PARAMETER SELECTION FOR IN-FLIGHT RECORDING

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The value of in-flight recording of operating and ambient conditions affecting aircraft has long been recognized and accomplished in varying degrees since the early days of aviation. Devices have been used in flight testing of aircraft and space vehicles quite successfully for many years. Flight recorders are mandated by the FAA for passenger-carrying commercial aircraft; cockpit voice recorders are currently being evaluated by many airlines and the FAA to assist in accident investigation; and biomedical recorders are used to monitor physiological affects on living creatures during space flights, to name only a few of the applications of in-flight recording.

The advent of the more complex jet powered aircraft; together with its sophisticated fuel control, navigation and electronic systems, has required development of new and whole concepts of aircraft maintenance. Among these new concepts is the Maintenance Recorder, a relative infant in the field of in-flight recorders. With intelligent selection of performance parameters, the Maintenance Recorder becomes a tool by which aircraft users can update their present methods of preventive maintenance. Maintenance requirements -- previously determined by accumulated operating hours of major components,-- can now be based on actual component condition. The Maintenance Recording System, including associated playback and data analysis equipment, is capable of analyzing aircraft performance under actual flight conditions and of detecting malfunctions or impending equipment failures before they become catastrophic.

The jet aircraft is potentially more reliable, more predictable and capable of longer life than its reciprocating predecessor. One method of capitalizing upon this potential reliability and predictability is to monitor, record, and evaluate performance "in flight". To be useful, such a monitor and evaluation system must present immediatety upon landing, in a form usable by flight-line mechanics, information as to the ability of the aircraft to perform its next mission, In addition, the monitor should record individual component and system data to permit evaluation of long-term trends, and, thus, be able to predict total remaining system-life. The recorder should also assist in rapidly isolating malfunctions once a component is determined to be defective.

When the Air Force made the transition from reciprocating to turbojet engine aircraft some years ago, predictions were made regarding engine performance and maintenance. In addition to improved aircraft performance, it was also anticipated that the jet engine would be potentially more reliable, more predictable, and capable of longer life than the reciprocating predecessor. Today, years later, the military (and even the commercial) jet engine has not fully met expectations.

In all probability, one of the major reasons contributing to performance deficiencies is **the** lack of an adequate maintenance support system. Not only the engine, but the entire jet aircraft and the systems thereof are more complicated than counterparts of the reciprocating engine aircraft. Skilled manpower required to maintain the aircraft has been diluted. Years ago, a mechanic or crew chief spent the major portion of his time in care of the engine. Today, he is able to devote only a small portion of his time to this important function. A maintenance recording system is one method of capitalizing upon the potential reliability and predictability of modern jet aircraft. It is based upon the measurement of selected performance parameters, and upon the interpretation of these measurements as a means of predicting remaining life or impending failure of a jet engine or other major components.

Selection of parameters to be monitored in a Maintenance Recording System should begin with a list compiled of inputs from the various subsystem engineering groups and from the engine and component manufacturers. The people involved in compiling the list will no doubt consider only their own particular systems. The final total list will at first seem formidable, and will require considerable pruning to eliminate parameters that are redundant, or that contain no information relevant to malfunctions, or that cannot be economically justified against the return-to-be-expected.

The second step will be to assign a priority to each parameter based upon the confidence-level and service records of each subsystem, with the highest priority being assigned to systems with the lowest confidence-level and poorest service records. A tabulation of Unsatisfactory Reports will be of much assistance in this phase of parameter selection. Space, weight, and economic limitations may further reduce the list. Typically, in the case of the most recent Lockheed Aircraft Service Company installation of a maintenance recording system in a Trans World Airlines Boeing 707, an initial parameter list of some **250** parameters was finally reduced to 211. Of these 211, **132** are engine parameters, **30** are electronic systems parameters, and **49** are other systems parameters.

After the list of parameters has been finalized, the next step is to evaluate each parameter as to the desired range of interest, accuracy, and frequency of response. Although a large number of parameters will be of interest from zero to some maximum value or limit, most will have a compressed range of interest. Use of normalizing and biasing in the signal-conditioning circuitry can expand the scale to give greater resolution and accuracy. Typically, these would be regulated pressures, temperatures, motor speeds and bus voltages. In some cases too, both course and fine readings of a parameter may be required, such as for altitude and airspeed.

Careful consideration must be given to the required accuracy of each parameter. The normal tendency is to ask for more accuracy than is actually required. As with any other type of system, this cannot help but incrcasc the cost, weight, and complexity of the recording system. However, accuracy must be sufficiently high to make the data meaningful. The overall accuracy must take into consideration the accuracies of the transducer, signal conditioning, recording, *and* playback. For a well designed maintenance recording system, overall accuracies of 2-1/2 percent can be expected.

