NASA Technical Memorandum 101731

Monitoring Techniques for the X-29A Aircraft's High-Speed Rotating Power Takeoff Shaft

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December 1990

National Aeronautics and
Space Administration

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ABSTRACT

The experimental X-29A forward-swept-wing aircraft has many unique and critical systems that require constant monitoring during ground or flight operation. One such system is the power takeoff shaft, which is the mechanical link between the engine and the aircraft-mounted accessory drive. The X-29A power takeoff shaft operates in a range between 0 and 16,810 rpm, is longer than most jet engine power takeoff shafts, and is made of graphite epoxy material. Since the X-29A aircraft operates on a single engine, failure of the shaft during flight could lead to loss of the aircraft. The monitoring techniques and test methods used during power takeoff shaft ground and flight operations are discussed in this paper. Test data are presented in two case studies where monitoring and testing of the shaft dynamics proved instrumental in discovering and isolating X-29A power takeoff shaft problems. The first study concerns the installation of an unbalanced shaft. The effect of the unbalance on the shaft vibration data and the procedure used to correct the problem are discussed. The second study deals with the shaft exceeding the established vibration limits during flight. This case study found that the vibration of connected rotating machinery unbalances contributed to the excessive vibration level of the shaft. The procedures used to identify the contributions of other rotating machinery unbalances to the power takeoff shaft unbalance are discussed.

INTRODUCTION

Dynamic instabilities are a serious concern in rotating machinery. If not accurately predicted, such instabilities can lead to fatigue failures, excessive wear on sensitive parts, reduced efficiency, and total system failure. A dynamic instability in the rotating machinery of an aircraft system could lead to loss of the aircraft and pilot. The power takeoff (PTO) shaft of an aircraft is a critical component of the power plant system. It is the mechanical link between the engine and the aircraft-mounted accessory drive (AMAD), which contains the power components for the hydraulic and electrical systems.(1) The X-29A PTO shaft operates in a range between 0 and 16,810 rpm, is made of composite material, and is longer than most PTO shafts of other high-performance vehicles like the F-16, F-18, and F-14A aircraft.(2) A PTO shaft failure during flight creates a serious emergency that would require the aircraft to return to base. The loss of the PTO shaft activates the X-29A emergency backup power systems to provide electrical and hydraulic power to the aircraft. Failure of the backup systems would subsequently lead to loss of the aircraft and possible loss of the pilot.

The X-29A PTO shaft assembly components were extensively tested to establish the design and manufacturing adequacy of the PTO shaft. Torque tests to failure showed a strength well above the maximum operating torque. Critical speed tests showed that the minimum critical speed of 20,000 rpm was met. These bench tests verified that the X-29A PTO shaft had met its design criteria. However, additional testing was required to ensure that the X-29A aircraft did not have a damaged or unbalanced shaft during the flight testing. The uniqueness and criticality of the PTO shaft and the lack of testing methods after installation brought about the test monitoring techniques for the X-29A aircraft. These techniques were used during flight and ground test operations.

The monitoring techniques and test methods developed for the shaft relate the operational vibration characteristics to the "health" of the PTO shaft. These monitoring techniques and test methods consist of a ground vibration test and the use of a spectrum analyzer to monitor the vibration levels of the PTO shaft subassemblies during engine runs and flights.

Test data are presented in two case studies where monitoring of the PTO shaft proved instrumental in discovering and isolating high vibration levels. The first case study discusses the effect of the installation of an unbalanced shaft on the measured vibration data. The second case study shows the contributions of other rotating machinery vibrations on the shaft vibrations, causing the measured acceleration level to exceed the established limits during flight.

NOMENCLATURE

AMAD	aircraft-mounted accessory drive
CST	combined systems test
EPU	emergency power unit
GVT	ground vibration test
g	gram
g	acceleration of gravity
Hz	hertz
N_2	engine core rotor speed
PTO	power takeoff
rms	root mean square
rpm	revolutions/min
S/N	serial number

DESCRIPTION OF THE X-29A VEHICLE AND SUBSYSTEMS

The X-29A Forward-Swept-Wing Aircraft

The X-29A aircraft (fig. 1) incorporates many new technologies, the most evident of which is the forward-swept wing. The wing employs aeroelastic tailoring of advanced composite wing skins designed to avoid structural divergence and to ensure structural integrity within the flight envelope. Double-hinged trailing-edge flaperons provide both aerodynamic camber and roll control. The variable incidence canards, along with the wings and flaperons, operate together to achieve minimum trim drag. The vehicle is unstable longitudinally, with a negative static margin of 35 percent of the mean aerodynamic chord at subsonic speeds, and it is neutrally stable at approximately Mach 1.4. The flight control system includes triply redundant digital computers that provide the information to safely fly the aircraft.

The X-29A aircraft utilizes one F404-GE-400 turbofan engine (General Electric, Lynn, Massachusetts). Two of the aircraft's power subsystems, the engine starting and secondary power system and the emergency power system, are described in the following subsections. Descriptions of the other systems can be found in reference 1.

Engine Starting and Secondary Power Subsystems

The engine starting and secondary power subsystems incorporate the engine start system and the PTO shaft. The engine start system consists of a jet fuel starter system and an AMAD. Figure 2 shows an enlargement of the mounted accessories of the AMAD which consist of a starter, two hydraulic pumps, and an integrated drive generator. The PTO shaft is the direct mechanical link between the engine and the AMAD as shown in figure 2.

The PTO shaft subsystem consists of the following five subassemblies (fig. 3):

1. AMAD
2. output flexible assembly
3. center composite shaft

4. input flexible assembly

5. engine gearbox

The first section, the AMAD, powers the two hydraulic pumps and the integrated drive generator, which supplies aircraft hydraulic and electrical power. The second and fourth sections, the output and input flexible assemblies, are designed to absorb any axial loads that the shaft may experience. They also provide a centering ball design which prevents the shaft from "whipping" in case of failure.(2) The third section, the center composite shaft, transmits the rotary power between the AMAD and the main engine in two modes. In the first mode, the engine starting-motoring mode, power is transmitted through the AMAD to the main engine gearbox which is geared to the main engine high-pressure compressor spool. In the second mode, the accessory drive mode, power is transmitted from the main engine gearbox to the AMAD to drive the AMAD-mounted accessories.

The high rotational speeds between 0 and 16,810 rpm of the X-29A PTO shaft require a high degree of dynamic balance between its subassemblies to prevent destructive vibrations and harmonics. The gearbox, AMAD, and composite shaft components of the assembly are balanced dynamically as a unit during manufacturing. The following table shows the balanced component matrix for two AMADs, three PTO shafts, and three engine gearboxes. Washers were used to balance the PTO subsystem and were mounted under the bolts connecting the engine gearbox to the input flexible assembly as shown in figure 3.

Component matrix of the PTO shaft subsystem.

Aircraft	AMAD S/N	PTO shaft S/N	Engine gearbox S/N, HPC	Balance washer requirements, g
1	0001	001	40	0
1[a]	0001	003	40	0
2	0002	002	42	0.42 (1 ea.)
2[a]	0002	002	37	1.09 (1 ea.)
				2.70 (1 ea.)
Spare	0002	003	42	1.74 (1 ea.)
Spare	0002	003	37	1.08 (1 ea.)
				2.70 (1 ea.)

[a] Backup

Emergency Power Subsystem

In the event of a PTO shaft failure, the X-29A aircraft would be forced to use the engine bleed air to run the power systems of the AMAD. The engine bleed air can be used for an unlimited duration. Therefore, the aircraft would have enough time to make a safe landing. If the single engine of the X-29A aircraft failed, resulting in a loss of the engine bleed air, the emergency power unit (EPU) would provide power to the flight control and hydraulic systems. The EPU is a self-contained, stored-energy system that provides for simultaneous generation of emergency hydraulic and electrical power for only 7 minutes using a monopropellant fuel (70 percent hydrazine and 30 percent water).(1) Flying with only EPU power means that if the PTO shaft failed or ran out of the monopropellant fuel, there would be no power to the flight control and hydraulic systems. The result would be loss of the aircraft and possible loss of the pilot.

