# INSTRUMENTED BLADE EXPERIMENTS USING A LIGHT AUTOGIRO

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## Abstract

Results from a program to instrument the rotor blades of a light autogiro are described. The work was initiated to provide additional data on rotor dynamic response as well as investigate practical implementation issues on the use of blade-mounted instrumentation for rotor state feedback. A description of the aircraft and rotor electronics hardware design and installation is given, along with results to date from the initial flight test program for complete system check-out.

## Introduction

Recent attempts to expand both the fidelity of engineering models for rotorcraft systems and the frequency bandwidth for helicopter flight controllers have required more accurate models of coupled rotor and airframe dynamics. The complexity of the engineering modeling problem, coupled with the general lack of sufficiently detailed flight test data, have made improvements in complete rotorcraft aeroelastic predictions difficult. Efforts to expand the available data for correlation exercises are underway [1], but such programs may experience funding and operational delays along with regulatory hurdles that preclude rapid turnaround for timely engineering research efforts.

As a means of addressing this data deficiency, a program is underway at Princeton University to instrument a Bensen B8-M Gyroglider for towed-flight investigations (Figure 1) [5]. This aircraft is an extremely simple teetering rotor autogiro whose power is supplied by towing the vehicle behind an auto along a runway or suitably paved surface. The University's inactive runway at the Forrestal Campus has served as the vehicle's testing ground. The use of a simple test aircraft provides the ability to perform fundamental aeroelasticity experiments on a full size vehicle without the additional burden of maintenance manpower associated with a production helicopter. The added capability of an "in-house" test vehicle affords the researcher the luxury of planning and executing tests that are driven by the nature of the test data and not the predetermined schedule of the test program.

The desire to conduct instrumented rotor experiments on full size aircraft was inspired by similar efforts being done on a model rotor at the Rotorcraft Dynamics Laboratory (Longtrack) at Princeton's Forrestal campus [2] and aided by results reported from an instrumented AH-1G Cobra helicopter test by the NASA [3]. The design goals of the instrumentation system, and the impact of flight safety and testing procedure on the realization of its mechanical and electrical components is described below.

## Basic Instrumentation Design Goals

### Data Acquisition

In order to provide a basis for comparison with model results, blade mounted accelerometers and strain gauges were selected for the autogiro rotor experiments described. These sensors typically provide differential outputs that require some form of amplification prior to sampling for data storage. On the model tests, both the sensor excitation voltages and differential outputs are transferred from the fixed to rotating frames using a slip ring assembly. Such a technique requires from two to four rings per sensor, plus the associated hub attachment for the sliprings and sensor wires. This type of installation was not possible, due to the inherent simplicity of the autogiro's hub. Since no torque is provided to the rotor, the primary aircraft control is performed through direct shaft tilt of the rotor, which is mounted in a pillow block attached to a sealed bearing assembly. Such an arrangement makes the main rotor shaft inaccessible for slipring attachment or routing of wires through its interior. Thus, the decision was made at an

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Presented at the 16th European Rotorcraft Forum, Glasgow, Scotland, September 18-20, 1990.

early stage to telemeter the data from the rotating to fixed frames without the direct use of rotating brushes or slipring pick-ups. Use of a rotor-mounted telemetering system thus requires a co-located electronic power source, since no direct wire transfer was then possible from the aircraft fuselage. In order to reduce battery size on the hub, all integrated circuits used CMOS chips wherever possible, with power supplied from two standard 9-volt transistor batteries. A photograph of the instrumentation assembly is shown in Figure 2.

An additional system requirement was that the instrumentation system not adversely affect the mechanical integrity or aerodynamic performance of the rotor blades. The blades on the autogiro are stock Bensen factory-built blades constructed from aluminum sheeting riveted to a solid spar. The airfoil is a Bensen design, having a flat underside and slight reflexed trailing edge, originally developed for construction by the homebuilder from plywood sheeting. Since access to the blade's interior was not possible, multi-conductor ribbon cable for sensor signal routing was secured to the flat underside of the blade using a combination of double-sided sticky tape and epoxy, covered with one spanwise and several chordwise segments of mylar adhesive tape.

