial Chinook

Boeing's vibration objective is to provide ≤ 0.05 g vertical on the floor at the predominant 3/rev excitation frequency, within ±5 rpm of rotor speed, at all operational fuel loads. This is to be accomplished by (1) isolating the floor from the airframe at 3/rev, attenuating the motion by 8 to 1, and (2) holding the frequency of the nearest airframe natural mode constant within ±0.2 Hz at all fuel levels encountered during a mission. The cabin environment of the CH-47, while reasonable (Figure 2), could be improved for commercial passengers on long trips. An additional complication is posed by the large fuel capacity, twice that of the military CH-47C. Fuel affects the airframe mode so that as fuel is consumed during flight, the frequency of this mode may pass through 3/rev of 225 rotor rpm (Figure 3), the predominant excitation frequency, thus increasing cabin vibration.

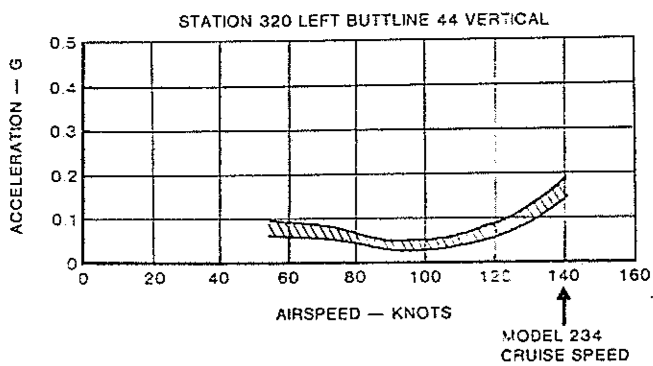

Figure 2. CH-47 Cabin Vibration

The approach chosen by Boeing to meet the stated vibration objectives is IFIS, an acronym for either Improved Floor Isolation System, which isolates the cabin floor from the airframe at one frequency independent of the load carried; or Improved Fuel Isolation System, which maintains relatively constant airframe natural frequency by preventing force feedback from the tanks, no matter what the fuel level.

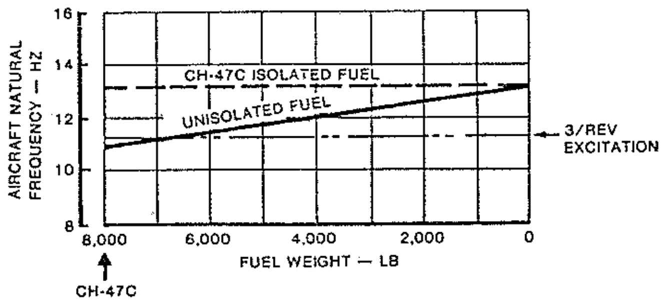

Figure 3. Effect of Fuel on Cabin Vibration

Both systems, based on the passive antiresonant isolation concept originally conceived by Kaman Aerospace Corporation[1], use the technology developed by Boeing Vertol for rotor isolation systems.[2, 3, 4]

FLOOR IFIS ANALYSIS

The working parts of an IFIS unit are shown schematically within the dotted line in Figure 4. They consist of a spring, K_I, which joins the floor to the airframe, and a stiff bar with mass m_I and inertia I. The bar is connected to the floor with a bearing at pivot B, and to the airframe with another bearing at pivot A, a distance r away from pivot B. The center of gravity of the bar is a distance R away from pivot B.

Floor, Z_F

$$\left\{K_I - \omega^2 \left[m_F + m_I \left(\frac{R}{r}-1\right)^2 + \frac{I}{r^2}\right]\right\} Z_F - \underline{\left\{K_I - \omega^2 \left[m_I \left(\frac{R}{r}-1\right)\frac{R}{r}+\frac{I}{r^2}\right]\right\}}\, Z_A = 0 \quad (1)$$

Airframe, Z_A

$$-\underline{\left\{K_I - \omega^2 \left[m_I \left(\frac{R}{r}-1\right)\frac{R}{r}+\frac{I}{r^2}\right]\right\}}\, Z_F + \left\{K_I + K_A - \omega^2 \left[m_A + m_I \left(\frac{R}{r}\right)^2 + \frac{I}{r^2}\right]\right\} Z_A = F \sin \omega t \quad (2)$$