MONITORING TECHNIQUES FOR THE PTO SHAFT SYSTEM

The need for effective monitoring of the unique X-29A PTO shaft system was understood early in the program. Therefore, monitoring techniques were developed for use during the operation of the X-29A aircraft. The techniques utilized consisted of a shaft ground vibration test (GVT), engine ground runs, and flight testing. These techniques checked the integrity of the PTO shaft and tracked its vibration levels.

Shaft Ground Vibration Test

The ground vibration test was conducted on the installed PTO shaft to ensure that the first resonant frequency was not excited by the small unbalances in the shaft during operation. The lowest natural frequency was required to be above 300 Hz. This frequency is above the maximum shaft rotation speed of 280 Hz, which corresponds to an engine speed of 16,810 rpm.

The ground vibration test of the installed PTO shaft was performed by exciting the structure with a hammer instrumented with a force transducer. An accelerometer was mounted on the end of the PTO shaft to measure the response which was recorded and analyzed to find the natural frequencies and mode shapes.

Engine Ground Run Monitoring

The engine ground run check of the PTO shaft was conducted on each aircraft before the first flight of the day to see if the shaft vibration levels were within the limits. The shaft vibration levels were measured by one accelerometer located on the AMAD and another accelerometer located on the engine gearbox (fig. 3). The accelerometer signals were telemetered to a ground station, where they were band-pass filtered from 160 to 315 Hz to eliminate noise. The acceleration data were routed to a strip chart and to a spectrum analyzer to find the vibration levels.

The day-of-flight PTO shaft vibration check consisted of operating the engine at 13,448 rpm (224 Hz). This speed is 80 percent of the maximum operating speed. If the shaft vibration levels did not show any unusual characteristics and were within limits, clearance was given to fly. The test was also conducted if the PTO shaft was removed and then reinstalled in the aircraft. If the test revealed excessive vibration levels, a more extensive engine run was performed.

This extensive engine run procedure consisted of measuring the shaft vibration levels during 13 stabilized engine power settings from a ground idle of 10,620 rpm and 177 Hz to the maximum operating speed of 16,810 rpm and 280 Hz. The vibration levels of the test were measured and compared with the data obtained using the PTO shaft in a known balanced condition as discussed in the next paragraph. If this test showed excessive vibrations, further evaluation of the PTO was required before the X-29A aircraft could fly. Case study one, appearing later in this paper, discusses this evaluation.

During the initial evaluation of the PTO shaft, engine runs were performed with the PTO shaft in both a balanced condition and in an out-of-balance condition. These tests determined the effect of a known shaft unbalance on the gearbox vibration levels. In figure 4, the unbalance increased the vibration levels throughout the operating rpm range.

Real-Time Flight Test Monitoring

The real-time flight test monitoring of the PTO shaft vibration characteristics was the main method used to assess the vibration levels of the shaft. The monitoring used the same equipment and methods of the engine ground runs. Vibration levels were measured using the accelerometers located on the AMAD and engine gearbox during flight throughout the operating speed range of the PTO shaft. Using a strip chart and a spectrum analyzer, the vibration levels were determined, tabulated, and compared with nominal balanced data (fig. 4) to determine PTO shaft performance.

GROUND AND FLIGHT LIMITS

The ground and flight limits established by the engine and airframe manufacturers were based on the allowable limit radial loads for the engine gearbox duplex bearings. Initial engine ground runs were accomplished with the PTO shaft instrumented with proximity probes (fig. 3) to establish a relationship between the shaft deflection and the engine bearing loads. This relationship was established because the accelerometer used for flight and ground monitoring was located on the engine gearbox assembly. The AMAD limits were developed in a similar procedure also based on the gearbox duplex bearing loads. The recommended acceleration limits, which were established by analysis and ground testing for the gearbox, consist of 2.7 *g* at 80 percent (227 Hz) of the engine speed during the engine ground runs and a 6.0-*g* limit during flight. The limits for the AMAD are shown in figure 5.

CASE STUDIES OF THE PTO SHAFT MONITORING

Case 1 — Out-of-Balance Shaft Installation

During the course of the X-29A program, a complete check of all systems including instrumentation, aircraft, and control room operation was conducted. This complete check is called a combined systems test (CST). The gearbox and AMAD data compiled for the second X-29A aircraft during its initial CST are shown in figures 6 and 7. The higher acceleration levels of the gearbox and AMAD indicate an unbalanced shaft installation.

Several ground runs were performed to troubleshoot the unbalanced PTO shaft. Figures 8 and 9 show the data for three of the engine runs along with the configuration of AMAD, gearbox, and the PTO shaft that was installed during the runs. The first run, the CST, was where the higher vibration levels were first seen. The second engine run was done after a complete check of all the PTO shaft accelerometers and the parameter setup in the control room for any anomalies. After the check, the data were found to be repeated with no significant decrease in the acceleration levels. A more detailed study of the installation procedure found that the PTO shaft was rotated 90° from the correct markings on the shaft. After the shaft was rotated correctly, another engine run was performed. The data showed no major reduction in vibration levels.

A shaft GVT was then performed to verify the structural integrity of the PTO shaft. The GVT test of the installed shaft measured the frequency of the PTO shaft mode and compared the data with previously measured data of a balanced PTO shaft. From the response signatures, the vertical and lateral mode frequencies were found to be 362 Hz and 353 Hz, respectively. Both responses are above the design criteria of 300 Hz. The normalized mode shape for the vertical mode is shown in figure 10 along with the mode shape from a known balanced PTO shaft. The data obtained from the GVT closely follow the mode shape of the balanced shaft. The GVT data indicate that the PTO shaft was not damaged and that a problem exists in the installation, or that the shaft assembly itself was unbalanced.

In lieu of rebalancing the current configuration (PTO shaft S/N 003, gearbox S/N HPC 42, and AMAD S/N 0002), it was decided to change to PTO shaft S/N 002, which had also been balanced with the current gearbox, and AMAD, as shown previously in the table. This PTO shaft was installed on the X-29A aircraft, and another engine run was performed. The data in figures 11 and 12 show a reduction in the vibration levels of the gearbox and AMAD, respectively. The reduction in vibration levels indicates that the configuration was installed correctly and was balanced.

The established procedures were instrumental in discovering and isolating the problem of installing an unbalanced PTO shaft combination in the aircraft. As indicated in the table, PTO shaft S/N 003 was documented as a balance combination, with one balance washer of 1.74 g. The vibration data showed that this combination was not balanced when installed in the aircraft. Without the established procedures for monitoring the PTO shaft vibrations, this anomaly may not have been found.

Case 2 — AMAD Vibration Limits Exceeded During Flight

The AMAD vibration limit was exceeded during the initial flight of the second X-29A aircraft. This occurred at approximately 199 Hz, which corresponds to an engine speed of just under 12,000 rpm or a frequency of 200 Hz (fig. 13). At frequencies above 200 Hz, the AMAD vibration levels were within the established limits. The gearbox data showed no unusual trends and did not exceed any limits. The data indicated that the PTO shaft was balanced and that another unbalance existed in the AMAD.

The data in figures 9, 12, and 13 show that as the frequency of the PTO shaft approached 200 Hz, the amplitude of the vibration increases. The AMAD strip chart trace in figure 14 shows that the signal from the AMAD accelerometer resembles a sine wave with a calculated frequency of approximately 0.40 Hz. This frequency was termed the beat frequency or frequency difference of two closely spaced modes of vibration. The second trace in figure 14 shows the engine speed in percent of the maximum speed. Interestingly, as the engine speed approached approximately 71 percent or 200 Hz, the amplitude of the beat increases confirmed the plotted acceleration data.

The power spectrum of the AMAD accelerometer in figure 15 zoomed in at approximately 200 Hz, confirming the presence of two closely spaced modes. The frequency difference calculated from the power spectrums indicated about the same frequency difference as the strip chart trace.

It was found that the integrated drive generator, which is one of the mounted accessories on the AMAD, has a speed of12,000 rpm. The integrated drive generator consists of a constant-speed drive which converts the variable AMAD input speeds, ranging from 4500 to 9000 rpm, to a constant 12,000-rpm output speed for driving the main generator rotor.[1] The PTO shaft and the constant-speed-drive unbalance reinforced or added to each other at approximately 200 Hz, which resulted in higher vibration amplitudes shown by the AMAD accelerometer.