Aerodynamic performance considerations dictated the scheme used to condition the sensor signals. Unlike the system used in Reference [3], cost considerations did not allow development of custom millimeter-thick integrated circuitry for sensor signal conditioning and amplification. Since stock integrated circuits (IC's) would be used, a minimum number of chips could be tolerated at each sensor station in order to reduce the adverse drag penalty from surface irregularities they introduce. Although sensor noise would be lowest for co-located sensors, amplifiers and analog to digital (A/D) converters, the associated multiplexing necessary would add at least an additional chip, bringing the total to three ICs at each sensor's spanwise location. Thus, only the sensor's amplifier is located on the blade span, with the A/D and multiplexing operations performed by a single IC at the rotor hub. This arrangement also required only four wires to extend over the entire rotor radius. An installed accelerometer and amplifier are shown in Figure 3.

Sensor signal A/D sampling rate was traded off against multiplexing capability for the digitizing of the rotor data, with the final choice using the TLC541 LinCMOS chip from Texas Instruments as the primary workhorse for conversion of the data to digital form. This IC provides 11 channels of multiplexing capability into an 8-bit A/D converter, with an equivalent throughput rate of 1,024 samples per second on each channel. Since the nominal rotor speed of the autogiro is 375 rpm, the system's Nyquist rate (maximum digital bandwidth) is 82/rev, well beyond any potential dynamic or aeroelastic phenomenon one might expect to observe. For this reason, there are no anti-aliasing filters used prior to A/D conversion.

The multiplexer chip, originally designed for interfacing with a microprocessor, allows for direct control of both channel addressing and serial bit output rate through reasonably complex interfacing with timing and address pins. In order to avoid the requirement of co-locating a dedicated microprocessor, the complex timing patterns and address lines were stored ("burned") into an EPROM, driven by a counter and clock. The individual data bits for each of the 11 channels are sequentially loaded onto the serial digital data bus, followed by a test channel for receiver synchronization purposes. This "synch" word is modified to produce a string of 9 bits that cannot be duplicated by any combination of the 11 channel's data words, thus providing a unique marker for each "frame" of data.

To save on the total number of chips at the rotor hub, the counter that drives the EPROM interface chip does not reset to a predetermined value, and thus the first 1024 8-bit words are cycled over for each frame. Since the timing pulses only occupy the first two-thirds of this address space, a blank sector is available in the current frame of serial data for future expansion. This might consist of either additional rotating frame channels, or inter-woven fuselage sensor data. This latter method would require a serial decoder and synchronizer in the non-rotating frame on the aircraft, a method that was not used on the current design concept. A diagram of the main circuit functional blocks appears in Figure 4.

## Data Transmission and Storage

In order to transmit the digital data from the rotor to the fuselage frame of the autogiro, the serial bit stream was Manchester encoded so as to provide a timing reference for individual bit transitions. While this format is particularly suited for direct radio frequency modulation, the additional weight and power requirements of a radio transmitter were deemed unacceptable. Instead, the coded signal is fed directly into the rotor blade's aluminum structure, with the pickup signal in the fuselage frame merely consisting of a wire secured to the metal airframe. Thus, the entire aircraft is electronically isolated from the sensor power signals, with the rotor data transmitted directly through the main rotor shaft bearing assembly. Alternate schemes using infa-red diodes, while conceptually feasible, were not nearly as simple as this technique.

Due to the limited amount of both ground support personnel and computational facilities, direct re-broadcast of the data from the autogiro to a ground station was not possible. Instead, appropriate signal modifications were made to the serial coded data so that it could be directly recorded onto an 8mm format video camera/recorder. The camera is a self-contained unit running from its own battery source, and is shock mounted to the autogiro directly in from of the pilot's seat, to allow for convenient access to both the record buttons and tape eject mechanism. Despite the high frequency of the Manchester encoded serial bit stream (1.3 MHz), such signals are well within the bandwidth of conventional NTSC video standards.

