



Control of Fan Blade Vibrations Using Piezoelectrics and Bi-Directional Telemetry

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Abstract

A novel wireless device which transfers supply power through induction to rotating operational amplifiers and transmits low voltage AC signals to and from a rotating body by way of radio telemetry has been successfully demonstrated in the NASA Glenn Research Center (GRC) Dynamic Spin Test Facility.

In the demonstration described herein, a rotating operational amplifier provides controllable AC power to a piezoelectric patch epoxied to the surface of a rotating Ti plate. The amplitude and phase of the sinusoidal voltage command signal, transmitted wirelessly to the amplifier, was tuned to completely suppress the third bending resonant vibration of the plate.

The plate's third bending resonance was excited using rotating magnetic bearing excitation while it spun at slow speed in a vacuum chamber. A second patch on the opposite side of the plate was used as a sensor.

This paper discusses the characteristics of this novel device, the details of a spin test, results from a preliminary demonstration, and future plans.

Introduction

NASA's Fundamental Aeronautics Program is interested in pursuing research in technology areas which facilitate the development of lighter, quieter and more efficient fans for propulsion applications. One such application is commercial fixed wing, powered flight. High performance fan blades designed to achieve such goals will be subjected to higher levels of aerodynamic excitations which will undoubtedly lead to more serious and complex vibration problems (Ref. 1). There is concern over the levels of vibratory stresses, the reduction of high cycle fatigue (HCF), and aeroelastic instabilities. Furthermore, blade material and mechanical damping become issues of concern when material is removed from the blade design and when advanced stage design increases the number of vibration modes within the engine operating speed range (Ref. 1).

Historically, NASA Glenn Research Center has used the Dynamic Spin Rig (DSR) to characterize the vibrations of fan blades and bladed structures and to study damping. In the past several years, this facility has been used to assess the effects of advanced blade damping concepts on flat plates and subscale fan blades. Damping concepts, such as viscoelastic material patches (Refs. 2 and 3), impact dampers (Refs. 4 and 5),

plasma-sprayed damping coatings (Ref. 6), and high-damping high-temperature shape memory alloy materials (Ref. 7) are typically investigated in this facility. Recent experiments explore the possibility of using piezoelectric materials in the form of patches to dampen problematic blade vibration modes (Refs. 8 to 10).

To facilitate the effective testing of damping concepts, an active magnetic bearing (AMB) support system was designed for the DSR with the intent of using it to excite blade vibrations (Refs. 11 to 13). A description of the AMB system for use as an exciter in DSR experiments can be found in Reference 14.

Slip rings are typically used in rotating machinery experiments to extract instrumentation signals from sensor devices on or in the rotating body. Electrical signals from the sensors travel through rotating brush contacts within the slip ring and out to external instrumentation. Since there is physical contact between the brushes and the stationary contacts within the slip ring, there is friction. Coolant is required to remove the resulting heat to mitigate rising temperature. Often, oil is mixed with the coolant to lubricate the contacts. The potential for brush degradation due to wear is possible.

Slip rings, although not usually designed for it, can also move signals from the stationary to the rotating system. Channel contacts are not typically designed to carry much power—usually a signal with a voltage up to 200 V, but with little current—on the order of milliamps. When more than tenths of a watt are required to be sent into the rotating frame, multiple channels can be used and the transfer duty shared.

Sending power in through a slip ring, while using it for obtaining measurements, can degrade signal quality and even create erroneous quantities, especially if the signals out are of low voltage. To avoid this problem in using a slip ring bi-directionally, Fulton and Ormiston (Ref. 15) used two slip rings—one for powering piezoceramic bimorph actuators in model helicopter rotor blades and a second slip ring for instrumentation. Baz and Ro (Ref. 16) used a single slip ring for sending and receiving information, however their 10 channel set-up was bulky and rated only to 500 rpm. Channels were so far apart, that cross-talk between channels was probably less of an issue.

