ENGINE/AIRFRAME INTERFACE DYNAMICS EXPERIENCE

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Abstract

Recent experience has highlighted the necessity for improved understanding of potential engine/airframe interface dynamics problems to avoid costly and time-consuming development programs. This paper gives some examples of such problems, and the manner in which they have been resolved. It also discusses a recent program in which contractual engine/airframe interface agreements have already proven helpful in the timely prediction and resolution of potential problems.

In particular, problems of engine/drive system torsional stability, engine and output shaft critical speeds, and engine vibration at helicopter rotor order frequencies are discussed, and test data and analyses presented. Also presented is a rotor/drive system dynamics problem not directly related to the engine.

General

This paper is an attempt to highlight some recently encountered problems in the area of helicopter engine and drive system dynamics. In comparison to the number of technical papers published in the area of rotor and blade aeroelasticity and stability, and fuselage vibration reduction schemes, there are relatively few indeed dealing with engine/airframe dynamics.

The paper does not present highly sophisticated methods of solution for these problems. It instead shows that solutions were attained by the application of basic engineering principles to state-of-the-art analytical and test techniques. Also, having encountered these problems, we are more cognizant of these potential "show-stoppers," the manner in which they manifest themselves, and the available courses of corrective action. It is essential that the knowledge gained through these programs be judiciously applied to new helicopters, and growth versions of existing models.

Engine/Drive System Torsional Stability

The usual stability requirements that dictate fuel control gain limits are complicated by the flexibility of the helicopter drive system and by the dynamics of a gas turbine engine. The interaction of the helicopter rotor and drive system, engine, and fuel control requires careful attention if a good or even workable fuel control is to be achieved. In the case of the T55-L-11 engine and the CH-47C aircraft, these items were growth versions of existing components. There was no requirement for new control concepts since operation had been successful on previous models. However, the fuel control gains had to be carefully re-evaluated for the new power levels.

Computer simulation of the CH-47C rotor system with the T55-L-11 turbine engine was accomplished before initial flight tests began. The simulation indicated favorable engine/control stability. However, as pointed out in Reference (1), unacceptable oscillations in engine shaft torque and rotor RPM were observed during initial flight tests (Figure (1)). These torque oscillations were audible, disconcerting to the flight crew, and were observed only in hover and on the ground (not in forward flight). The frequency of the oscillation was also higher than the predicted drive system torsional natural frequency.

Since the torsional instability was not predicted by the computer simulation, a study of pertinent system parameters was undertaken. It was discovered that the only parametric change having a significant effect on torsional stability was the slope of the blade lag damper force-velocity curve below the preload force level. When this curve was artificially "stiffened" beyond its actual limits, as shown in Figure (2), the oscillation was reproduced. This fact suggested that by "softening" the actual damper preload slope, the oscillation might be suppressed. Once analytically reproduced, the oscillation could be eliminated by simulating a fuel control with a reduced steady state gain and a slowed time constant. The computer analysis, therefore, revealed two potential solutions to the torsional oscillation problem: a lag damper modification and a fuel control modification.

Flight tests with a set of lag dampers with significantly reduced preload slope, together with the original fuel controls, were conducted. These tests revealed that the torque oscillation was apparently suppressed. However, since the lag dampers were on the aircraft for ground resonance reasons, this significant load change reduced damping capacity and produced some degradation in the ground resonance characteristics of the helicopter. Therefore, damper modification to remedy torque oscillation was rejected.

Fuel controls with a 30% reduction in steady-state gain were flight tested, and yielded acceptable torsional stability. However, this degraded to marginal instability in colder ambient temperatures. Controls incorporating a gain reduction plus an increase in time constant provided acceptable engine torque stability in the cold and over the entire engine operating envelope. Fuel control frequency response curves are shown in Figure (3). Pilots also noted that engine response to input power demands was not perceptibly degraded with these slowed-down controls. Therefore, this fuel control modification was considered an acceptable production fix.

Representation of the lag damper with just the force-velocity curve in the engine/drive system/fuel control simulation had been shown to be insufficient to accurately reproduce the torque oscillation phenomenon. Therefore, a more accurate math model of the damper was deemed necessary for further analysis, and for a more complete understanding of the problem. The derivation of the upgraded lag damper math model is shown in Reference (1). Inclusion of this lag damper math model into the torsional stability computer simulation accurately reproduced the torque oscillation with the original fuel controls. Frequency of oscillation, phasing and magnitude of damper force, shaft torque oscillation, and fuel flow fluctuation were now simulated accurately. Final simulation may be seen in Figure (4). The primary difference between this damper simulation and the earlier version is that the new model included the hydraulic spring effect of the damper.

The reduced gain-increased time constant fuel control fix has provided satisfactory torsional stability for the CH-47C production fleet. However, several early production aircraft reported instances of a "pseudo-torque oscillation". This phenomenon is a torque split, followed by a low amplitude torque oscillation of the high torque engine. The problem was traced to high levels of vibration affecting the internal workings of the fuel control. Vibration at cross shaft frequency caused an instantaneous increase in the effective gain of the control, increasing its torque output with respect to the other engine, and making it susceptible to torsional instability. The problem was resolved by closely monitoring cross shaft vibration, and with minor fuel control component modifications.

During the latter part of the torque oscillation program, it became apparent that the engine and airframe manufacturers can easily coordinate their efforts to prevent this type of incompatibility. Lycoming has now provided Vertol with a mathematical model of the engine and fuel control system, so that rotor/drive system design changes may be evaluated for their effect on torsional stability. It is equally important that as accurate a representation as possible of the rotor and drive system be given to the engine manufacturer.

There has been some mention in recent years about the possibility of using a zero torsional stiffness coupling (Reference (2)) to effectively isolate the engine from the rotor drive system, thereby precluding torque oscillation. At this time, potentially high developmental costs, uncertainty of transient behavior, and added weight to the drive system seem to rule out the z.t.s. coupling. However, continued research may yield an acceptable concept that may be the design solution for torsional instability for the next generation of increasingly larger, faster and more complex VTOL rotorcraft.