As the engine speed trace in figure 14 confirms, the higher AMAD vibration levels occur when the engine compressor speed is in the range of 71 percent of the maximum operating speed of 16,810 rpm, the flight idle speed of the X-29A aircraft. Figure 16 shows that a high vibration level could only occur below 10,000 ft and Mach 0.6. These conditions would most likely occur during the takeoff and landing of the X-29A aircraft.

A decision was reached to continue the X-29A research without an intensive analysis for the following reasons: (1) exceeding the vibration levels was not a PTO shaft problem, and (2) the flight conditions were known when the higher vibrations occurred. To maintain flight safety, the established limits were maintained throughout the PTO shaft speed range except near 200 Hz. An increase in the AMAD allowable limit from 1 *g* to 2 *g* at 200 Hz was allowed. The flight monitoring techniques developed for the X-29A PTO shaft were instrumental in identifying the cause of the higher AMAD vibration levels and in evaluating their acceptability, thus avoiding an extensive downtime for unnecessary PTO shaft maintenance.

CONCLUDING REMARKS

The unique power takeoff shaft design on the X-29A aircraft has led to the establishment of monitoring techniques for assessment of the PTO shaft's dynamic stability during ground and flight test operations. The monitoring techniques consisted of ground vibration tests, engine runs, and flight tests. The ground vibration test was used to assess the structural integrity of the PTO shaft by measuring the first natural frequency and mode shape of the PTO shaft. The engine runs and flight tests consisted of accelerometers mounted on the PTO shaft to obtain power spectrums and acceleration levels. The power spectrums and acceleration levels were tracked and monitored for any unusual trends and characteristics of the PTO shaft. The monitoring techniques used for the X-29A PTO shaft were found essential and were instrumental in discovering and isolating vibration anomalies and in determining unbalances in the shaft and other rotating machinery within the system.

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2. Gargiulo, Domenick J., "Design and Development of a Power Takeoff (PTO) Shaft for the X-29 Forward Swept Wing (FSW) Demonstrator Aircraft," AIAA-85-4045, Oct. 1985.

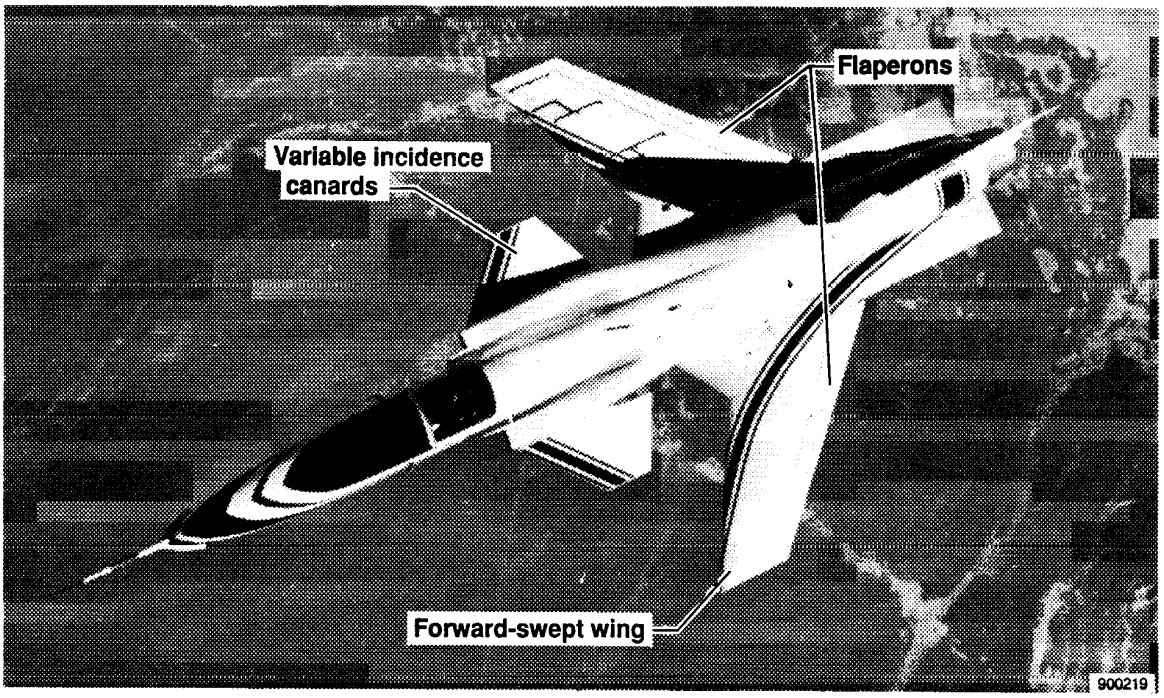

Figure 1. The X-29A forward-swept-wing aircraft.

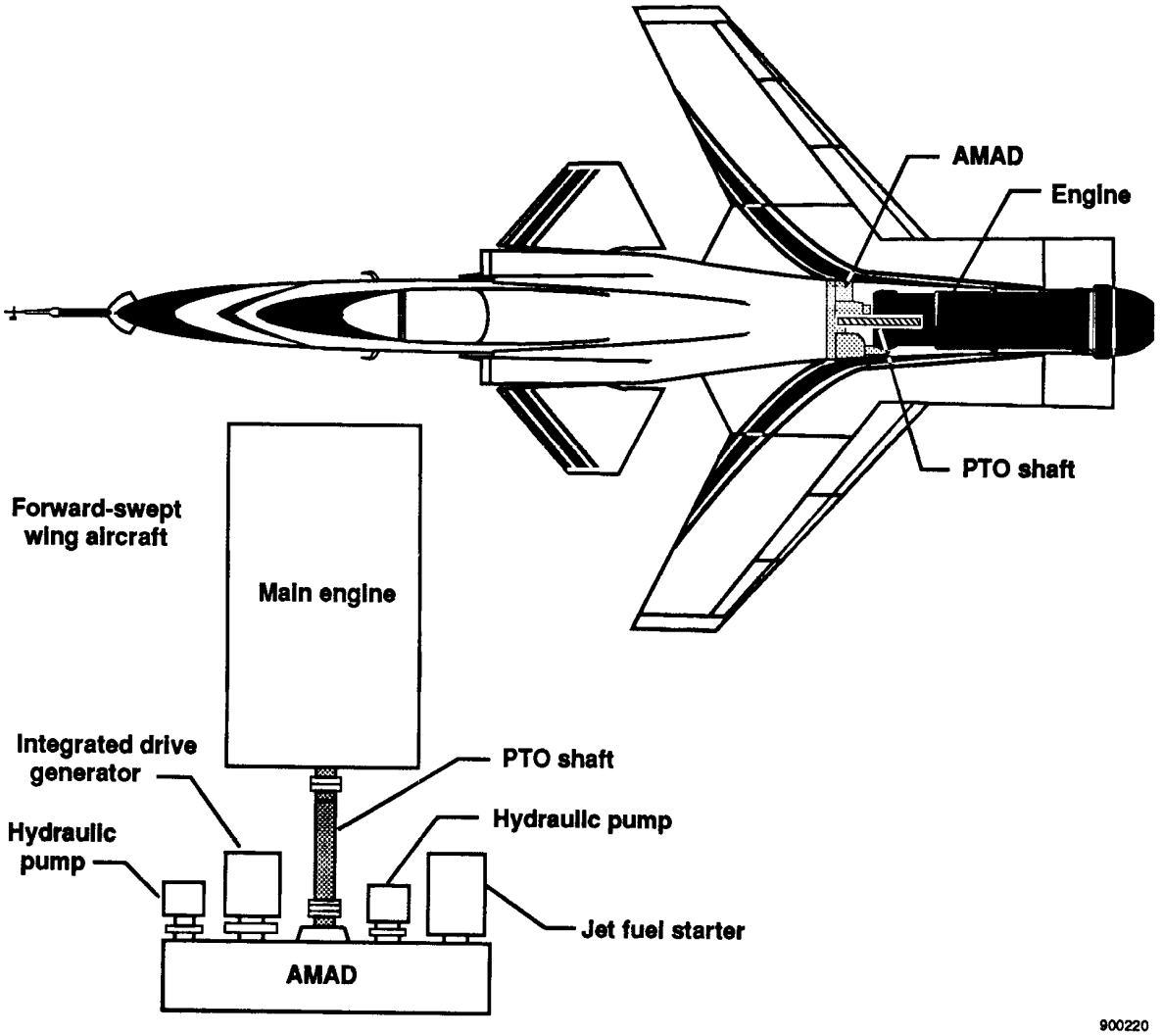

Figure 2. PTO shaft and AMAD.