Post-flight data processing consist of playing back the recorded signals into a serial-to-parallel digital data synchronizer. The circuitry used to perform the data extraction, shown in functional form in Figure 5, consists of signal conditioning to standard logic levels, bit synchronization using a phase-locked loop (PLL), and data decoding with clocked flip-flop circuits. In order to provide for discrimination between channels, a search/synchronizer scheme using another EPROM and comparitor was employed. Since the frame word consisted of a unique 9-bit digital bit pattern, a shift register and bit comparitor were used to detect a "match" with this word indicating the beginning of the serial data frame. When the match was detected, the EPROM clock/counters were reset, and each channel was clocked through the shift register, combined with the four bits representing the channel count, and sent into a high-speed parallel digital data port on an IBM-PC/AT. This data was then stored onto floppy diskettes for additional analysis and processing. After the EPROM cycled through its 11 channels of serial data timing, it entered a "re-match" state in which it looked for another frame start pattern. If this pattern was not found, the synchronizer would enter a "search" mode and warn the user (via light and buzzer) that synchronization was lost and data is invalid. If the pattern was matched, indications of a "locked" state would be given, and the process would cycle over each additional frame of serial data.

## Auxiliary Data System Components

In order to interpret the rotor structural dynamic data, some measurement of the operating state of the autogiro flight condition was required. Of particular importance is the rotor advance ratio, and the associated angle of attack of the rotor blades. As the detailed flow of the rotor is unavailable, several fuselage-mounted sensors were used to infer this information. These sensor data were routed to a pulse-width modulator (PWM) box having a capacity for 43 channels of analog data sampled at 20Hz per channel. This data acquisition system was previously used in flying qualities experiments at Princeton on variable-stability general aviation aircraft and gliders [4]. The PWM signal was in turn fed into the separate audio input channel of the 8mm video camera, thus providing separate but synchronous data recordings for both rotor and fuselage sensor data.

The rotor speed was measured using a magnet mounted on the rotor hub, and a Hall-effect sensor on the rotor mast just below the hub pillow block assembly. The pulses were fed into a PLL circuit that output an analog voltage proportional to pulse frequency, with this information displayed to the pilot and sent to the fixed-frame data commutator system. Autogiro angle of attack and sideslip were measured through two vanes mounted on low friction potentiometers, and airspeed was taken from a cup anemometer. Rotor shaft tilt was measured from stick potentiometers, and rudder pedals were instrumented as well. A picture of the data system components is in Figure 6.

Power for the PWM commutator was provided from four 9-volt batteries tied in series, regulated to a nominal 28-volt DC level. Although larger power rechargeable batteries were available, their significant increase in weight deemed them unacceptable for initial flight tests and data system check-outs. Additional instrumentation, such as use of Princeton's Inertial Measurement Unit [4], will require upgrading the available power source on the autogiro airframe.

Since monitoring of the video tape index during flight could jeopardize safety through increased pilot workload, the FM communicators used between pilot and tow vehicle personnel was coupled into the audio input channel of both the on-board video recorder and the tow car's video camera. Since this same space on the tape is used by the fixed-frame sensors, voice markers were stored only during push-to-talk operations of the pilot. Simultaneous voice recording allowed for approximate synchronization between the signals from both cameras during postflight analysis.

## Preliminary Testing

As a means of both adjusting amplifier offsets and confirming data transmission, storage and retrieval/synchronization, an impact test was made of the rotor blade. An instrumented force hammer in conjunction with the blade-mounted accelerometers were recorded for a series of impacts at several spanwise locations in order to identify the non-rotating mode shapes of the autogiro rotor blade. Such information is essential for accurate post-processing of the accelerometer data, as is pointed out in [2].