Engine Vibration at Helicopter Rotor Frequencies

The CH-47/T55 engine installation is "hard-mounted", as shown in Figure (5). It employs two front mounts on a yoke at the engine inlet housing, and an aft vertical support link at the engine diffuser flange. The outboard yoke airframe point is connected to take out high fore-aft maneuver loads. Engine vibration had rarely been a problem on the CH-47A and B models with this type installation.

However, field service reports indicated an increase in engine, engine component and engine mount vibration-related problems with the installation of the T55-L-11 and -11A engines in the CH-47C helicopter. These problems led to a full scale engine and strain survey, the purpose of which was to determine the dynamic characteristics of the engine installation, especially the vibration/strain relationships. The engine survey (Reference (3)) provided a wealth of information concerning the CH-47C engine/airframe interface dynamic characteristics. In particular, the survey identified rotor 3/rev as the predominant excitation frequency in the engine mounting system.

Also, inlet housing stresses and drag strut load increased significantly with frequency (rotor speed), as if approaching a resonance, as shown in Figure (6). As a result of this discovery, a ground shake test was recommended to define the characteristics of the apparent engine/airframe mode being excited by rotor 3/rev. The shake test setup is shown in Figure (7).

The CH-47C/T55-L-11 engine shake test revealed a 14.2 H_z rigid body yaw mode. Installation of -11A engines (an additional 40 lbs.) caused a .4 H_z downward shift in modal frequency, and a twofold increase in 3/rev inlet housing strains. Additional testing showed that reducing drag strut bolt torque could lower the engine yaw mode frequency into the CH-47 operating range (11.5 to 12.5 H_z). Complete elimination of the drag strut lowered the mode to 7.5 H_z, well below the CH-47C operating range. Shake test frequency sweeps are shown in Figure (8). Removal of the drag strut, however, is not a practical solution. It is needed to assure acceptable cross shaft alignment under high maneuver G and jet thrust loads. The solution, therefore, was to retain the drag strut, but slot one end to eliminate dynamic stiffness for small amplitude motions, resulting in a structurally detuned installation.

Flight evaluation of the slotted drag strut was desired, and the Model 347 research helicopter was available as a testbed. The 14 H_z yaw mode fell within the operating n/rev frequency range (14-16 H_z) of the four-bladed Model 347 and, therefore, it would be possible to verify the inflight placement of the mode. However, rotor speed sweeps of from 210 to 240 RPM with the standard strut failed to show a peak inlet housing stress response in the expected frequency range. Reducing rotor RPM still further finally located the engine yaw mode at 13.2 H_z.

Installing the slotted drag strut on one engine completely eliminated the 13 H_z peaks, and resulting 4/rev inlet housing stresses were reduced by as much as 75%. Lateral 4/rev vibration at the engine diffuser showed as much as an 85% reduction. These load and vibration reductions are illustrated in Figure (9).

It is noteworthy that analytical efforts to predict the installation dynamic characteristics met with limited success. This analysis first made use of assumed values of fuselage backup structure stiffness, and later used values calculated from a finite element structural model of the entire fuselage. However, the accuracy of these stiffness values is a function of idealization accuracy and validity, and end condition assumptions. The analytical predictions began to resemble the actual test results only when static load-deflection test data at the engine support points was used in the analysis. It is important here to point out two other factors that contributed to the CH-47C engine vibration stress problem; the increase in normal rotor RPM from the A to C model to improve the flight envelope resulted in a higher forcing frequency, and the increasing engine weight and inertia of the more powerful engine moved the resonant frequency downward.

Engine bending was not a contributing factor in this installation. In engine installations where it is a factor, the analysis becomes much more complex. Close coordination between engine and airframe manufacturers, through engine/airframe interface agreements, will be necessary to accurately describe the installed engine dynamics in this case.

In the overall design of an engine installation, it is imperative to choose the engine dynamic characteristics (isolated, detuned or hard mounted) such that output shaft alignment is not jeopardized. Or, conversely, output shaft couplings must be tailored to the vibratory environment of the engine. In an isolated engine installation (where most engine modes are placed well below predominant forcing frequency), output shaft couplings with high misalignment capability must be employed. In a hard-mounted or detuned installation, low misalignment couplings, such as the Thomas coupling, may be utilized.

Rotor/Drive System B/Rev Torsional Resonance

The Boeing Vertol Model 347 research helicopter is a derivative of the CH-47C Chinook helicopter, the primary differences being a 30 inch higher aft pylon, a 100 inch longer fuselage, and an increase in rotor blades from 3 to 4 per rotor (Reference (4)). A Holzer torsional analysis of the CH-47C revealed natural modes at roughly .3/rev, .9/rev, 4.1 and 4.2/rev; therefore, the Chinook was considered to be free from b/rev torsional resonance (3/rev in this case). A similar analysis on the Model 347 revealed almost identical non-dimensional torsional frequencies, despite a lengthened aft rotor shaft and forward synchronizing shaft, and a reduction in rotor RPM. There was some concern about the proximity of the third and fourth torsional modes to b/rev (4/rev in this case). However, it was believed that forcing levels and phasing would not be sufficient to excite these modes. The Model 347 drive system torsional modes are shown in Figure (10).

The Model 347 program was flown successfully, until the aircraft was flown at high gross weights. Here, high 4/rev blade chordwise bending moments in transition and high speed forward flight became a structurally limiting factor. Examination of flight test data revealed that the chordwise bending moments of all four blades on each hub were exactly in phase. Data also revealed substantial rotor shaft 4/rev torque fluctuations, with the forward and aft rotor systems opposing each other as shown in Figure (11), and 4/rev chordwise bending moments increasing sharply with RPM, as if approaching a resonance (Figure 12).

Analytical parametric studies were conducted to evaluate the effect of various system modifications on the apparent 4/rev resonance. Modifications such as forward and aft rotor shaft stiffness changes, synchronizing shaft stiffness changes and effective lag spring stiffening were all found to be effective to some extent. However, these changes were rejected due to the magnitude of change required to move the resonance and sensitivity to RPM changes. A much more acceptable modification was found to be raising the blade uncoupled chordwise bending natural frequency. On the CH-47C, this blade frequency was just above 5/rev; consequently, the largest blade bending loads are at 5/rev. However, with these same blades on the Model 347, the largest blade bending loads were at 4/rev, indicating the blade/drive system coupling effect.