As mentioned, signal noise is an issue with slip rings. The noise is a result of the nature of the transmission. The brush/contact environment is a noisy place. Channel isolation is difficult as the channels usually are packed closely together at the rotating contact point.

GRC's DSR slip ring was not designed for bi-directional use. There is a limit of 0.2 W per channel affecting its potential for commanding the rotating operational amplifiers. Signal noise was also a concern when considering extracting-low power sensor signals and sending higher-power actuation signals through the same device. As a result, the authors and their team sought to find a different mechanism to provide these functions.

Slip rings have been used in the DSR in the past, with limited success. Despite aforementioned concerns, upcoming piezoelectric damping experiments will be performed using a slip ring. In these tests, a 100 channel unit will be used to send signal into the rotor and also extract sensor information. Input signals will power fan blade specimen piezoelectric actuators. The true capability of the slip ring to facilitate active feedback control of rotating blade vibration will be assessed.

Telemetry is a non-contacting method of signal transfer and was selected as a signal transfer alternative and upgrade for the DSR. Commercially available telemetry devices are designed to only extract signals from the rotating components. Bi-directional communication was required to meet the requirements of DSR experiments. In order to control vibrations from the stationary frame, controllable power sources would be needed on the rotating side. A device with such requirements was not commercially available, so a new device was conceived of at GRC and a prototype constructed.

Device Description

The wireless inductive power and telemetry device (WIPTD) was designed by the authors and the Mesa Systems Company as an alternative to slip rings for providing active feedback control of blade vibrations and damping techniques.

There are two primary components of this device—a rotating component and a stationary one (see Fig. 1). The rotating component is attached to the end of the DSR AMB rotor. The stationary structure is fixed to the rig's lower bearing housing (Fig. 2). There is a gap of 0.5 mm between these two components during testing. The rotating part is 10 cm in diameter and 20 cm long. It weighs about 13 N. The stationary apparatus is made up of three circuit boards and weighs about 4.5 N.

This device allows for bi-directional communication via capacitive coupling with the rotating system. The WIPTD contains rotating operational amplifiers which can provide commanded AC power to rotating actuators. Rotating electronics receive their power from a wireless inductive apparatus. This element is essentially a transformer with an input stage/primary coil composed of a pulse width modulator located in the stationary unit, and two secondary coils, located in the rotating unit. The primary coil is located flush with the top surface of the stationary unit directly in line with the secondary coils. The primary coil is powered by a 24 V supply, which is then transformed in one secondary coil to

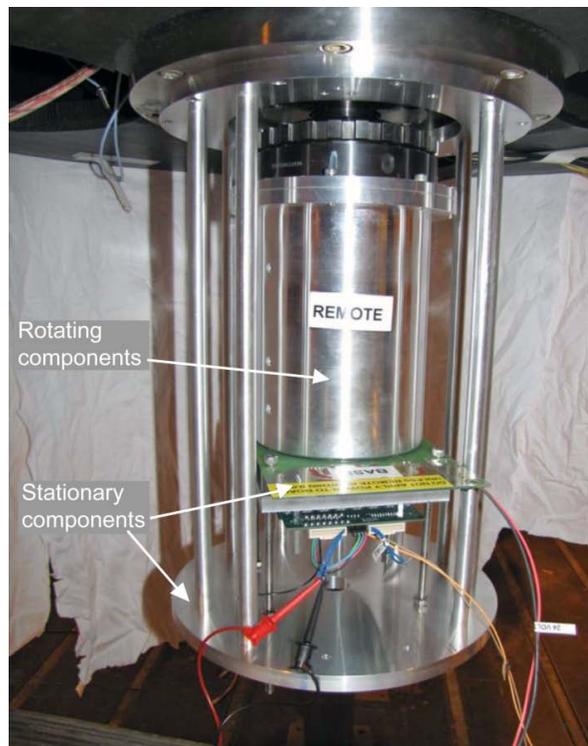


Figure 1.—Close up of WIPTD showing stationary and rotating components.



Figure 2.—Dynamic Spin Rig rotor system showing WIPTD at the bottom.