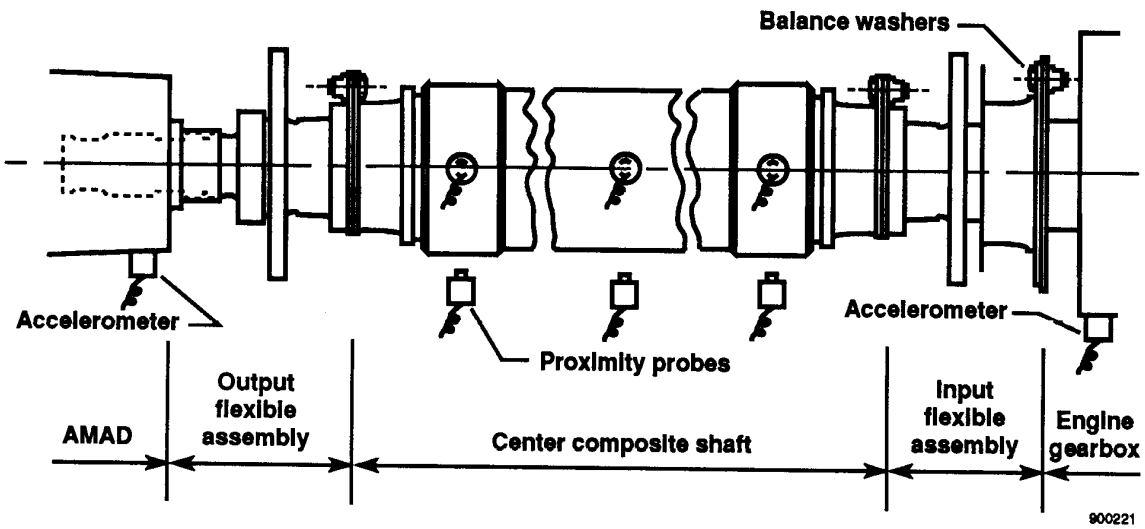

Figure 3. PTO shaft subsystem.

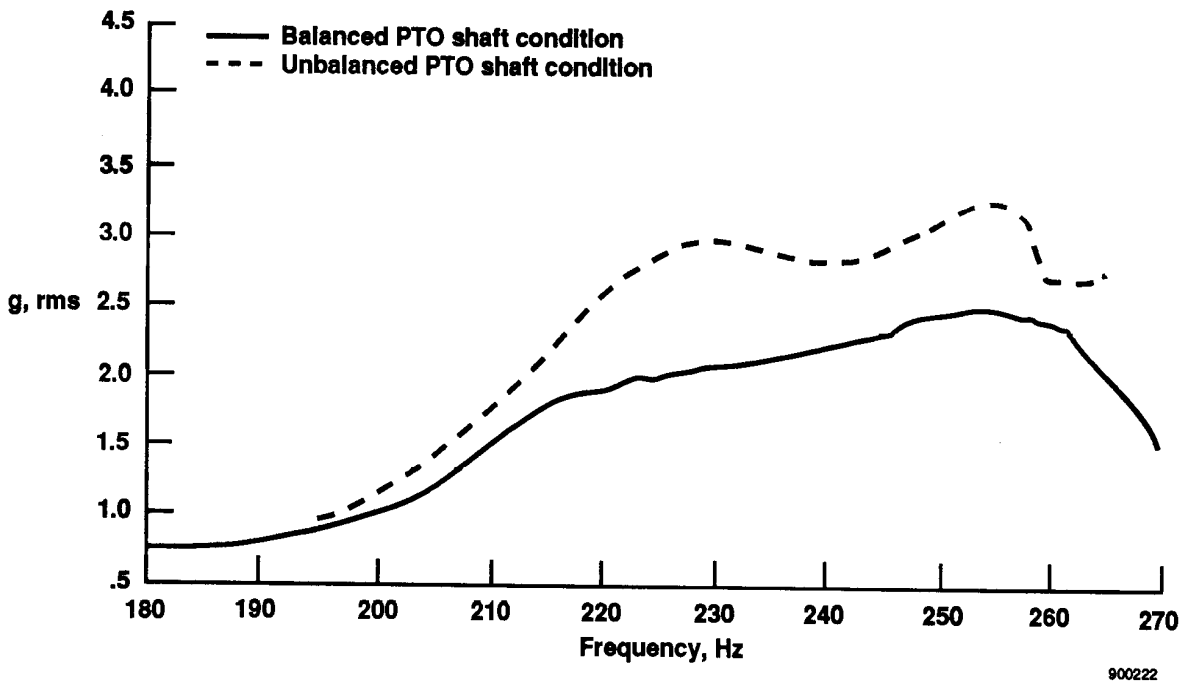

Figure 4. Effect of an unbalance on PTO shaft vibration levels.

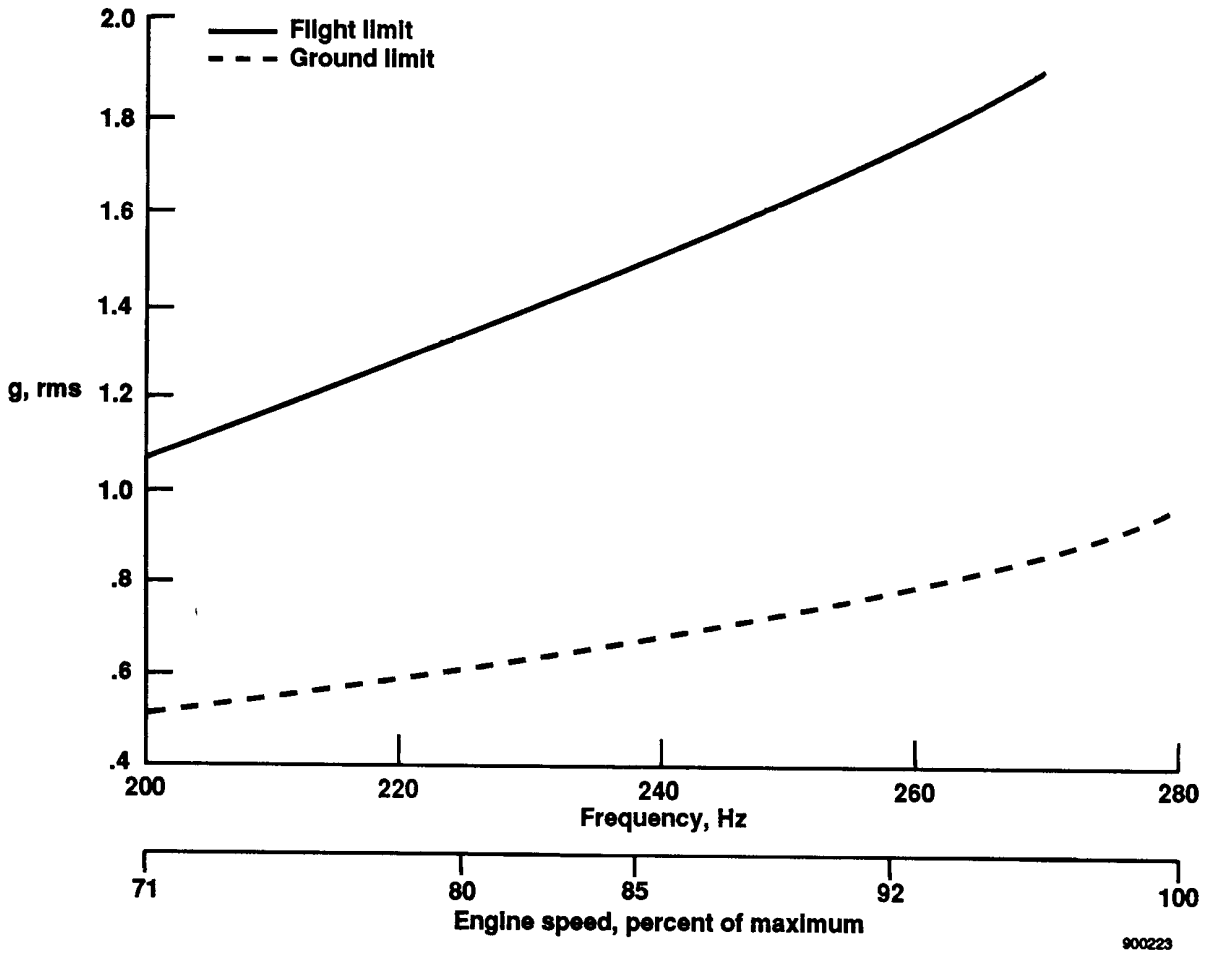

Figure 5. The X-29A AMAD vibration limits.