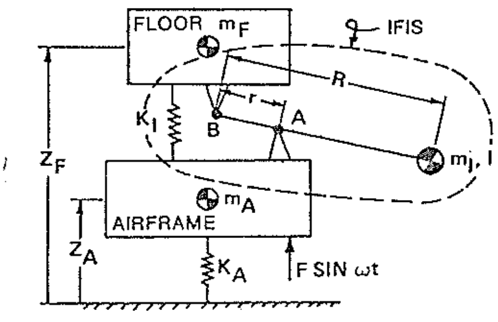

Figure 4. Improved Floor Isolation System

Consider the equations of motion above and concentrate on the underscored terms. In addition to being identical, they are composed entirely of IFIS parameters and are therefore completely independent of the floor mass, m_F, and airframe mass, m_A. If these underscored terms could be induced to become zero, the remaining term in the floor equation would have to be zero, and since the contents of the { } brackets are nonzero at the same time, the floor motion Z_F must now be zero. We would succeed in decoupling the floor from the airframe.

The condition necessary to accomplish this is

$$K_I = \omega^2 \left[m_I\left(\frac{R}{r} - 1\right)\frac{R}{r}+\frac{I}{r^2}\right], \quad (3)$$

from which it is obvious that if we fix all physical parameters, there will be only one frequency which satisfies equation 3. This frequency is referred to as the antiresonant frequency, ω_A, for instead of a maximum, the floor has a minimum response at this frequency value:

$$\omega = \omega_A = \sqrt{\frac{K_I}{m_I\left(\frac{R}{r} - 1\right)\frac{R}{r}+\frac{I}{r^2}}} \quad . \quad (4)$$

For the Model 234 application we need ω_A equal to 3/rev (11.25 Hz), so that the values of K_I, M_I, I, R, and r are chosen such that equation 4 yields 70.69 rad/sec (11.25 Hz).

Solving the floor motion as a function of airframe motion, Z_F/Z_A, equation 1 yields

$$\frac{Z_F}{Z_A} = \frac{K_I - \omega^2 \left[m_I \left(\frac{R}{r} - 1\right) \frac{R}{r}+\frac{I}{r^2}\right]}{K_I - \omega^2 \left[m_F + m_I \left(\frac{R}{r} - 1\right)^2 + \frac{I}{r^2}\right]}, \quad (5)$$

which shows algebraically that where the forcing frequency, ω, coincides with the antiresonant frequency, ω_A, the numerator in equation 5, and thus Z_F, become zero no matter what the airframe motion, Z_A, is.

Figure 5 shows the frequency trend of an ideal undamped IFIS system tuned to 3/rev. The floor response relative to the airframe starts at unity, passes through a maximum whose frequency is determined by the denominator of equation 5, drops to zero at the tuned antiresonant frequency of 3/rev, and increases again toward the higher frequencies. Unfortunately, there is no such thing as a physical system without damping, so that perfect isolation is not realistically attainable. But perhaps damping is not a completely negative quality, for it beneficially limits response amplitude at resonance. Even though floor motion cannot be reduced to zero (Figure 6), there is the possibility that attenuation may be satisfactory over a wide enough band width to be useful.

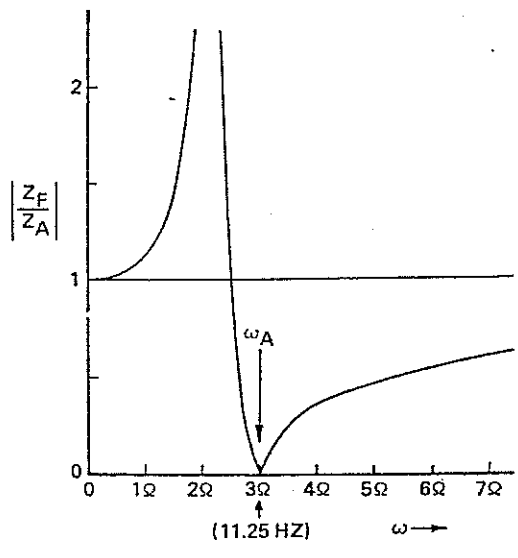

Figure 5. Perfect IFIS Performance

Analysis predicts that the antiresonant frequency does not change with floor weight (Figure 7), and that damping has an increasingly detrimental effect as the floor weight is decreased.