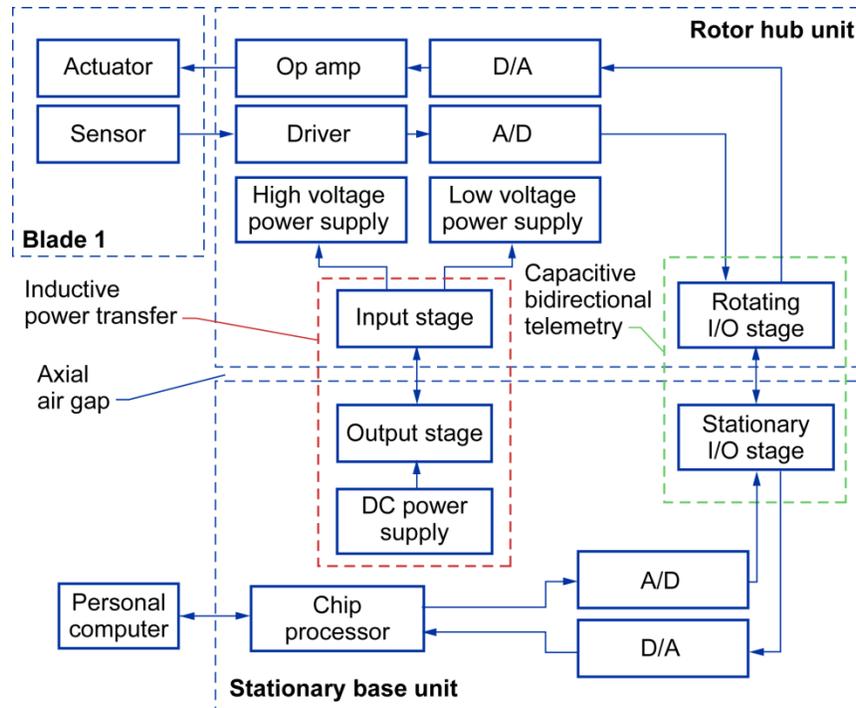


Figure 3.—WIPTD and blade vibration suppression system block diagram.

provide 200 V dc, after conditioning, to drive rotating operational amplifiers. The other secondary coil provides 5 V dc to power other onboard electronics.

The device mode of operation is as follows; a vibration voltage signal from the piezoelectric sensor is transmitted through wires to the rotating unit which houses, among other supporting electronics, a driver or conditioning circuit and an A/D converter circuit. The signal from the A/D converter then passes to conducting strips, which are fashioned in the shape of concentric rings on the underside of the rotating unit. The stationary base unit also has concentric rings which are mirror images of the concentric rings positioned on the rotating unit. The concentric rings on both units, including the air gap, constitute a capacitive plate coupler. The conductive rings on each unit serve as sides of an air core capacitor. The sensor signal from the rotating unit is transmitted capacitively to the stationary base unit. Subsequently, this signal is converted from a digital to an analog signal by a D/A converter, which is located in the base unit. The signal is then passed to a microchip or, as in our case, a rapid-prototyping controller where it is processed into a vibration suppression signal. This suppression signal is then retransmitted, in a sequence inverted to that described above, through to an operational amplifier which actuates the piezoelectric patch on the test blade.

The block diagram in Figure 3 shows details of the WIPTD and vibration suppression system constructed for the demonstration described herein. The WIPTD has the capacity to control eight actuators and transmit eight sensor signals. However, only one actuator channel and one sensor channel are shown for simplicity.

Device Characterization

Figure 4 shows a plot of the transfer function between commanded voltage input pre-telemetry and power amplifier voltage output post-telemetry versus frequency on the rotating side. This figure shows that the magnitude of the output to a command input stays constant out to at least 2 kHz. The measured gain is 48.75, which is very close to the design goal of 50. An amplifier with a gain of 50 on the rotor allows for a voltage maximum of 250 V to be applied to an actuator patch.