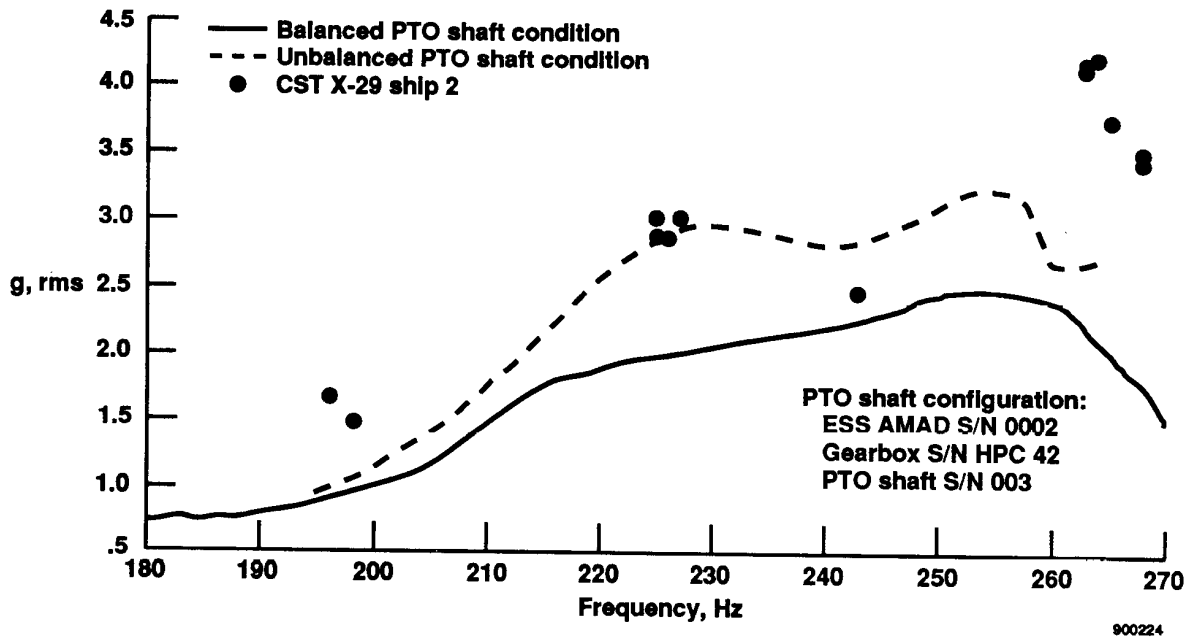

Figure 6. Combined systems test gearbox acceleration data.

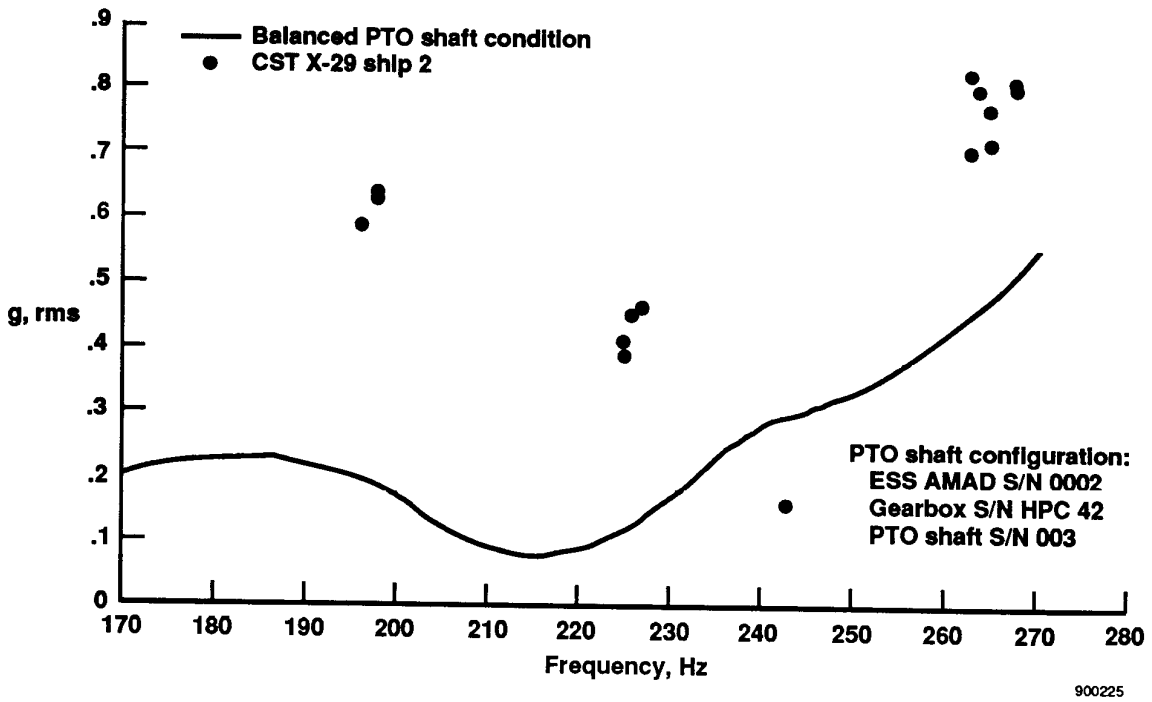

Figure 7. Combined systems test AMAD acceleration data.

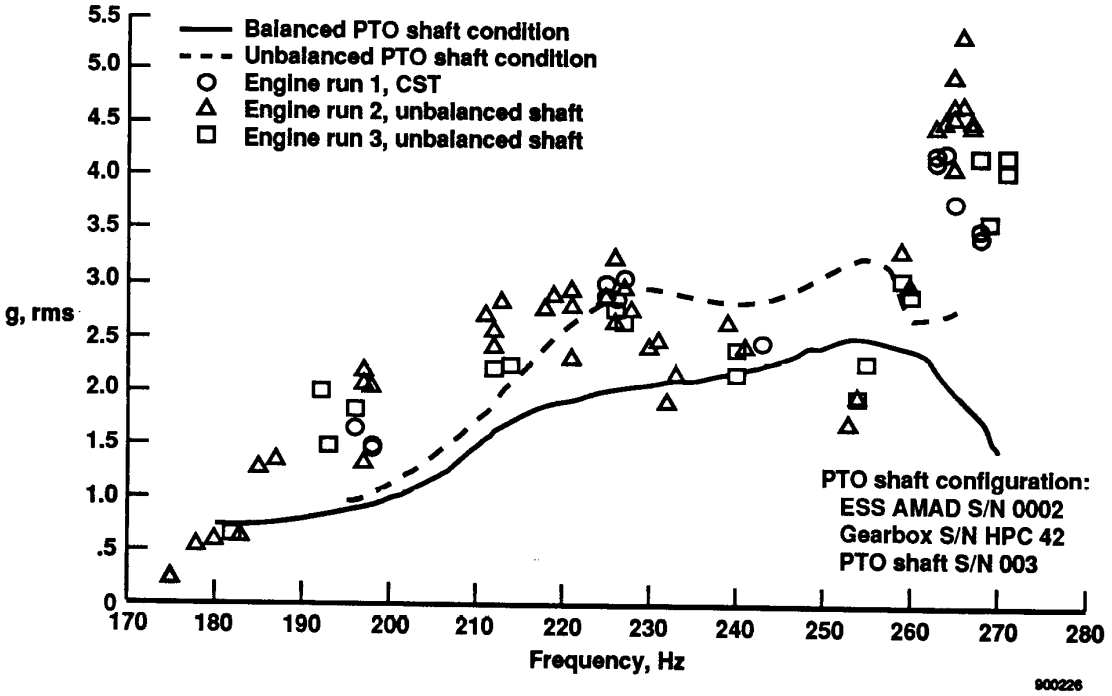

Figure 8. Gearbox engine run data during unbalanced shaft installation.