Both blade softening and stiffening were investigated. It was found that decreasing the blade chordwise bending frequency was more effective in moving the drive system resonance than the same percentage increase, as shown by the Figure (13) analysis. But it was felt that this blade softening would present too great a structural degradation problem in the blade. Hence, raising the blade chordwise frequency, and with it the coupled blade/drive system torsional resonance, was the design goal. Analysis revealed that a 4 H_z increase in blade natural frequency would result in satisfactory detuning of the blade/drive system resonance.

The most effective location to attempt a chordwise frequency increase is at the trailing edge. It was necessary in this case to add on a material of high stiffness and minimum weight, such that chordwise balance and CF loads are not grossly affected. The design selected consisted of top and bottom boron fiber doublers bonded to the stainless steel trailing edge from 30% to 70% span, and boron skins applied to several blade boxes. The benefit of the boron stiffening is twofold, for in addition to increasing the chordwise frequency to avoid resonance, strength is increased.

The addition of boron stiffening moved the blade uncoupled flexible chordwise frequency from 5.26/rev to over 6/rev. This resulted in a shift in the blade/drive system natural frequency to over 4.2/rev (at 235 RPM) or to 4.3/rev (at 220 RPM). This was sufficient to preclude high 4/rev amplification, since blade chordwise trailing edge loads are now highest at 6/rev (the uncoupled blade frequency).

This problem does not fall strictly into the category of engine/airframe interface dynamics. However, the influence of the engine in the drive system dynamics, and the potential impact of such a problem on the engine cannot be ignored. For example, to accurately predict drive system modes, the power turbine inertia must be accurately known.

Engine Output Shaft Critical Speed Analysis

The Boeing Vertol Heavy Lift Helicopter prototype will incorporate three Detroit Diesel Allison XT701-AD-700 turboshaft engines. These engines have been developed from the Allison 501-M62B as part of a program to procure representative engines for the HLH Advanced Technology Component (ATC) dynamic systems test rig. Many helicopters built in the past were designed around existing engines. However, in the case of the HLH, initial development of the engine is to be fully coordinated by the prime contractor; hence, development of both engine and airframe will be in parallel. The HLH engine program is discussed in Reference (5).

A development problem was encountered during the program which involved the engine/airframe output drive shaft interface. The original design of the engine output shaft was a short splined shaft with the torquesensor mounted within the main frame of the engine. Based on more detailed engine nacelle design, it was requested that the splined shaft interface be moved forward to reduce inlet blockage and to facilitate inspection of the shaft coupling. This change was agreed upon, and the drive shaft connection was moved to a point 17 inches forward of the front face of the engine. The torquesensor was also housed in the resulting engine "nose". A cutaway view of the torquesensor and housing is shown in Figure (14).

The original shafting concept on the HLH was to drive into the main transmission directly, without right angle gearboxes, resulting in a substantial weight savings. A layout of the original HLH engine/mixbox shaft configuration is shown in Figure (15). The original engine-to-mixbox shafting consisted of two 7.25 inch diameter sections of equal length with a single bearing support point. However, in an attempt to further reduce inlet blockage and reduce weight, the shaft diameter was reduced to 6 inches. This decision was based on preliminary analytical trade studies which used an initial estimate of engine flexibility. Critical speed placement was analyzed to be more than 25% above normal operating speed (11,500 RPM).

As the detailed design of the engine progressed and was included in the critical speed analysis, it became apparent that the anticipated critical speed margin would not be realized. The analysis was expanded to include the torquesensor, its housing, bearings, and effective engine radial and moment flexibility. This more detailed analysis, performed at Detroit Diesel Allison and confirmed by Boeing Vertol, revealed the shaft/torquesensor whirl mode in the area of 12,500 - 13,000 RPM, or only about 10% above normal operating speed. The analytical mode shapes and frequencies are shown in Figure (16).

Working together, both companies conducted parametric analyses to evaluate various potential fixes. Prime candidates were inlet housing and torquesensor housing stiffness increases, a shorter engine nose, auxiliary support struts, stiffened torquesensors, plus combinations; however, when they were analyzed in combination with a complete engine dynamic model, none proved satisfactory. In fact, with the complete engine model, the critical speed of the original configuration was around 10,200 RPM, below normal operating speed. The mode involved substantial whirl of the torquemeter housing, some shaft bending and some case bending, and was very sensitive to output shaft coupling weight and unbalance.

This analysis revealed that the only practical solution was a drastic shortening of the torquesensor and housing, such that the shaft adapter is an integral part of the engine output shaft, and the flexible coupling is now only 5.3 inches from the front face of the engine. Due to the increased distance between the engine and combining transmission, the output shaft was changed to a 3-section configuration. This also reduced the amount of weight hung off the engine. Analysis of this configuration placed the natural mode at about 14,200 RPM, which was basically power turbine conical whirl interacting to some extent with the torquesensor shafting. Another mode at about 17,200 RPM showed compressor conical whirl with rotor, power turbine and case participation. Forced response analysis showed both these modes were only mildly responsive to mass unbalance at the output shaft coupling, as shown in Figure (17). This indicates that the desired shaft/engine dynamic decoupling has been accomplished.

It is interesting to note how design decisions not directly related to engine shaft dynamics provided constraints to the solution of the interface problem. For example, the decision to move the shaft interface well forward of the engine front face led to the long torquesensor housing design, which brought about the shaft/torquesensor whirl problem in the first place. Also, the engine/shaft interface could not be moved very much closer to the engine front face without shortening the torquesensor. Since torquesensor accuracy is a function of length, the decision to drastically shorten the torquesensor and housing was made with reluctance, since torquesensor accuracy had to be compromised to some extent.

Another interesting aspect of this problem is the fact that the critical speed of the engine-to-mixbox shafting could not be accurately analyzed until the complete engine dynamics were included. This is where the engine/airframe interface agreement in effect between Boeing Vertol and Detroit Diesel Allison has been instrumental. It has led to excellent working agreements between the companies that have helped to reveal, analyze and solve this potential problem before it reached the hardware stage. Preliminary shaft critical speed work was done at Boeing Vertol. However, when it became apparent that engine dynamics must be included to accurately predict the critical speeds, all work was done jointly with Allison.