Figure 5 shows the phase angle for this transfer function in a linear graph format. A linear curve fit provides an equation for the phase lag as a function of input signal frequency. Using this equation, the time delay due to signal transfer through telemetry and signal processing can be computed. The time delay is simply the ratio of the phase angle in radians to the frequency of the command signal in radians/sec. The time delay is consistent across the frequency range shown at 0.0015 sec, or 1.5 msec.

Figures 6 and 7 show similar results for the transfer function between a simulated sensor signal on the rotating side and a measured signal post-telemetry on the stationary side. Note that the gain is 1 and that there is no degradation in signal amplitude until 20 kHz. 20 kHz is a sufficient sensor signal bandwidth. Also note that the linear curve fit to the phase angle delay in Figure 7 is almost identical to that in Figure 5 for the amplified signal. The time delay for this signal is also 1.5 msec.

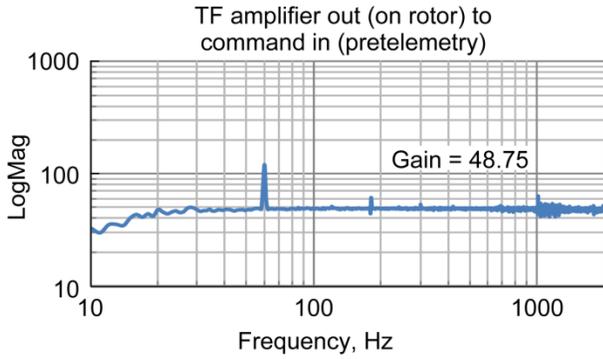


Figure 4.—WIPTD rotating operational amplifier gain.

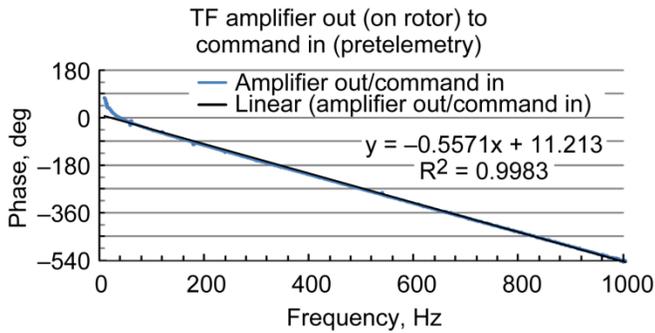


Figure 5.—WIPTD input phase angle which provides channel time delay information.

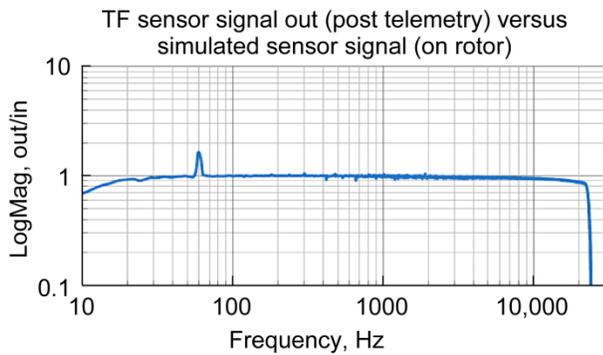


Figure 6.—WIPTD sensor channel frequency response.

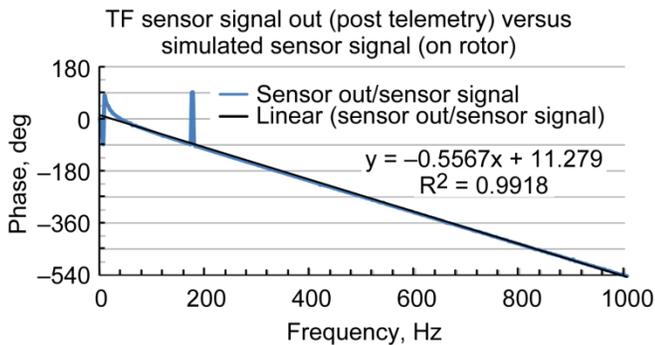


Figure 7.—WIPTD output phase angle which provides channel time delay information.