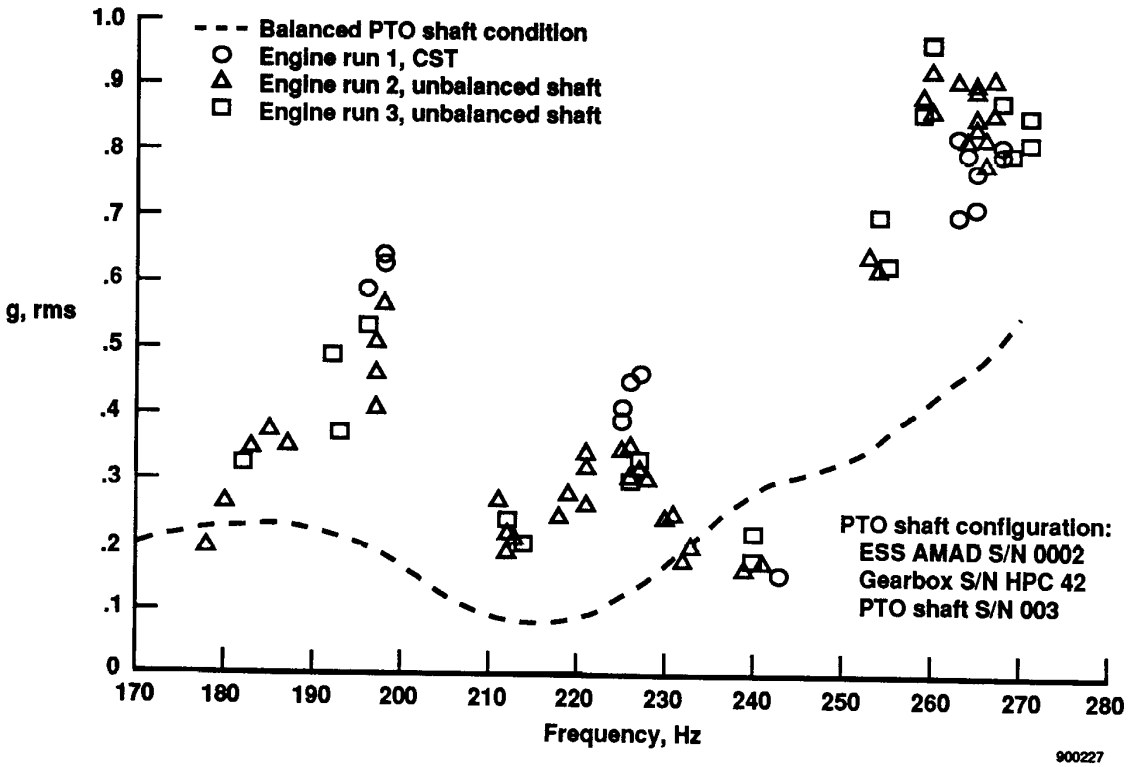

Figure 9. AMAD engine run data during unbalanced shaft installation.

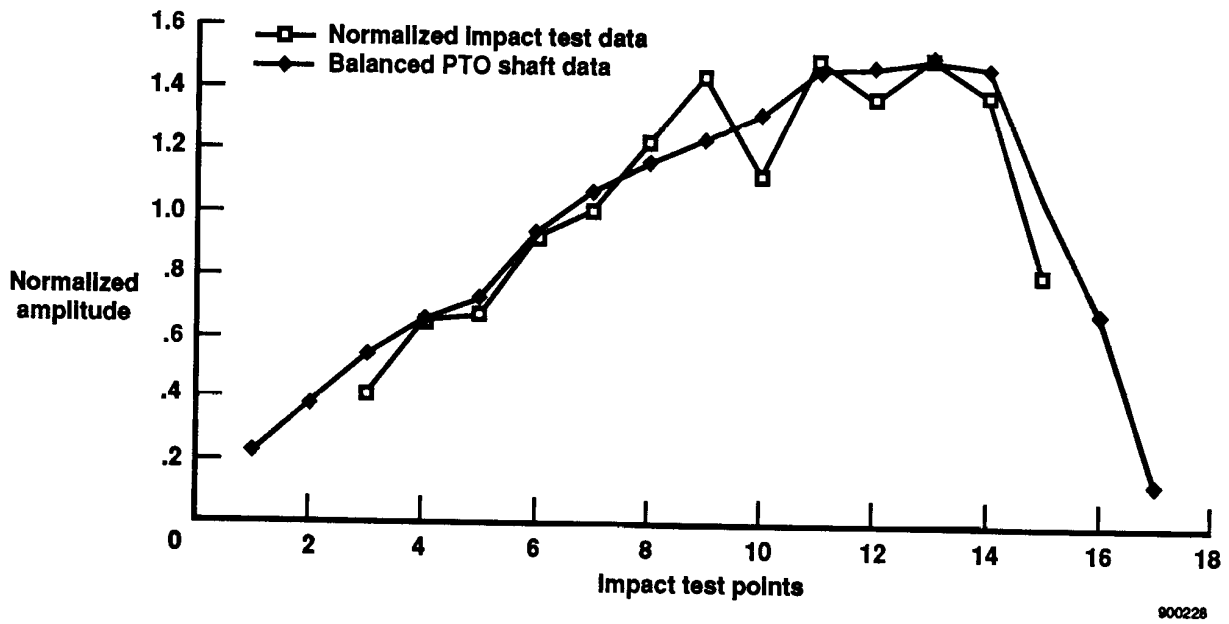

Figure 10. PTO shaft mode shapes comparison.

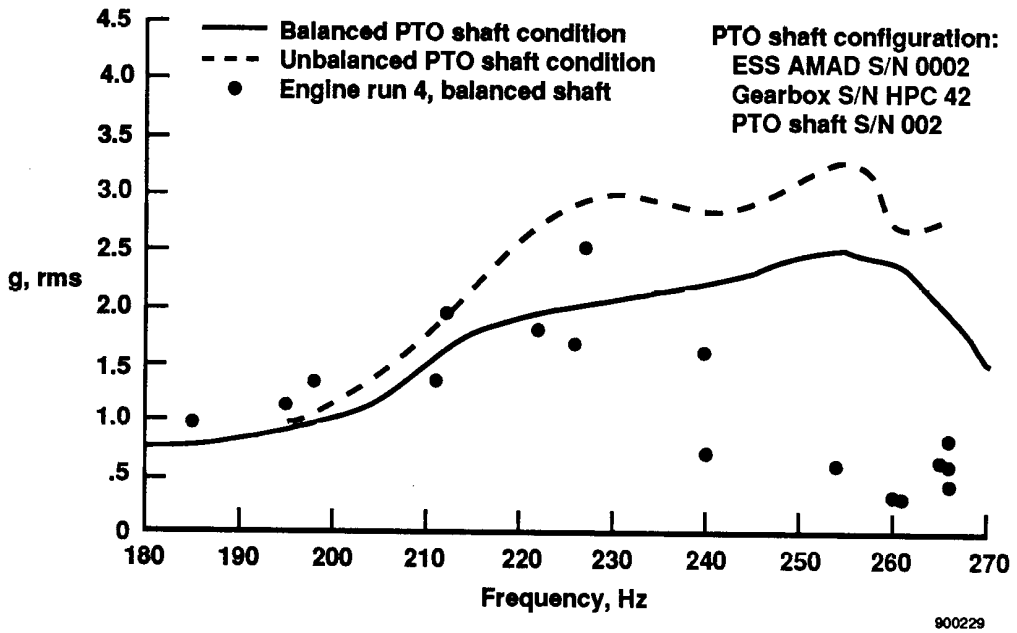

Figure 11. Gearbox engine run data after PTO shaft change.