Since the spanwise accelerometers are oriented to measure out-of-plane accelerations, as the blade deflects out of the plane of rotation, these sensors will measure both blade vertical acceleration as well as a component of rotational acceleration proportional to the local slope at the sensor's spanwise location (see Figure 7). This information can then be used in a processing scheme called a Kinematic Observer [6] to reconstruct rotor blade state variables. On the autogiro, however, the ratio between the measurement of fundamental teetering (flapping) acceleration and teetering displacement is constant for any spanwise station. For any accelerometer at spanwise location r, it will sense contributions from each mode's acceleration ($\ddot{g}(t)$) and each mode's displacement ($g(t)$) according to:

$$\text{accel}(r,t) = \sum_{i=1}^{\infty} \eta_i(r)\, \ddot{g}_i(t) + \frac{\partial \eta_i(r)}{\partial r}\, r\, \Omega^2\, g_i(t)$$

where $\eta_i(r)$ represents a particular blade natural mode shape. For the case of the rigid teetering mode, $\eta_1(r) = r$, giving contributions from the teetering mode $\beta_1(t)$ as:

$$r\ddot{\beta}_1(t) + r\Omega^2\, \beta_1(t)$$

and for simple harmonic flapping at 1/rev, these two terms cancel. For this reason, a potentiometer was installed in the rotor hub to measure rigid teetering motion, and the accelerometers were positioned so as to maximize their sensing of the various higher blade vibratory modes.

Flight operations for testing the autogiro instrumentation are currently underway at the inactive runway at Princeton University's Forrestal Campus. Since the autogiro has no engine, it is towed by a nylon rope attached to its nose from an automobile. While this results in limited continuous flight time, the runway's 3000 foot length allows flight experiments of approximately 45 to 60 seconds duration, depending on wind direction along the tow path. Communications are kept with the tow vehicle driver and observer using FM transceivers, and a glider tow hitch with release may be operated by the pilot in the event of fouling of the tow line.

Rotor data power has been tested to provide consistent data for over two hours of operation, and fuselage batteries have a roughly equivalent life. Battery life on the video camera used for serial data storage is slightly under an hour, resulting in approximately fifteen flights during a standard sequence of runs. Such a record provides a wide range of test points for analysis, the results of which will appear in a forthcoming paper.

## Acknowledgements

Partial support for this work was provided from a Marshall Scholarship from the

Department of Mechanical and Aerospace Engineering at Princeton University. The authors especially wish to thank the substantial contributions from Mr. James E. Risser, also of Princeton University.

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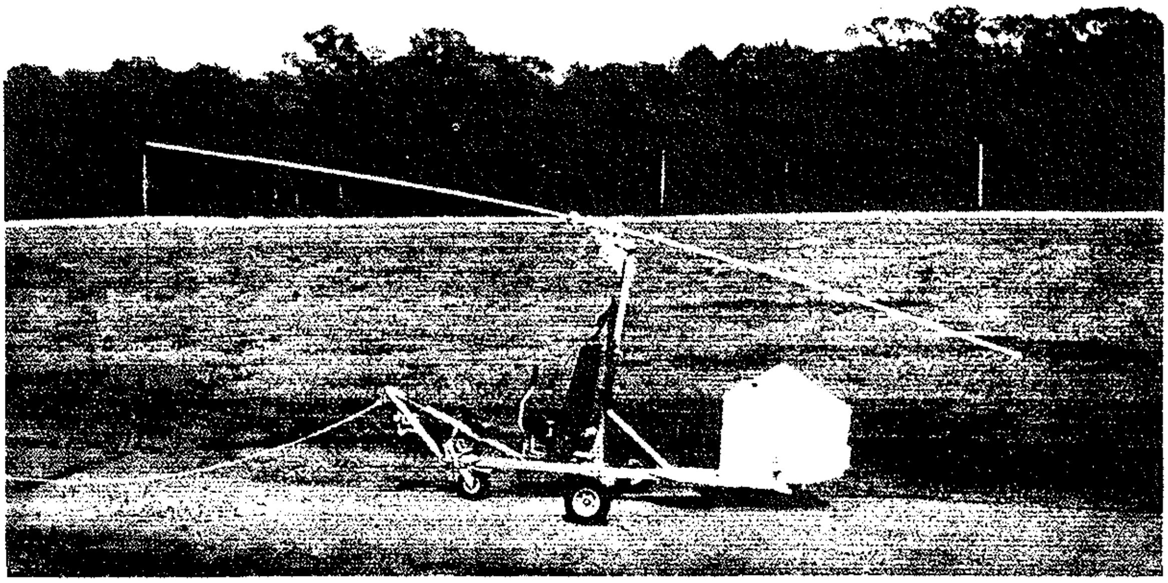