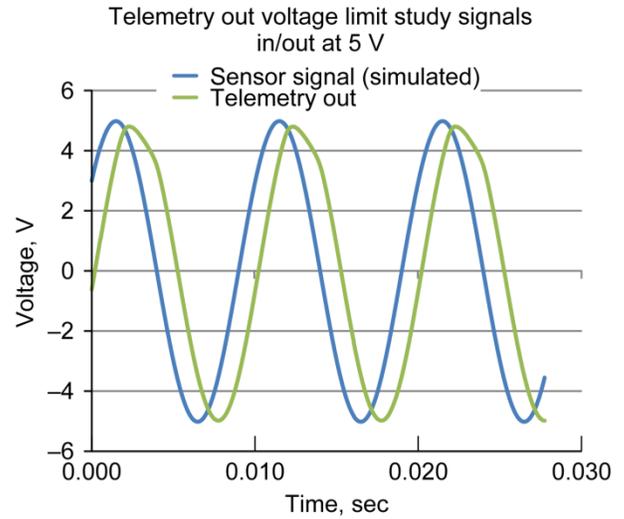


Figure 8.—WIPTD sensor signal characteristics at 5 V.

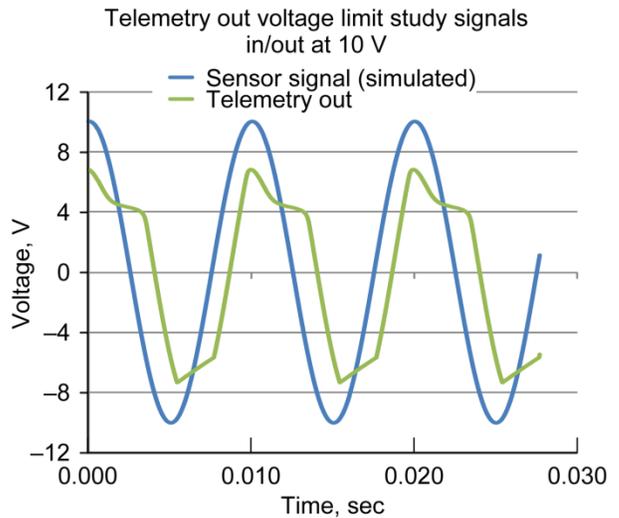


Figure 9.—WIPTD sensor signal characteristics at 10 V.

When considering closed-loop control of fan blade vibrations, where the controller is physically located off the rotor, the combined time delay is 3 msec. This amount of delay would cause vibration control instability at the blade frequencies of interest—typically in the kHz range. If, however, the controller was resident in a DSP chip located on the rotor, this signal transfer delay would not be problematic.

Figure 8 shows the signal output received on the stationary side of the unit when a simulated 5 V sensor signal is input on the rotating side. Notice that the magnitude out is preserved; however, the signal shape is mildly augmented. In Figure 9, the sensor signal is 10 V. The output is saturating at about 7 V and the signal is severely affected by this saturation. This test shows that the hardware voltage limit from a sensor signal is ± 5 V. Voltages from piezoelectric patches used as sensors like the one shown in Figure 10 can reach at least 50 V under

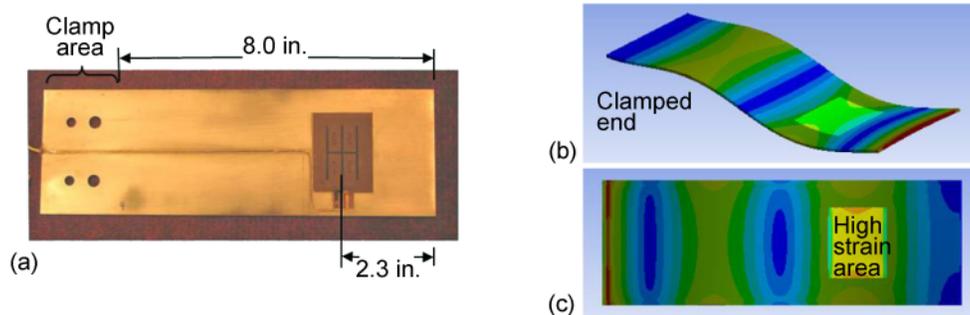


Figure 10.—Ti plate FEA third bending results. (a) Piezoelectric patch location optimized for third bending mode. (b) Third bending modal deformation. (c) Von Mises strain results.

typical test conditions. The prototype WIPTD cannot accommodate this. A future model of this device would include circuitry to impose a voltage reduction so that the output voltage is in the 5 or 10 V range.