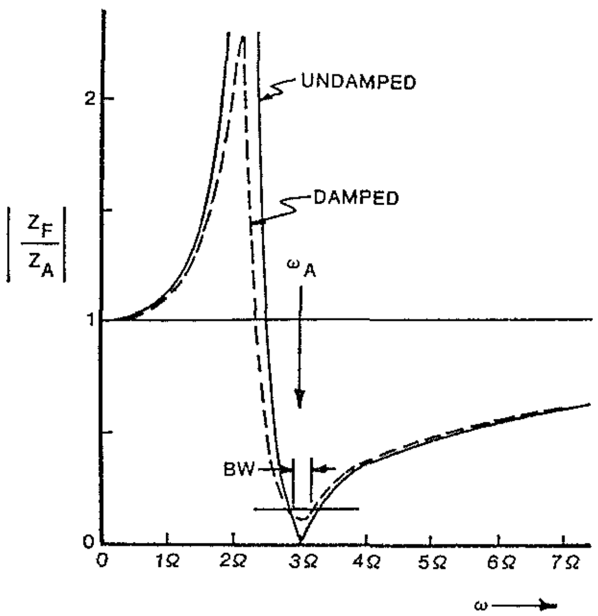

Figure 6. Damped IFIS Performance

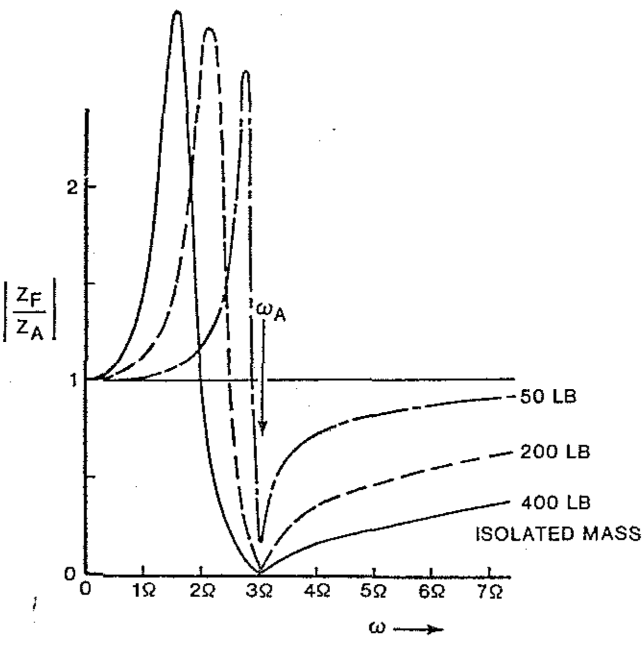

Figure 7. Effect of Floor Weight on Floor IFIS Performance

SINGLE FLOOR IFIS UNIT DESIGN AND BENCH TEST

These predictions were sufficiently encouraging to proceed with design and fabrication of six floor IFIS units. One of these is shown in Figure 8, exhibiting a fixed cantilever spring between the floor fitting and the airframe fitting, the inertia bar with adjustable tuning weight, and two needle bearings. Each of the six units was individually bench-tuned to 11.25 Hz (3/rev) with excellent results (Figure 9). The analytically predicted floor response trends with floor weight variation were confirmed: the antiresonant frequency did not change with floor load, but the lightest load had the poorest isolation (damping effect). All floor loads showed 8-to-1 or better motion attenuation in a frequency band of ±5 rpm of the rotor (±0.25 Hz at 3/rev).