Figure 1: Instrumented Bensen autogiro (glider)

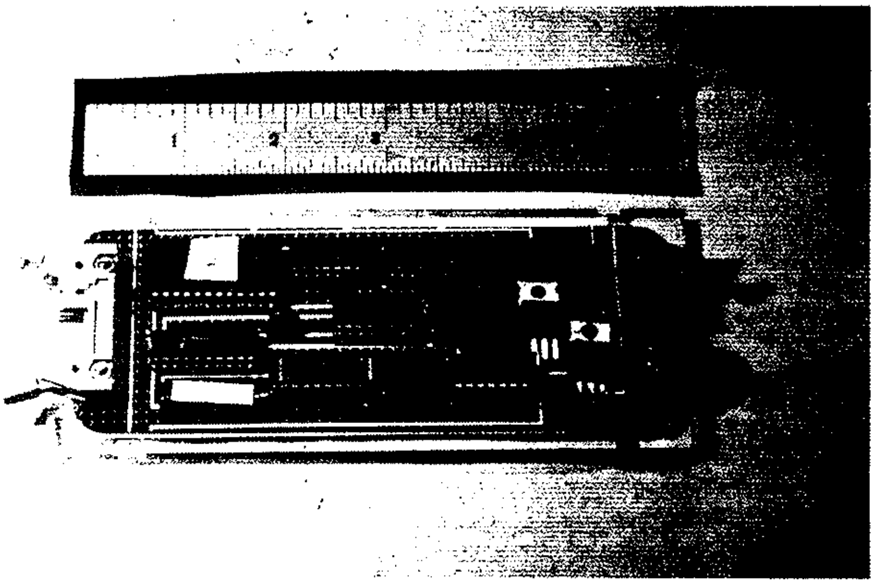


Figure 2: Digital data acquisition and telemetry circuitry

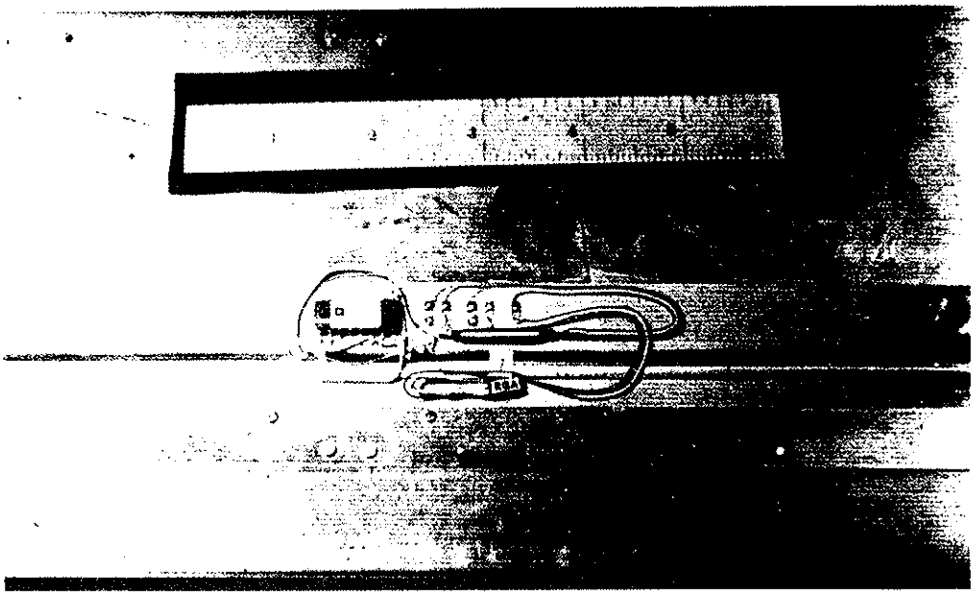