Conclusions

(1) Helicopter engine/drive system torsional instability may be prevented if care is taken to accurately represent both engine and rotor systems in the analysis, including such effects as hydraulic compressibility of the blade lag damper.

(2) Accurate analysis and/or shake testing of all engine installations, whether hard mounted, detuned, or isolated, is required to determine potential engine vibration and stress problem areas.

(3) Helicopter rotor blades and drive systems must be designed such that blade lag flexibility does not couple

with drive system torsional flexibility to produce a resonance at the number of rotor blade's frequency (b/rev).

(4) Formal engine/airframe interface agreements have already proven beneficial in the timely resolution of potential interface dynamics problems.

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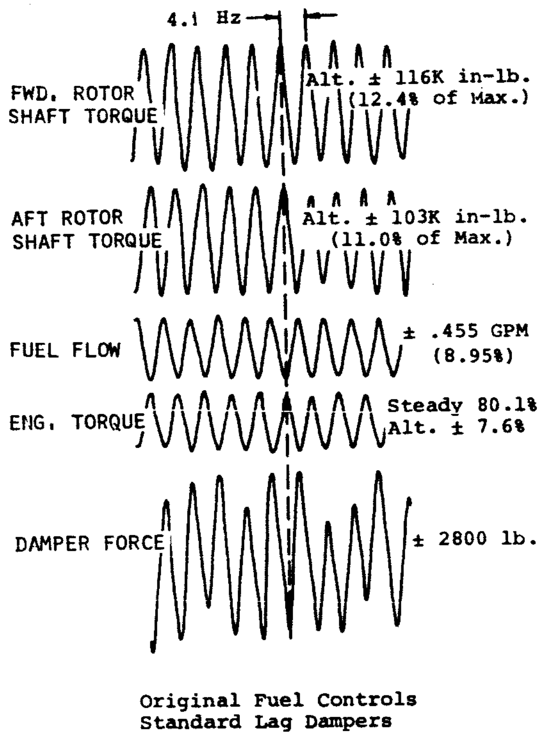