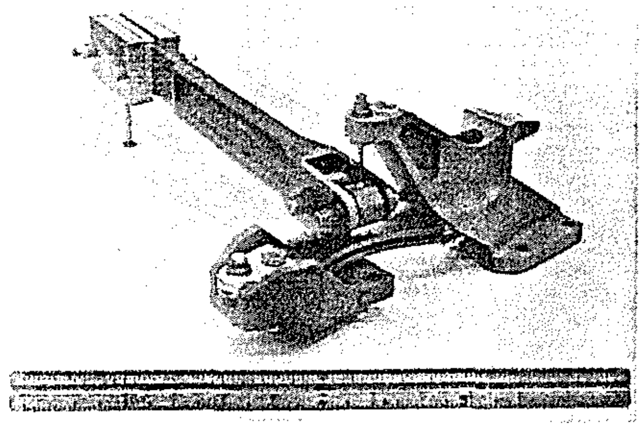

Figure 8. Detail of Single Floor IFIS Unit

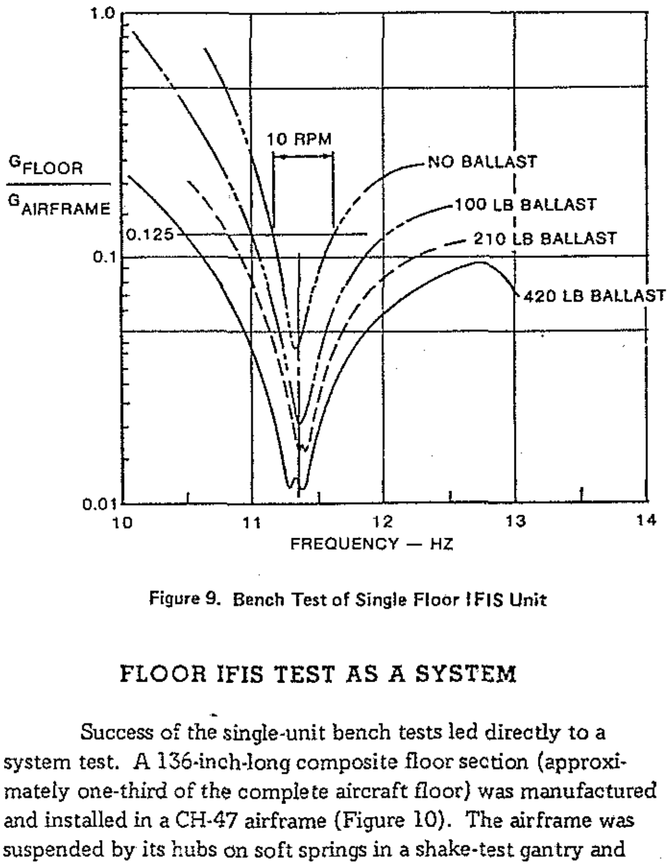

Figure 9. Bench Test of Single Floor IFIS Unit

FLOOR IFIS TEST AS A SYSTEM

Success of the single-unit bench tests led directly to a system test. A 136-inch-long composite floor section (approximately one-third of the complete aircraft floor) was manufactured and installed in a CH-47 airframe (Figure 10). The airframe was suspended by its hubs on soft springs in a shake-test gantry and excited with electromechanical shakers to yield approximately uniform vertical airframe motion at the stations where the test floor was attached.

The performance of the six IFIS units as a system was not quite as outstanding as that of each unit by itself, but was very impressive nonetheless. With only minor adjustments from the bench-tuned settings, the floor vibration values at 3/rev (225 rotor rpm) were greatly reduced from the adjacent unisolated airframe whose levels reflected a simulated 140-knot-cruise environment (Figure 11).

Evaluation by people, during which the airframe was subjected to the vertical vibration environment anticipated at the cruising speed of 140 knots, resulted in most passenger comments being favorable, judging the vibration environment to be sufficiently low to be comfortable on long trips.