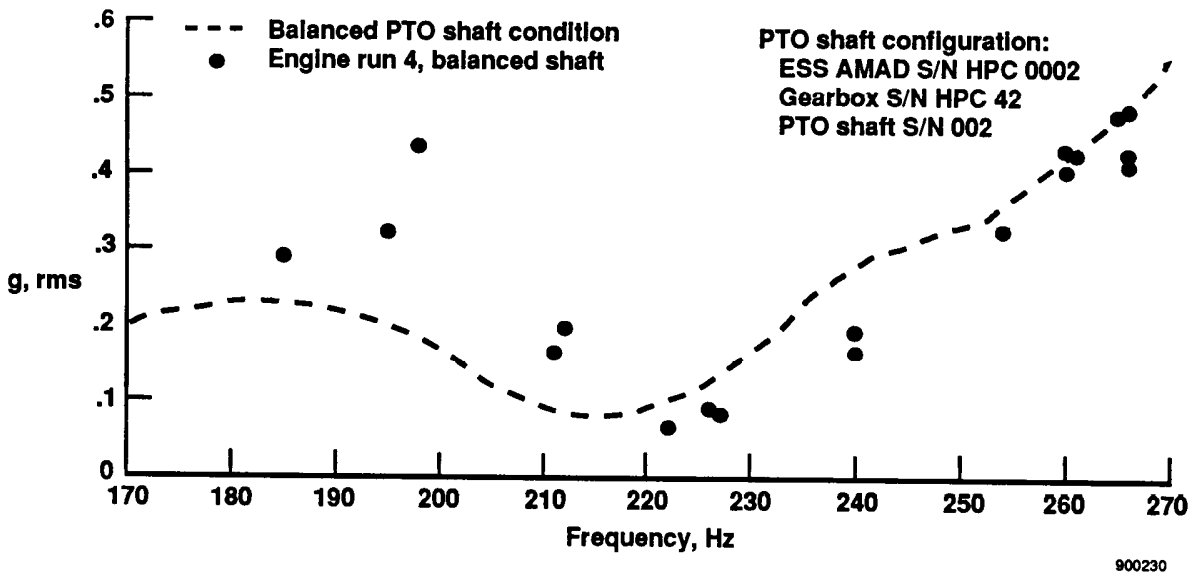

Figure 12. AMAD engine run data after PTO shaft change.

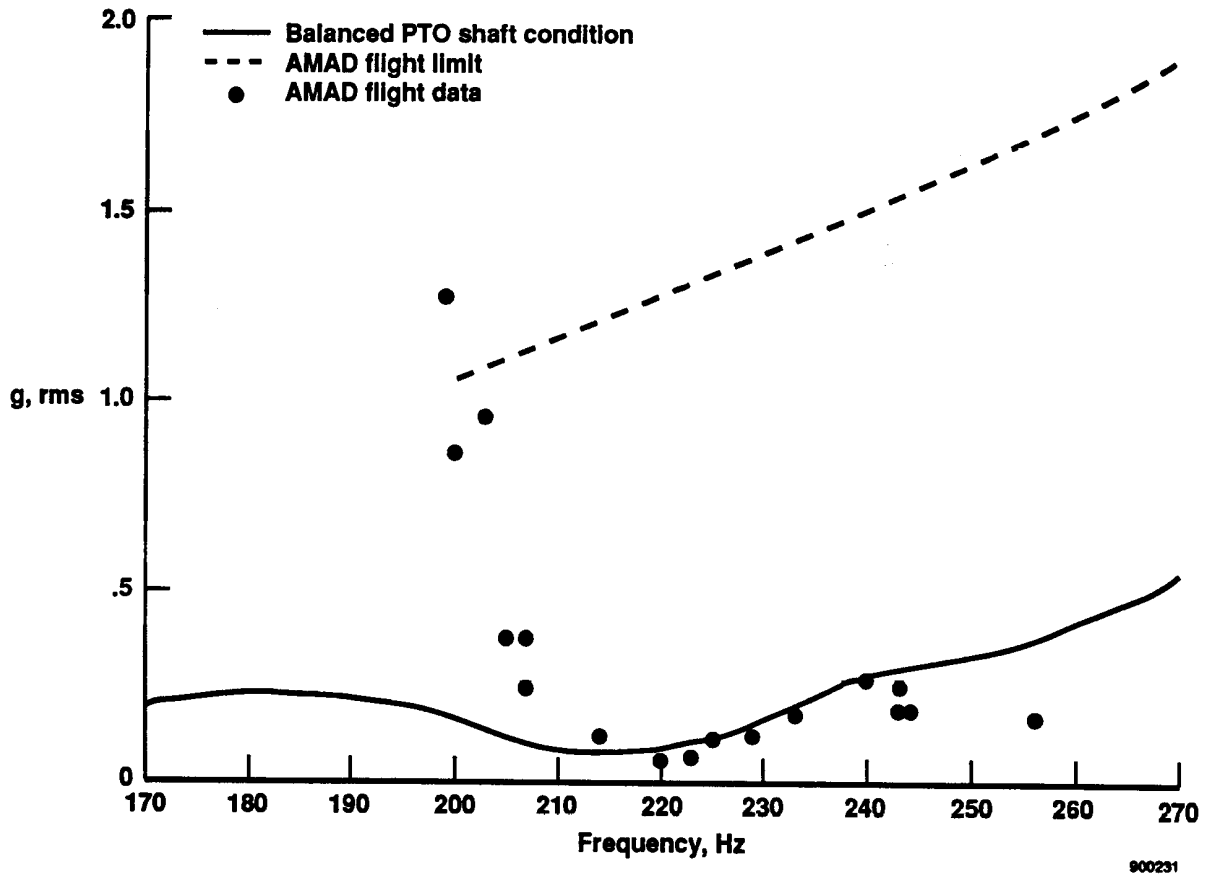

Figure 13. The X-29A AMAD vibration data, ship 2, flight 1.