Figure 1. Torque Oscillation Flight Test Data

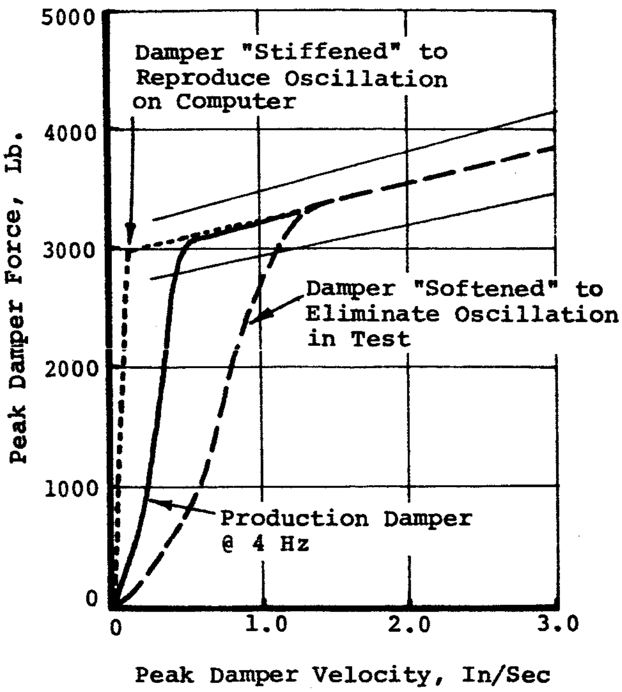

Figure 2. Lag Damper Force-Velocity Curves

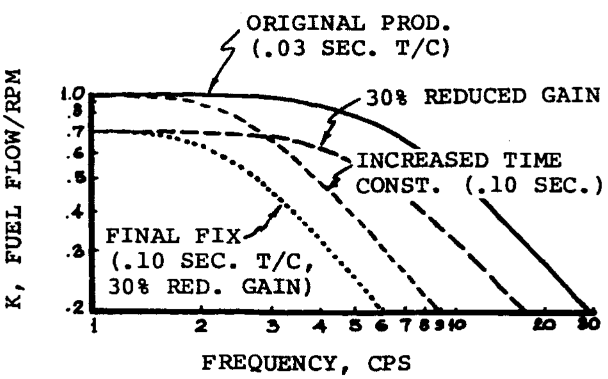

Figure 3. Fuel Control Frequency Response

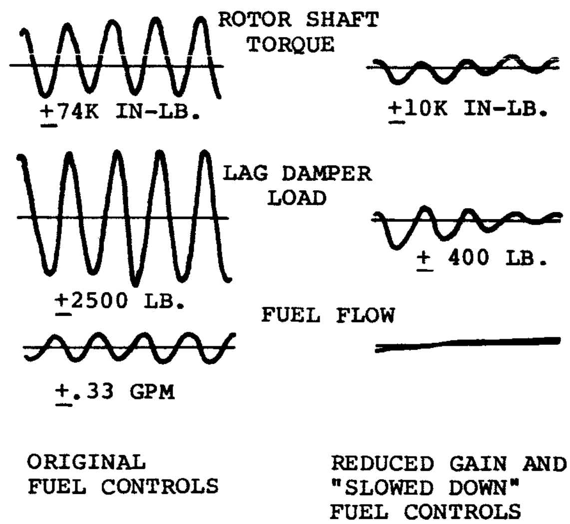

Figure 4. Final Torque Oscillation Simulation

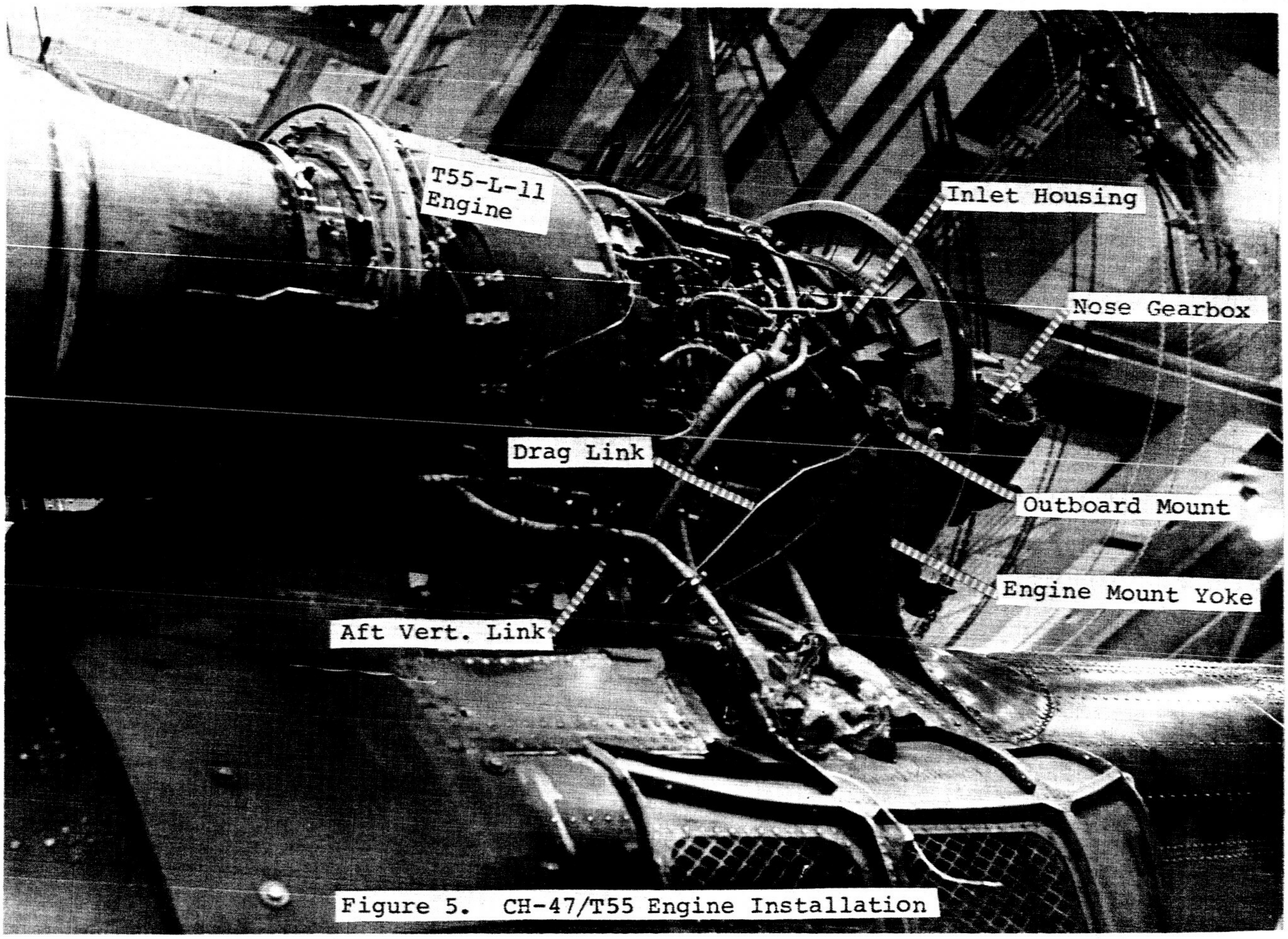

Figure 5. CH-47/T55 Engine Installation