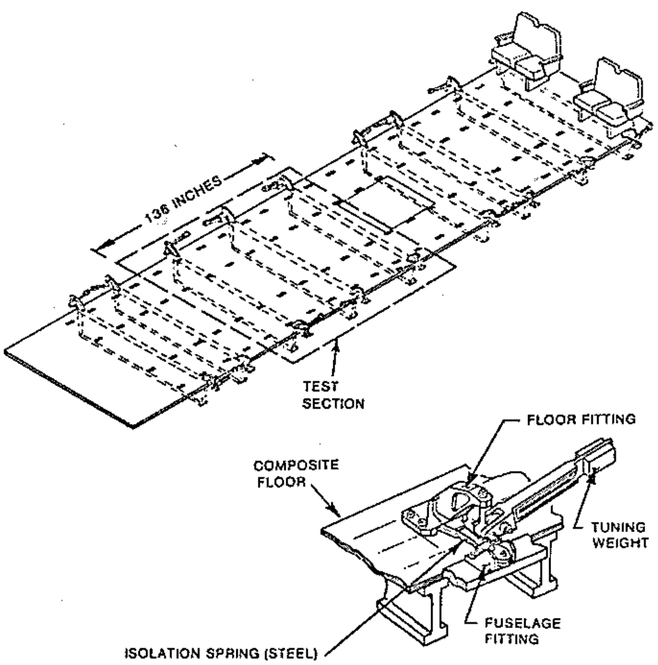

Figure 10. Isolated Cabin Floor

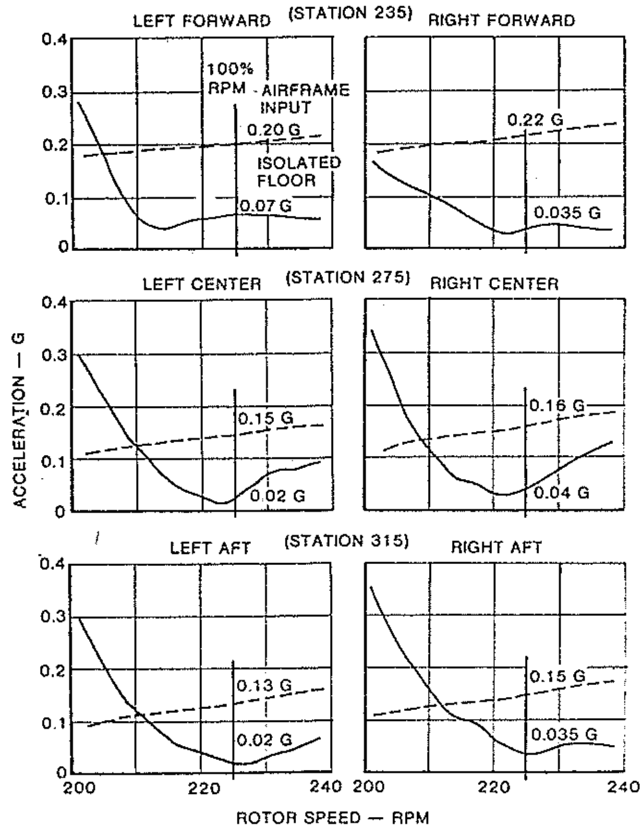

Figure 11. RPM Range Sweep at 3/Rev Vibration Levels During Test of Isolated Floor Section

FUEL IFIS ANALYSIS

As mentioned earlier, one of the CH-47 airframe bending modes would be strongly affected by unisolated fuel. This problem is illustrated by the simplified model in Figure 12. With full fuel (7,000 pounds in each of two tanks) the frequency of the airframe mode is below 3/rev, and above 3/rev with no fuel. Somewhere in between the frequency of the airframe mode would therefore coincide with 3/rev and seriously degrade the cabin vibration environment unless we can manage to prevent that modal frequency from changing with fuel quantity. In the existing CH-47 fleet, this is avoided by conventional passive isolation of the fuel mass with rubber isolators. For the larger fuel quantities of the Model 234, the IFIS was applied.

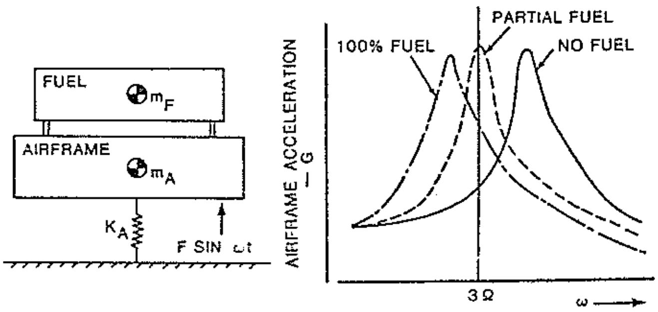

Figure 12. Unisolated Fuel Induces Airframe Resonance

Let us turn our attention once more to the IFIS mathematical model, only this time the floor is replaced by fuel (Figure 13):

Fuel, Z_F

$$\left\{K_I - \omega^2 \left[m_F + m_I \left(\frac{R}{r}-1\right)^2 + \frac{I}{r^2}\right]\right\} Z_F - \left\{K_I - \omega^2 \left[m_I \left(\frac{R}{r}-1\right)\frac{R}{r} + \frac{I}{r^2}\right]\right\} Z_A = 0 \quad (6)$$