Experiment

The Dynamic Spin Test Facility at NASA Glenn Research Center was used to demonstrate the capability of the WIPTD. The experimental setup is described in (Refs. 13 and 14). A vertical rotor suspended magnetically in a vacuum environment was used. The rotor has two clamped flat titanium plates bolted to the rotor hub. One of the plates has two piezoelectric patches both located in a high third bending strain region on either side of the plate (Fig. 10). The other plate is primarily for balance. The telemetry unit's rotating system is attached at the bottom of the rotor. The stationary system is mounted to a cage structure which is mounted to the DSR's lower bearing housing (see Figs. 1 and 2). The axial gap was 0.5 mm during operation. One patch was used as a sensor and the other as an actuator. The sensor patch was connected to a telemetry-out circuit. The actuator was attached to the amplifier circuit.

The rotor system was spun up to 565 rpm. This speed was the maximum out-of-tank speed achieved and was selected as the speed for the vacuum spin test. Since this was a prototype unit, speed was limited to circumvent potential damage. The WIPTD prototype was rated to 1500 rpm and at the time of writing had been spun to 1000 rpm. At speed, the radial AMB's were used to prescribe a rotating sinusoidal excitation to the plates. The frequency and phase of this excitation with respect to the rotor's once per rev signal were tuned to maximize the plate's third bending vibration amplitude. The third bending frequency was determined and optimized by tuning the excitation in the region of the experimental value determined from a static test and the out-of-tank test. Oscilloscope visual feedback was used in this manual tuning procedure. The phase of the excitation force, which is really the angle between the blade row and the rotating AMB excitation force (Ref. 14), was then tuned to maximize the response. Amplitude then was tuned to produce a clean sinusoidal plate response.

The actuator patch was used to reduce the plate's third bending response. An open loop control scheme was used. A sinusoidal voltage with the same frequency of the AMB excitation was sent from the control computer through telemetry to the rotating power operational amplifier attached to the actuator. The amplitude and phase of this command were also tuned using the sensor patch signal as visual feedback to eliminate the vibration. The successful results of this test are shown in the next section. This test proved that the bi-directional telemetry unit worked. This was a demonstration of active fan blade vibration control under rotating conditions without using slip rings and without contact with the rotor.

Results

Results for the experiment described in the previous section are presented here. Figure 11 shows the power spectral density (PSD) of the voltage signal from the sensor patch signal while the rotor was spinning freely without excitation or control. Recall that both the sensor and actuator patches are located on opposite sides of the plate in a region of high strain (Fig. 10). A small 80 mV signal component is evident at the plate's third bending frequency of 669 Hz. The feedback control of the AMB system induces noise into the rotor system which can excite rotor and rotor hardware resonances on its own. Often, notch filters in the AMB controller are used to reduce or eliminate these responses (Ref. 14). The third bending resonance at 565 rpm is close to the first harmonic of the rotor's first bending resonance. A notch for this rotor mode was not used. As a result, a small plate response occurred.

Figures 12 and 13 show the sensor response when a 669 Hz AMB excitation is applied to the rotor causing the instrumented plate to vibrate. The constant excitation amplitude evident in Figure 12 proves that the AMB excitation is indeed rotating with the rotor. The response frequency matches the excitation frequency. The PSD in Figure 13 shows the increase in third bending signal component amplitude.