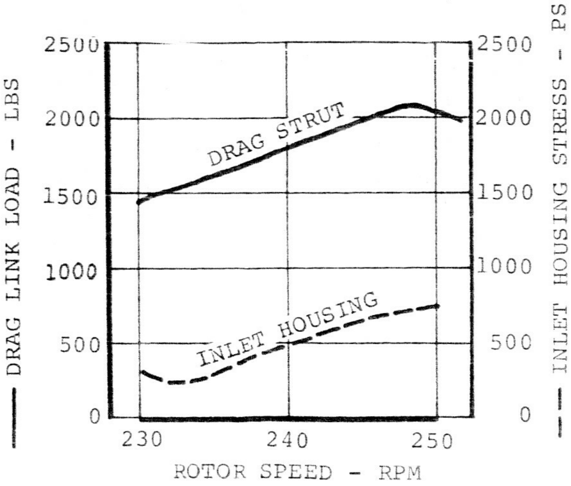

Figure 6. Inlet Housing Stress & Drag Link Load vs. RPM

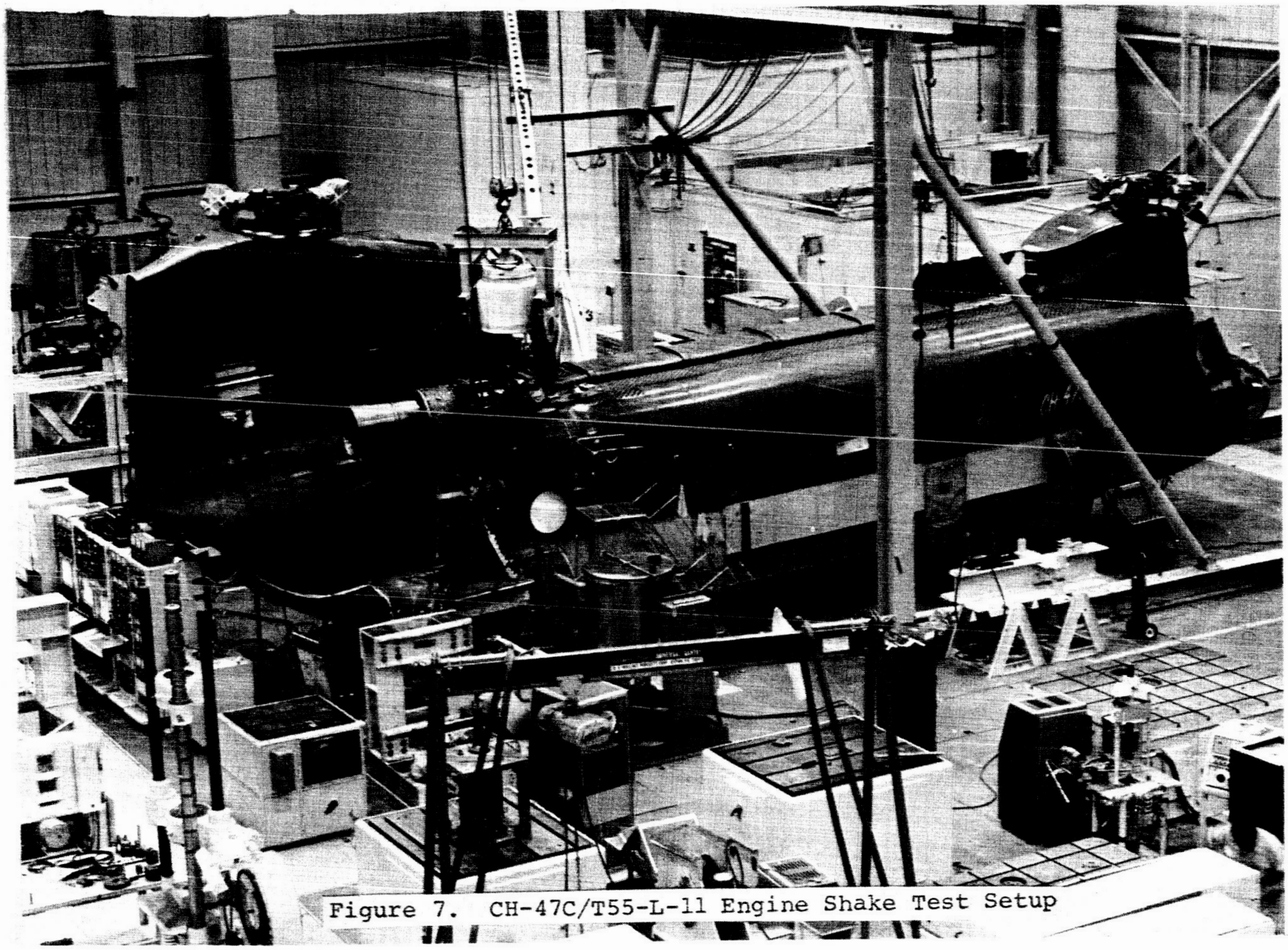

Figure 7. CH-47C/T55-L-11 Engine Shake Test Setup

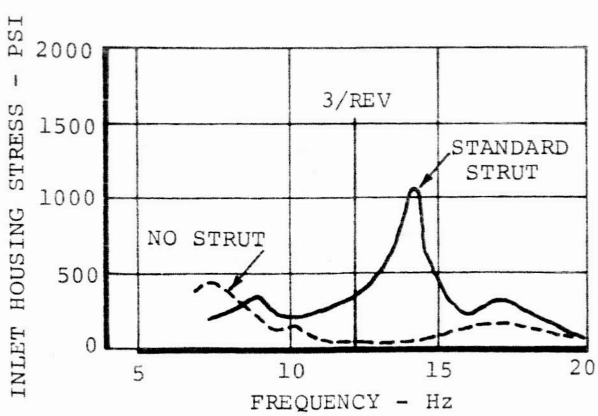

Figure 8. CH-47C/T55-L-11 Engine Shake Test Results

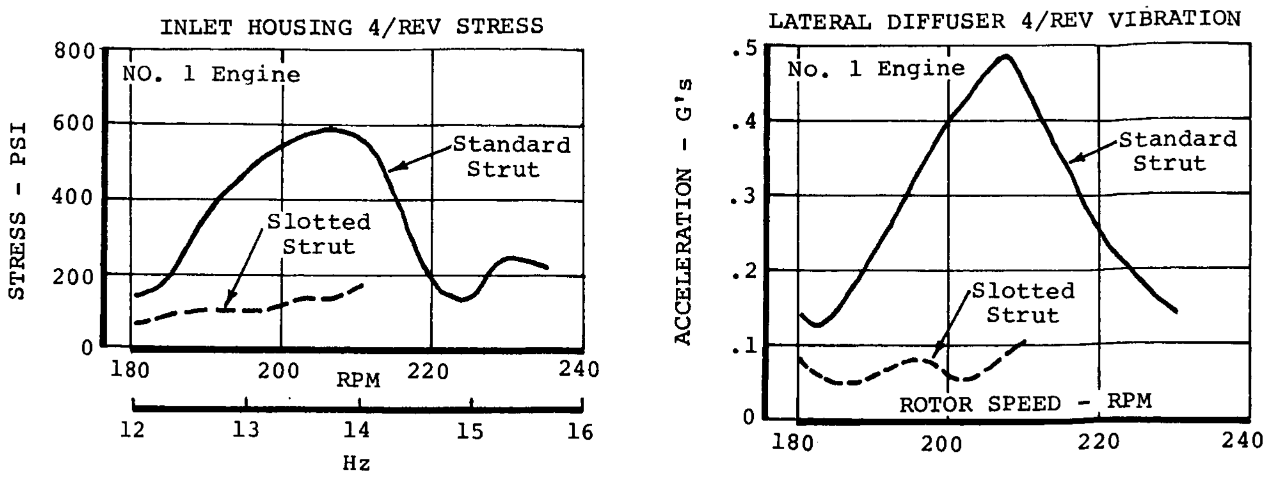

Figure 9. Vibration and Stress Reductions with Slotted Drag Strut

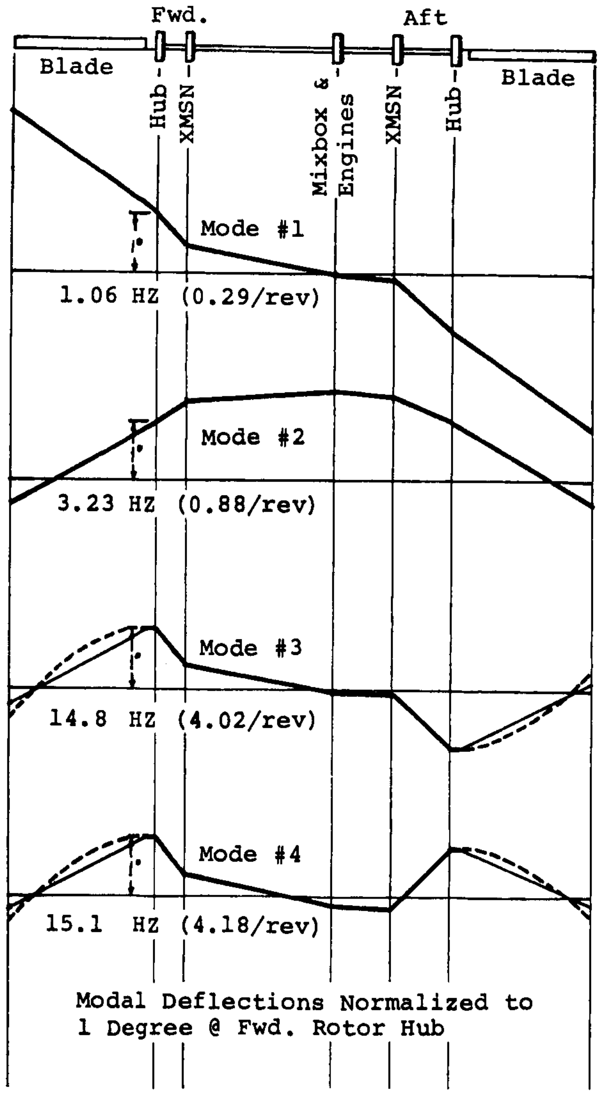