Airframe, Z_A

$$-\left\{K_I - \omega^2 \left[m_I \left(\frac{R}{r}-1\right)\frac{R}{r} + \frac{I}{r^2}\right]\right\} Z_F + \left\{K_I + \underline{K_A} - \omega^2 \left[\underline{m_A} + m_I \left(\frac{R}{r}\right)^2 + \frac{I}{r^2}\right]\right\} Z_A = \underline{F \sin \omega t} \quad (7)$$

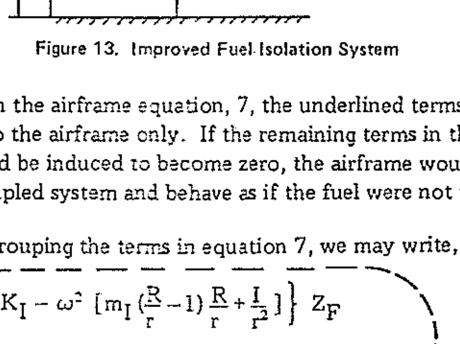

Figure 13. Improved Fuel Isolation System

In the airframe equation, 7, the underlined terms are related to the airframe only. If the remaining terms in that relation could be induced to become zero, the airframe would become an uncoupled system and behave as if the fuel were not there at all.

Regrouping the terms in equation 7, we may write,

$$-\left\{K_I - \omega^2 \left[m_I \left(\frac{R}{r}-1\right)\frac{R}{r} + \frac{I}{r^2}\right]\right\} Z_F + \left\{K_I - \omega^2 \left[m_I \left(\frac{R}{r}\right)^2 + \frac{I}{r^2}\right]\right\} Z_A + \left\{K_A - \omega^2 m_A\right\} Z_A = F \sin \omega t \quad (8)$$

Setting the terms within the dotted line equal to zero yields

$$\omega_F = \sqrt{\frac{K_I}{m_I \frac{(R/r)^2}{1 + m_I/m_F} + \frac{I}{r^2}}} \quad , \qquad (9)$$

which may be interpreted as follows:

If we select the fuel IFIS parameters such that equation 9 is satisfied, then the airframe becomes decoupled from the fuel at the forcing frequency $\omega = \omega_F$. Since the troublesome frequency for the fuel is the same as that for the floor, namely 3/rev, we will choose ω_F = 3/rev. Note that the fuel IFIS tuning equation contains m_F, the fuel mass, so that fuel IFIS tuning will change with fuel load. Practically, this shift is very small, for the largest ratio of m_I/m_F turns out to be 0.1, so that the tuning frequency shift will certainly be less than 5 percent ($1/\sqrt{1 + 0.1} = 1/1.05$). Analytical results show (Figure 14) that the airframe acceleration level will indeed remain independent of fuel at the tuned 3/rev frequency (225 rotor rpm). This is due to the fact that at this frequency there is no force feedback from the fuel to the airframe as shown in Figure 15. The same figure also shows that the slight detuning effect at low fuel is of no great importance since the transmitted force levels remain so low that their effect could not be seen in the airframe response (Figure 14), which remained virtually unchanged for fuel levels ranging from 10 to 100 percent.