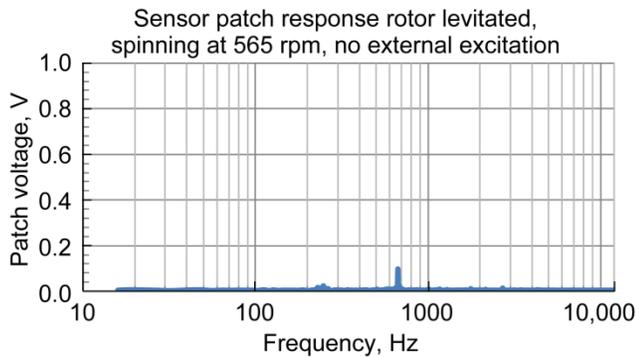


Figure 11.—Piezoelectric sensor response before excitation was applied.

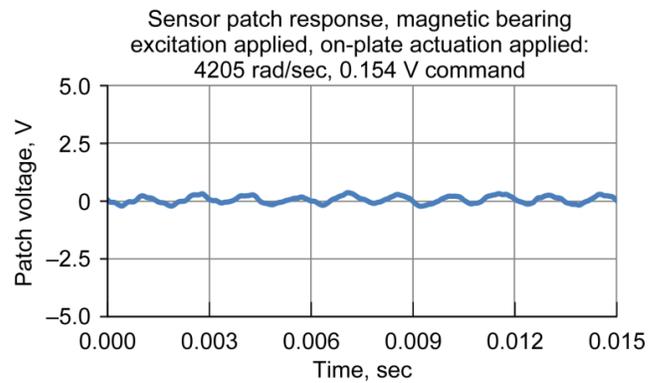


Figure 14.—Piezoelectric sensor signal showing reduced Ti plate vibration amplitude at third bending resonance.

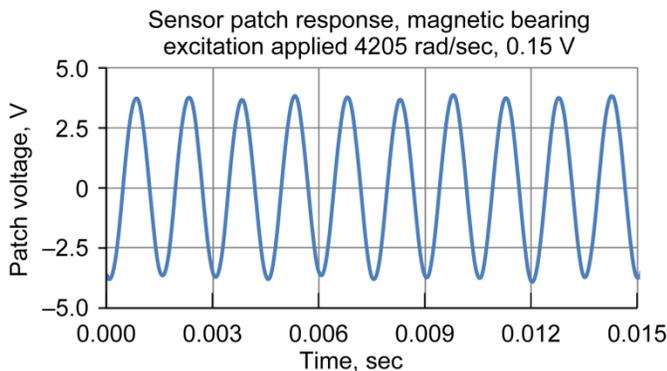


Figure 12.—Piezoelectric sensor signal showing Ti plate vibration amplitude at third bending resonance.

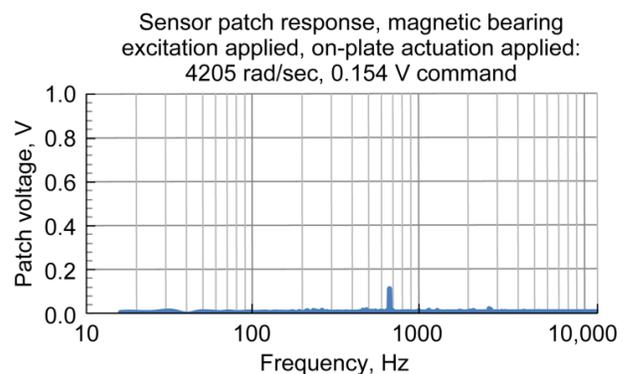


Figure 15.—Piezoelectric sensor response showing successful suppression of the third bending response.

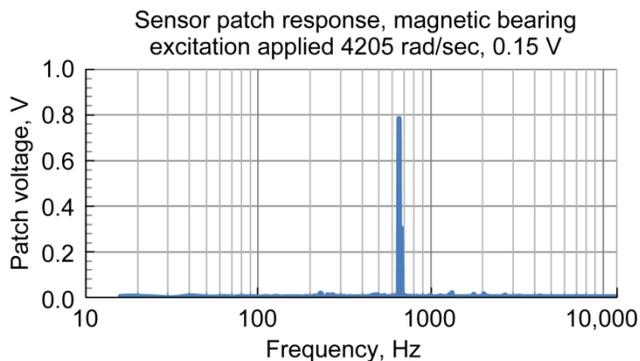


Figure 13.—Piezoelectric sensor response showing third bending excitation frequency and amplitude.