Figure 3: Accelerometer and amplifier installation on blade underside

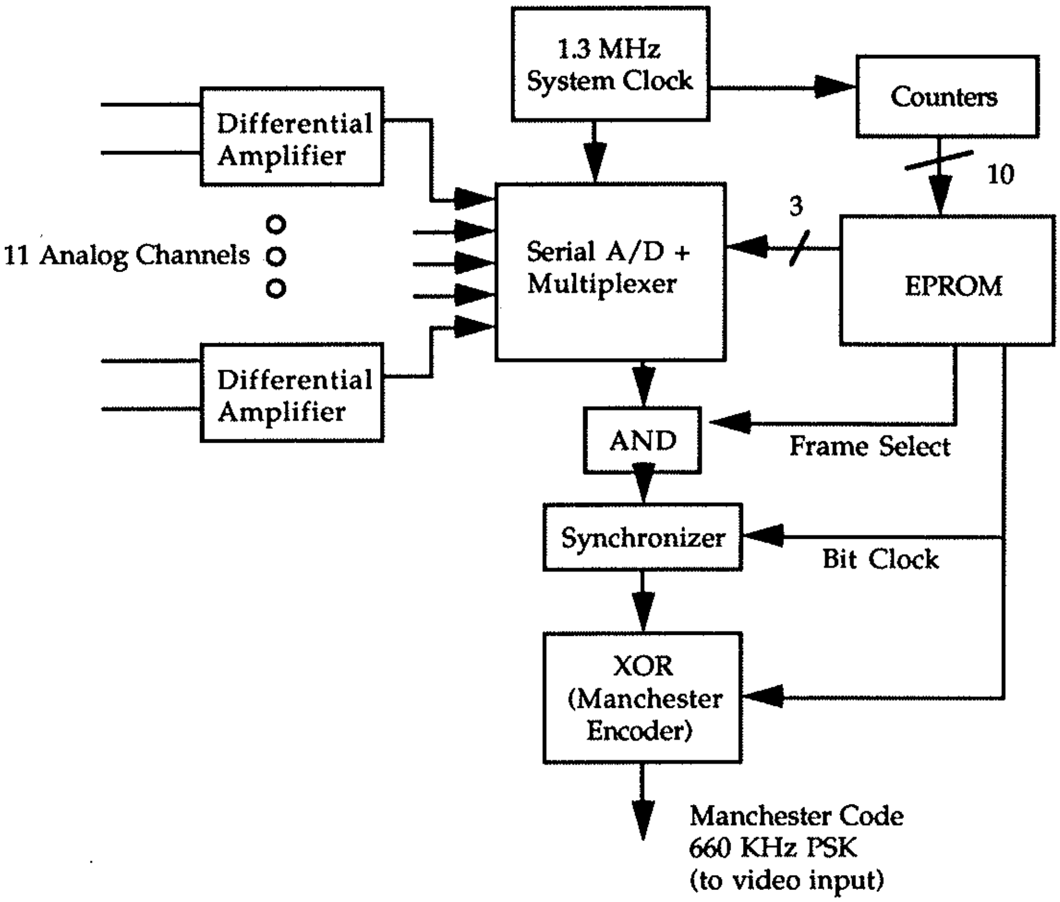


Figure 4: Rotor data acquisition circuit functional diagram

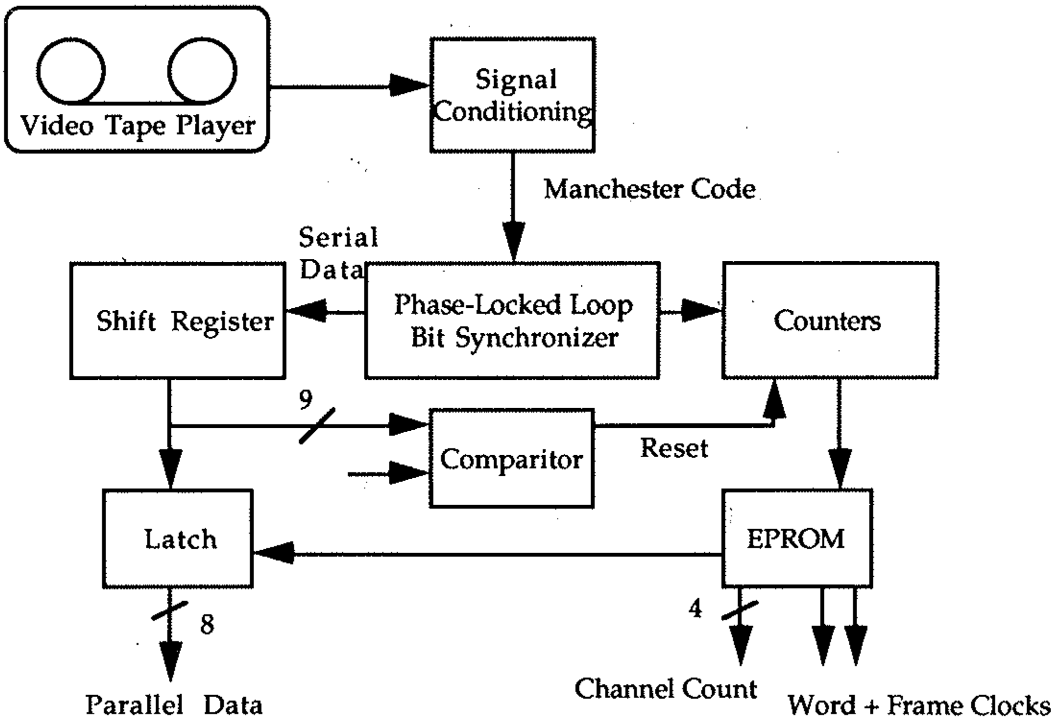