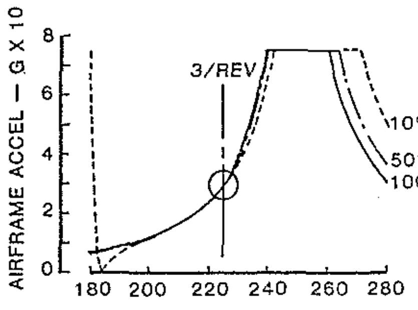

Figure 14. Airframe Vibration With Fuel IFIS

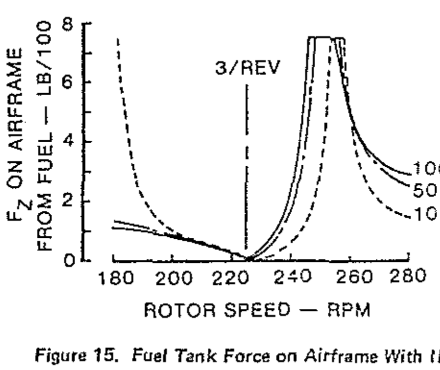

Figure 15. Fuel Tank Force on Airframe With IFIS

FUEL IFIS DESIGN AND SHAKE TEST

The fuel IFIS system, consisting of two composite fuel tanks, two IFIS units per tank, and two support beams, was designed and fabricated. Figure 16 shows one fuel IFIS unit which is quite similar to a floor IFIS unit, only larger. Two such units support each fuel tank, one at the forward end, the other at the aft end (Figure 17). There are no other ties with the aircraft. The two forward fuel IFIS units are attached at the lateral extremities of a support beam which in turn is connected to the airframe at the skin buttline. The same arrangement is repeated at the aft fuel IFIS installation.

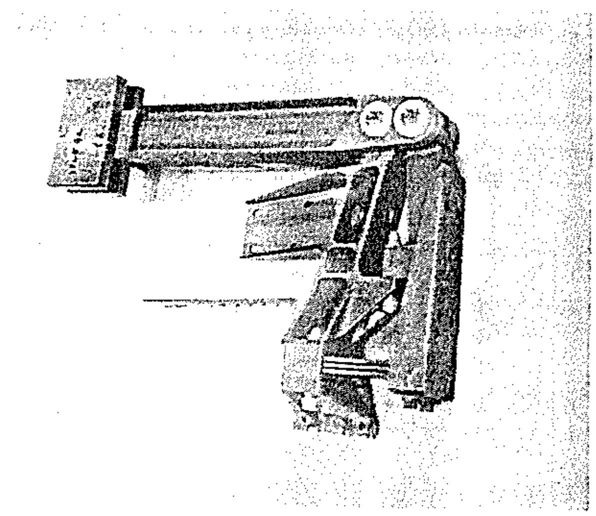

Figure 16. Detail of Single Fuel IFIS Unit

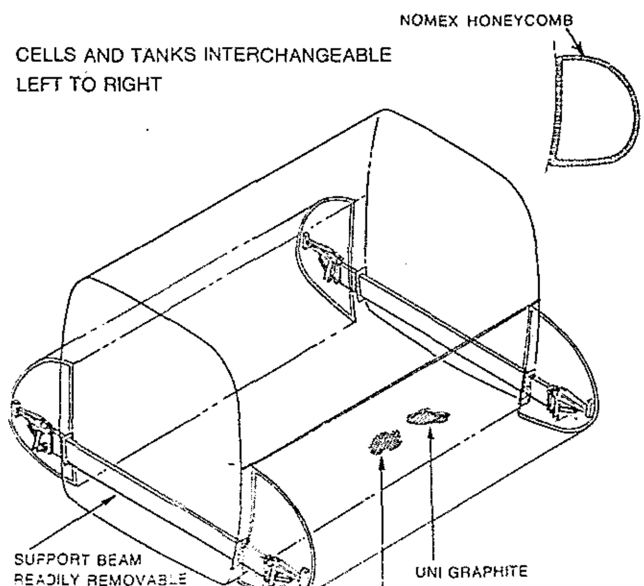

Figure 17. Fuel IFIS Installation

This configuration was installed on the same aircraft as the floor IFIS system and shake-tested to prove the concept. Each portion of the outboard support beam was instrumented for vertical shear. Fuel IFIS tuning was accomplished by monitoring these four shear measurements and adjusting the IFIS tuning to yield *minimum shear at the desired 3/rev frequency.*

Figure 18 presents the measured resultant shear transmitted to the fuselage for fuel loads ranging from 10 to 100 percent. There is a substantial reduction of transmitted load at all fuel levels when compared to unisolated fuel data which was obtained by locking out the IFIS. Note that the locked-out data indicated fuel resonance which starts out well below 3/rev near 9 Hz with full fuel, progresses through 3/rev, and winds up above 3/rev with 10 percent fuel.

With the fuel IFIS free and operating, the frequency of the troublesome fuselage bending mode changed only slightly, as predicted. The location of greatest response in this mode, the forward hub in the longitudinal direction, was monitored and, as shown in Figure 19, the resonance did not shift by more than ±0.2 Hz between the extreme fuel levels, as was desired.