Figures 14 and 15 show the plate response once the actuator control signal is manually tuned to suppress the plate response to AMB excitation. The frequency of the command was identical to the excitation frequency and the amplitude and phase were tuned to optimize (reduce) the response. Figure 14 shows a small signal amplitude—virtually identical to the excitation-free data. A comparison between the PSDs in Figures 11 and 15 shows how effective this open loop technique was at suppressing the blade response.

Summary

A wireless bi-directional telemetry device which includes rotating amplifiers for powering rotating actuators was demonstrated in the DSR at NASA Glenn Research Center. Although this wireless concept is not entirely new (Ref. 17), it is possible that this is the first embodiment of the idea and the first demonstration thereof. A patent application was filed for the WIPTD and its potential use in suppressing turbomachinery blade vibrations. Some details and characteristics of the device were provided in this paper.

In the demonstration explained herein, a third bending plate vibration was suppressed using open loop control of a piezoelectric actuator patch glued to the surface of the plate while the plate was rotating at 565 rpm. A second piezoelectric patch was used as a sensor to help set the excitation and the actuation. Results show that the plate resonance was completely suppressed.

Concluding Remarks

Slip rings are used successfully in experiments. Telemetry has become popular and test rigs, especially at GRC, are being upgraded to include telemetry systems. Signals transmitted via radio telemetry are less noisy and these systems require less maintenance.

The development of the WIPTD was not done solely to create a device which could replace a slip ring. It was developed keeping in mind the eventual application of active blade vibration suppression or damping using piezoelectric elements. A wireless device, which doesn't require cooling, reduces the potential maintenance requirement of a contacting signal transfer component, is inherently less noisy and could facilitate eventual application to ground-based and aero-derivative turbomachines. DeAnna discussed what it might take to implement telemetry in gas turbine engines in Reference 18.

When considering the use of piezoelectrics for damping fan blade vibrations in aero-derivative engines, is it more feasible to consider adding slip rings or telemetry to a turbine rotor? Perhaps in the final adaptation of this damping technique, communication with the rotor would not be required—eliminating the need for either. Each piezoelectric patch used for a blade would be connected to circuitry which rotated with the rotor. This circuitry would be designed to dissipate vibratory energy. The power for this system (if needed) could be extracted via energy harvesting or received from a small induction ring. Perhaps an autonomous controller can be developed which can be downloaded to a DSP chip directly on the rotor. For health monitoring, communication with the rotor would be needed.

Future experiments in the DSR will include the testing of improved WIPTDs where the signal time delay is minimized. This will facilitate the testing of closed-loop feedback control systems. Metal and composite subscale blades that represent those from real aircraft engines will be modified. Piezoelectric elements will be incorporated in unique ways into their design and their ability to dampen or suppress vibrations will be determined.

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14. ABSTRACT A novel wireless device which transfers supply power through induction to rotating operational amplifiers and transmits low voltage AC signals to and from a rotating body by way of radio telemetry has been successfully demonstrated in the NASA Glenn Research Center (GRC) Dynamic Spin Test Facility. In the demonstration described herein, a rotating operational amplifier provides controllable AC power to a piezoelectric patch epoxied to the surface of a rotating Ti plate. The amplitude and phase of the sinusoidal voltage command signal, transmitted wirelessly to the amplifier, was tuned to completely suppress the 3 rd bending resonant vibration of the plate. The plate's 3 rd bending resonance was excited using rotating magnetic bearing excitation while it spun at slow speed in a vacuum chamber. A second patch on the opposite side of the plate was used as a sensor. This paper discusses the characteristics of this novel device, the details of a spin test, results from a preliminary demonstration, and future plans.					
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