Figure 5: Digital data synchronization and parallel output functional diagram

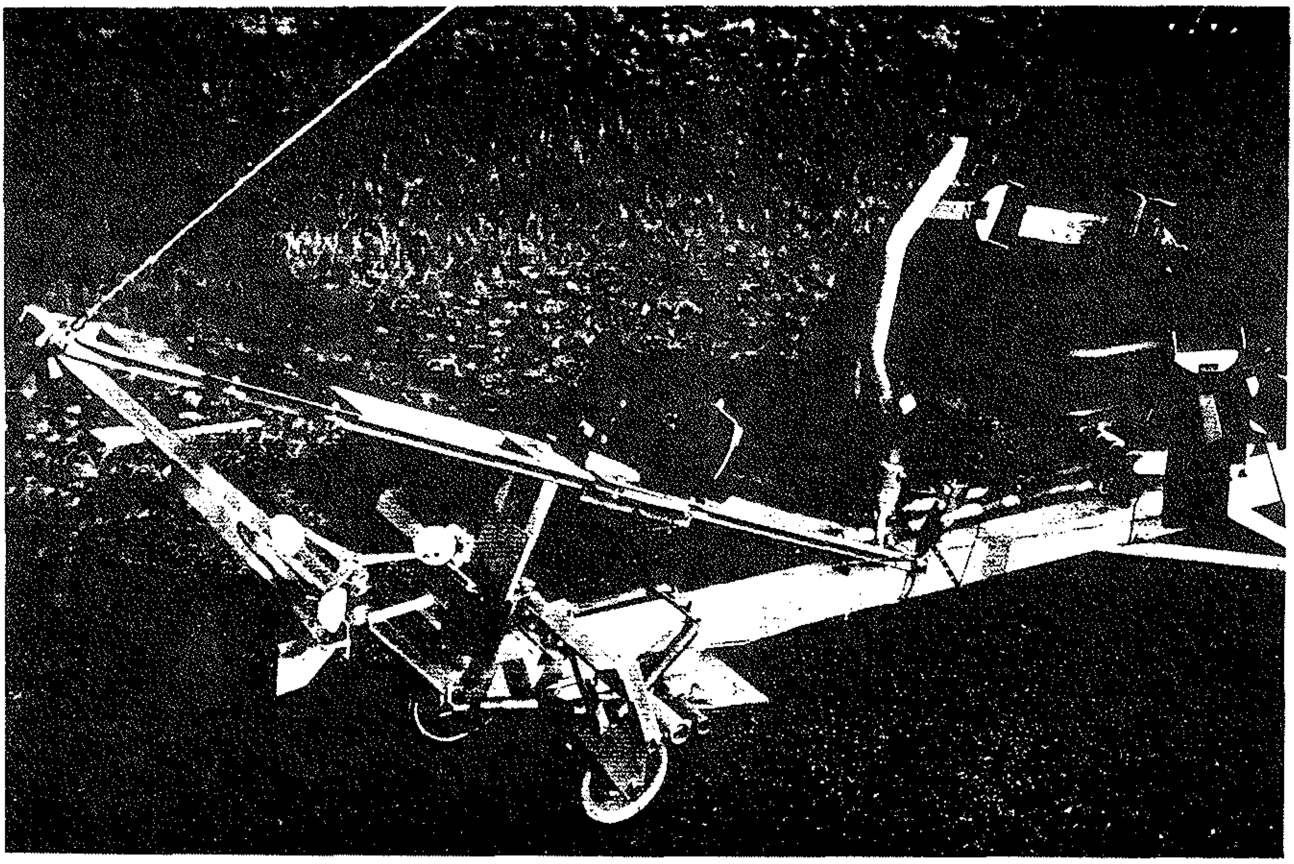
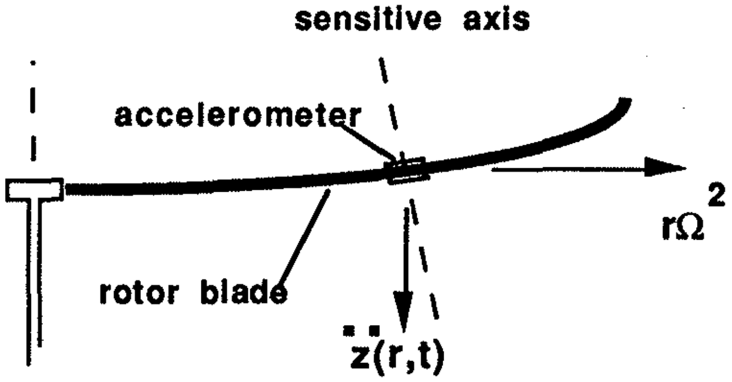


Figure 6: Fuselage mounted airdata sensors and camera attachment



$$\text{accel}(r,t) = \sum_{i=1}^{\infty} \eta_i(r)\, \ddot{g}_i(t) + \frac{\partial \eta_i(r)}{\partial r}\, r\, \Omega^2\, g_i(t)$$

Fig. 7: Out-of-plane accelerometer sensing schematic