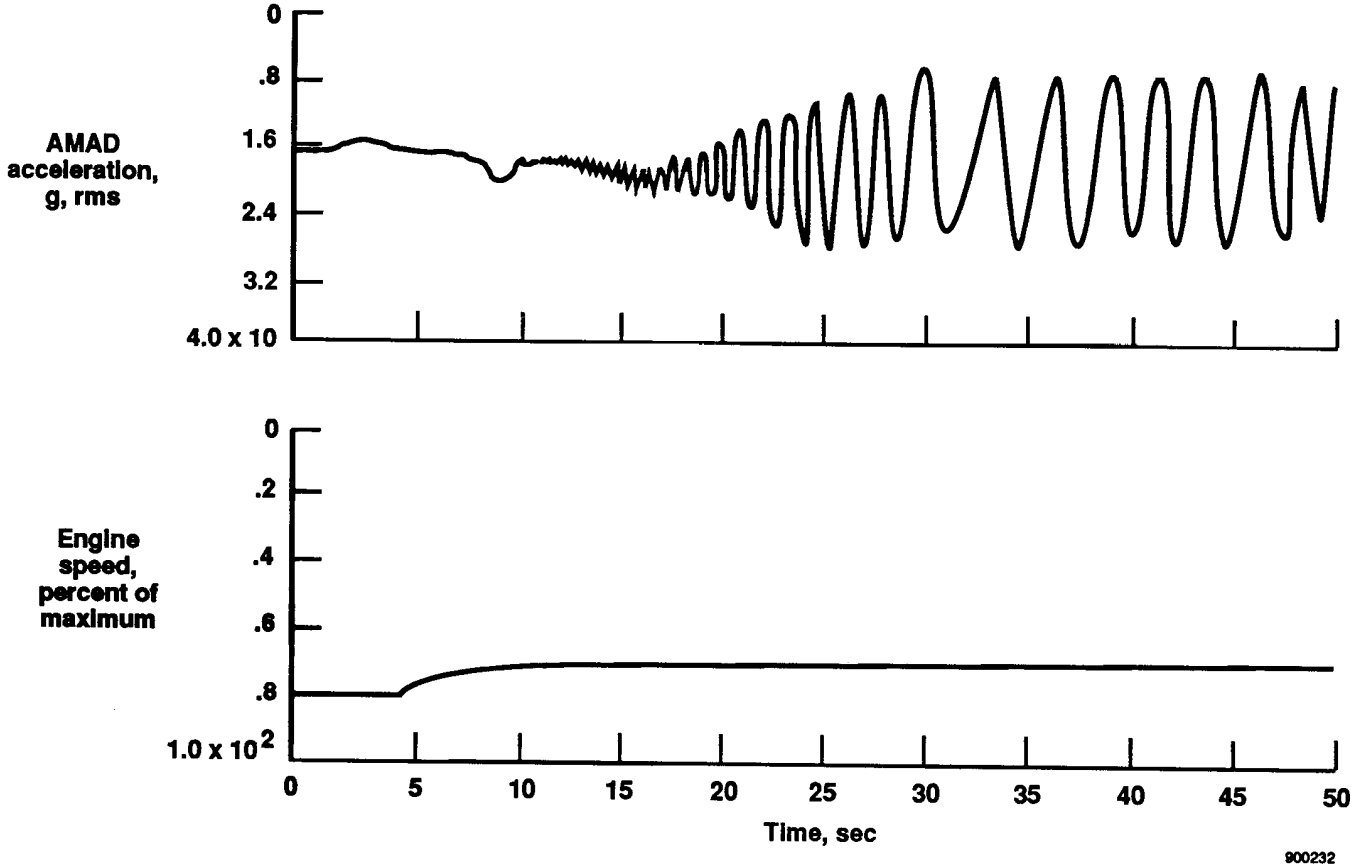

Figure 14. AMAD vibration and engine speed time history.

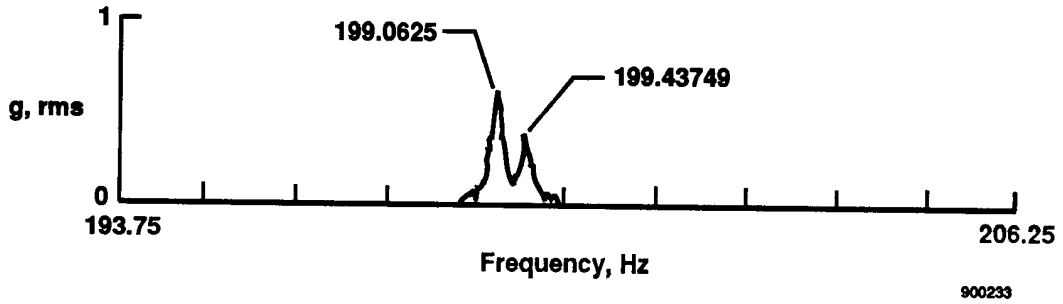

Figure 15 AMAD accelerometer power spectrum.

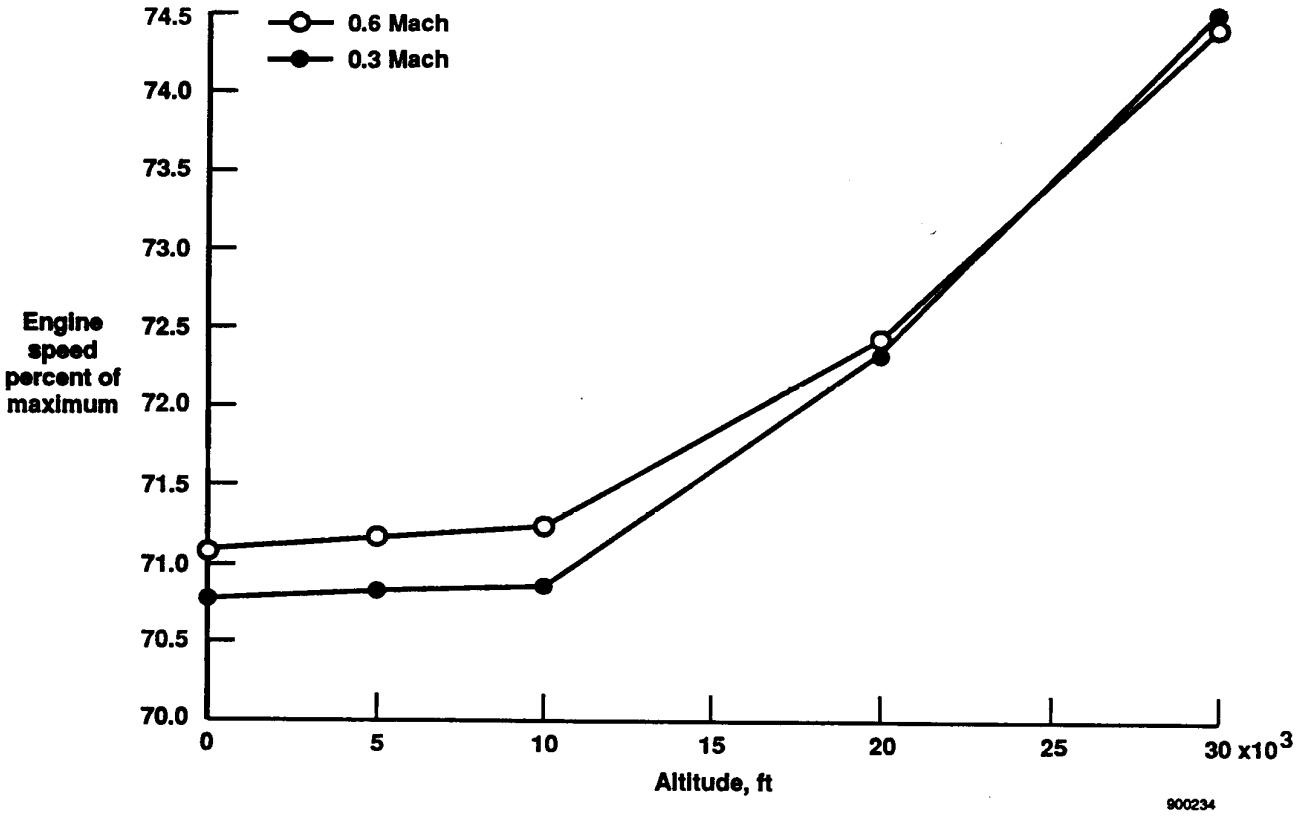

Figure 16. Engine speed variation.

NASA
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Report Documentation Page

1. Report No. NASA TM-101731	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Monitoring Techniques for the X-29A Aircraft's High-Speed Rotating Power Takeoff Shaft		5. Report Date December 1990 6. Performing Organization Code
7. Author(s) David F. Voracek		8. Performing Organization Report No. H-1680 10. Work Unit No. RTOP 533-02-51
9. Performing Organization Name and Address NASA Ames Research Center Dryden Flight Research Facility P.O. Box 273, Edwards, California 93523-0273		11. Contract or Grant No. 13. Type of Report and Period Covered Technical Memorandum
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, DC 20546-3191		14. Sponsoring Agency Code

15. Supplementary Notes

Presented at the 2nd International Machinery Monitoring and Diagnostic Conference, Los Angeles, California, October 22–25, 1990.

16. Abstract

The experimental X-29A forward-swept-wing aircraft has many unique and critical systems that require constant monitoring during ground or flight operation. One such system is the power takeoff shaft, which is the mechanical link between the engine and the aircraft-mounted accessory drive. The X-29A power takeoff shaft operates in a range between 0 and 16,810 rpm, is longer than most jet engine power takeoff shafts, and is made of graphite epoxy material. Since the X-29A aircraft operates on a single engine, failure of the shaft during flight could lead to loss of the aircraft. The monitoring techniques and test methods used during power takeoff shaft ground and flight operations are discussed in this paper. Test data are presented in two case studies where monitoring and testing of the shaft dynamics proved instrumental in discovering and isolating X-29A power takeoff shaft problems. The first study concerns the installation of an unbalanced shaft. The effect of the unbalance on the shaft vibration data and the procedure used to correct the problem are discussed. The second study deals with the shaft exceeding the established vibration limits during flight. This case study found that the vibration of connected rotating machinery unbalances contributed to the excessive vibration level of the shaft. The procedures used to identify the contributions of other rotating machinery unbalances to the power takeoff shaft unbalance are discussed.

17. Key Words (Suggested by Author(s)) PTO shaft Rotating machinery X-29A		18. Distribution Statement Unclassified-Unlimited Subject category 05	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 25	22. Price A02

NASA FORM 1626 OCT 86

For sale by the National Technical Information Service, Springfield, Virginia 22161-2171