Figure 10. Model 347 Drive System Torsional Modes

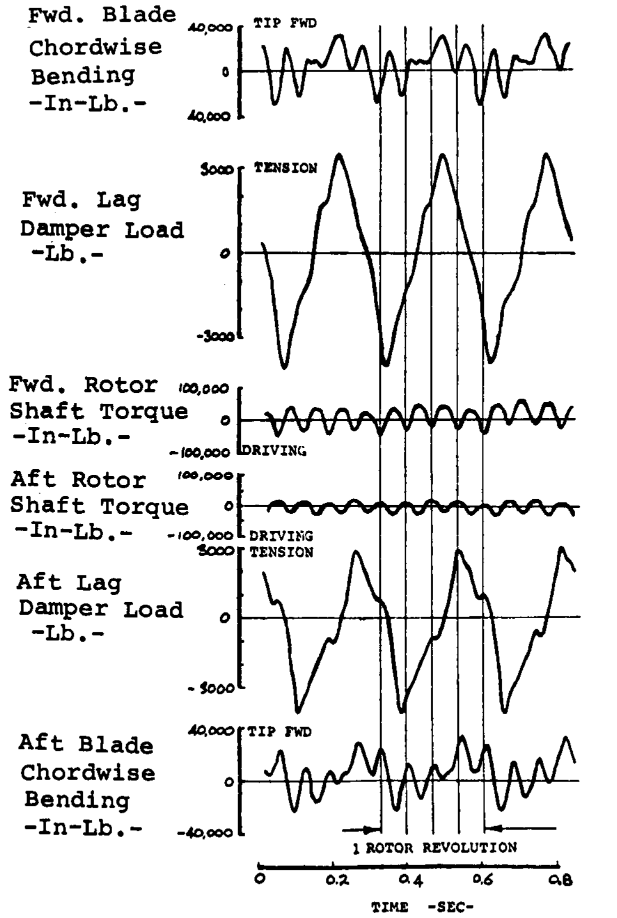

Figure 11. Model 347 Rotor/Drive System Flight Test Data

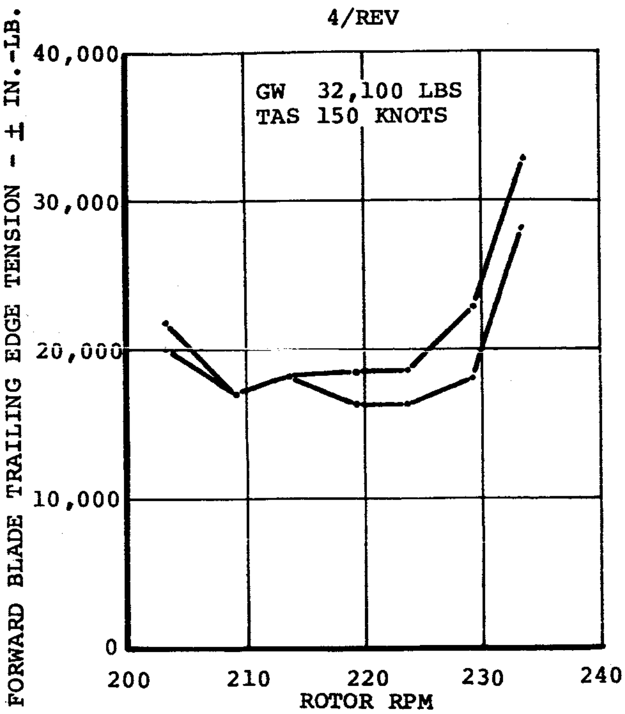

Figure 12. Model 347 Blade Chordwise Bending Moment vs. RPM

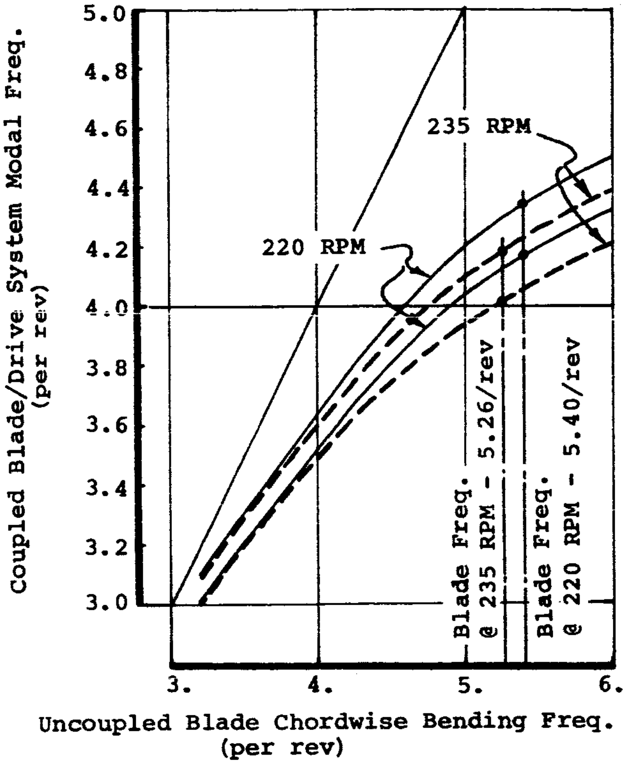

Figure 13. Effect of Chordwise Blade Bending Frequency on Model 347 Drive System Modes