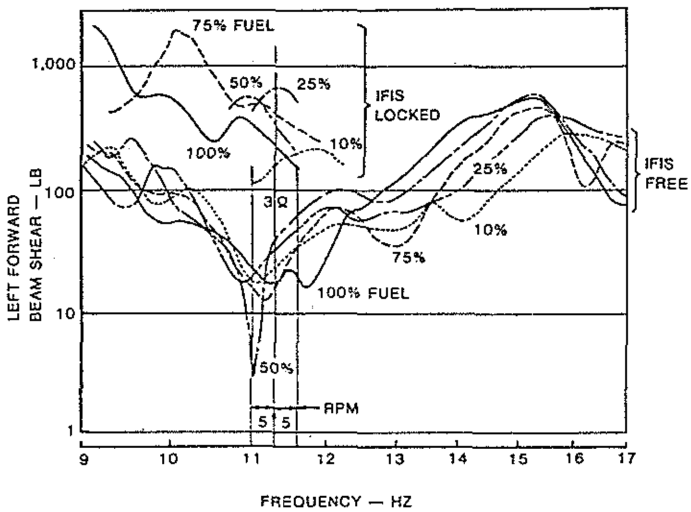

Figure 18. Fuel IFIS Shake Test Transmitted Shear From Tank to Airframe

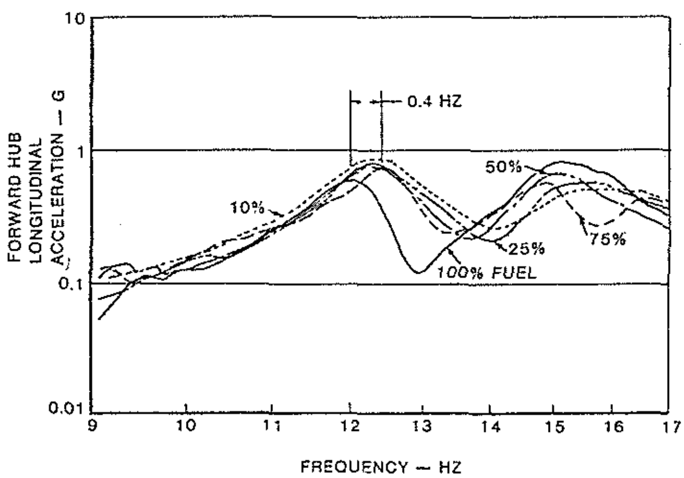

Figure 19. Frequency of Aircraft Mode Does Not Change With Fuel Quantity

Cabin vibration remained essentially the same (Figure 20), meeting the real objective of the fuel IFIS concept.

Floor IFIS performance was checked periodically during fuel IFIS testing. No deterioration was found at any fuel level.

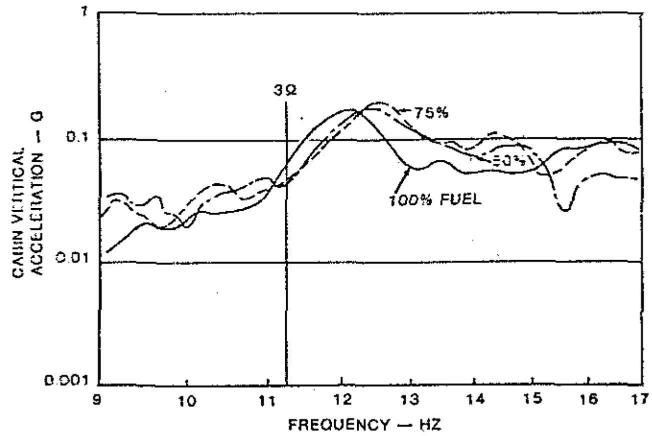

Figure 20. With IFIS, Cabin Vibration Remains Same at 3/Rev for All Fuel Levels

CONCLUSIONS

1. Analytically predicted performance trends of both the floor and fuel IFIS systems were confirmed by shake test.

2. The fuel IFIS is capable of maintaining consistent 3/rev vibration levels at all operational fuel levels by preserving relatively constant airframe natural frequency.

3. The floor IFIS reduces airframe vibration at 3/rev to acceptably low levels on the isolated passenger floor.

4. The floor and fuel IFIS functions combine harmoniously to form an integrated floor/fuel isolation system on the helicopter.

ACKNOWLEDGMENT

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