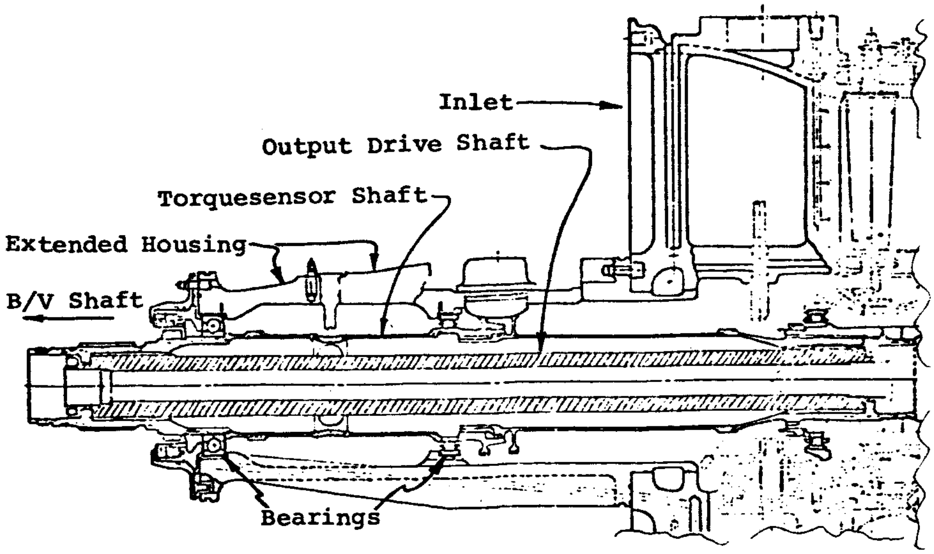

Figure 14. Original 501-M62B Torquesensor Configuration

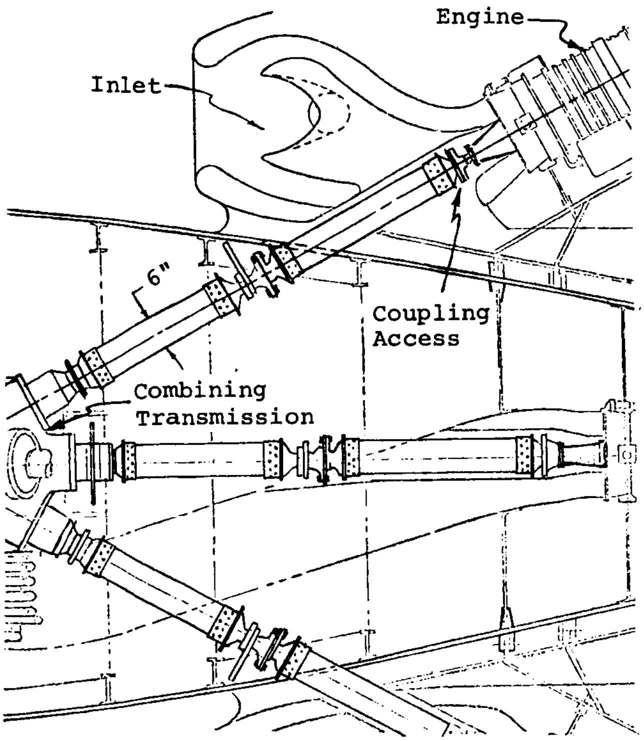

Figure 15. Original HLH Engine to Combiner Box Shafting

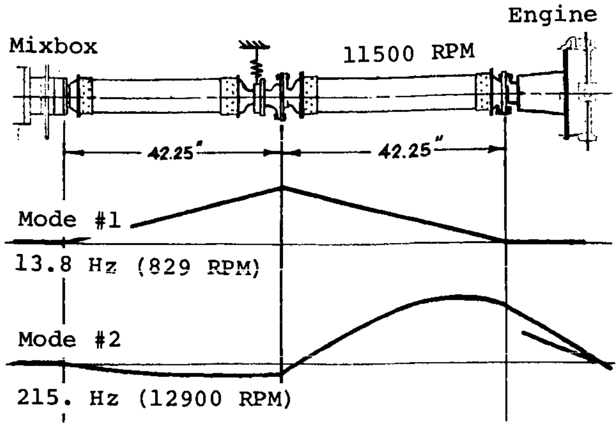

Figure 16. Preliminary Engine/Shaft Dynam Analysis showing Torquesensor/ Conical Whirl Mode

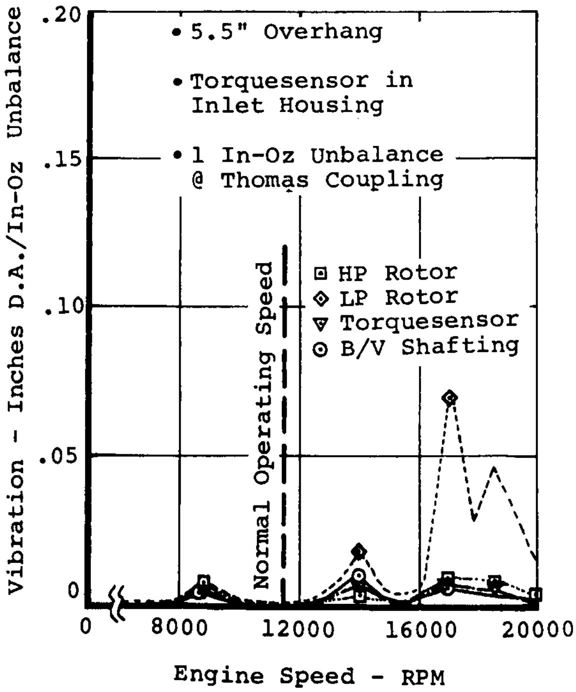

Figure 17. Final HLH Engine/Shaft Analysis - Response to Unbalance