For *a* given recorder design, with a fixed tape capacity, maximum frequency-response is limited by the continuous, recording-time requirement, which in turn, fixes tape speed. The higher the tape speed, the higher the frequency response, but the shorter the continuous recording time. For a wide band frequency modulation system (proven the most desirable for maintenance recording) the frequency response is limited by the maximum carrier frequency that can be recorded on the tape and played back with an acceptable signal-to-noise ratio. This maximum response can only be attained when recording a single parameter directly onto a tape track Direct recording. of course, limits the capacity of a recording system. Some method of time-sharing or multiplexing of many signals is desirable to increase capacity of the system. Multiplexing of signals, however, has the effect of reducing frequency response.

To best understand the trade-off between system capacity, maximum, continuous recording time, and frequency-response, let us examine a typical maintenance recording system.

Specifications

Recorder Type:	Wideband FM magnetic tape recorder
Manufacturer:	Lockheed Aircraft Service Company
Model:	7D60
Tape Length:	1800 ft.
Tape width:	1/2 inch
Continuous recording time:	60 hours
Parameter capacity:	270 (45 multiplexed signals per data track)
Multiplexing switch rate:	1 revolution per 6 seconds
Tape speed:	0.1 inch per second
Carrier frequency:	70 cps
Deviation:	±25 percent

This system is conservatively designed for a tape-packing density of 700 cycles per inch at the center frequency of the carrier. Thus, for a tape speed of 0.1 inch per second the carrier center frequency is 70 cycles per second. For adequate fidelity of reproduction of a signal, there must be at least seven cycles of carrier for each cycle of the highest frequency component of input signal to be recorded; therefore, at 0.1 inch per second tape speed and a 70 cycle per second carrier, the frequency response covers the range from d-c to 10 cps for a continuous (not multiplexed) channel. Sixty hours of recording are obtained without reloading of tape.

For a multiplexed signal the same basic ratio of seven samples of recording for each cycle of input signal applies. With a multiplexing switch speed of one revolution per six seconds, seven samples would, therefore, require seven revolutions of the switch (or 42 seconds) to record one cycle. This results in *a* frequency response from d-c out to 1.4 cycles per minute. Thus, this system offers a choice of flat frequency response of from d-c out to 10 cps for direct recording or from d-c out to 1.4 cpm for multiplexed sampling of 45 parameters per channel (270 parameters total). This might appear to be too wide a discrepancy, and that many parameters may need a higher frequency response than the lower figure, but certainly much less than the higher figure. In such cases, two, three, or up to 16 contacts equally spaced around a wafer of the multiplexing switch can be connected to the same parameter signal to increase the range of frequency response for multiplexed signals from d-c to 1.4 cpm to d-c to 22.5 cpm. This is done, however, with a corresponding reduction in parameter capacity.

Reducing the continuous recording time of the above system by an increase in tape speed will give a corresponding increase in frequency response of the system without the sacrifice of parameter capacity, or again, paralleling of wafer contacts will give even a further increase in frequency response of multiplexed signals in a trade-off with parameters. For example, increasing the tape speed to 1.0 inch per second (giving a continuous recording time of six hours), will increase the frequency response of direct recorded signals to 100 cps and of multiplexed signals to 7.1 cpm for single contacts per signal and to 115 cpm for 16 contacts per signal. So you can see that considerable trade-off is available for optimizing the system for the desired recording time, number of parameters, and frequency response.

Modern gas turbine design has advanced rapidly in the past few years. However, the ability to cope with problems of maintenance has not kept pace. Twenty or more parameters interact to establish the performance characteristics of some engines. These include rpm, fuel flow, fuel pressure, fuel temperature, air flow, air pressure and temperature, ram and altitude conditions, exhaust gas or turbine inlet temperatures, compressor discharge pressures, and many other functions within the engines. Existing engine instruments often do not accurately present variations of these functions. The best technician in the field cannot isolate malfunctioning causes without the use of complicated equipment, which is usually not available; thus, the trial-and-error process of elimination is being used to troubleshoot malfunctions by removal and replacement of accessories and by expensive teardown inspection procedures. A method of automatically evaluating the mechanical and performance parameters of the engine is needed to expedite maintenance and to decrease down time.

An aircraft instrumentation system should provide data needed to arrive at the answers to two basic questions concerning the power plant. These are:

1) Is the power plant operating correctly, and if *so*, for how long will it continue to operate correctly under anticipated operating conditions?

2) If it *is* not operating correctly, what is wrong and what corrective action must be taken?

For reciprocating engines, standard cockpit instrumentation, supplemented in many cases by an airborne analyzer, provides sufficient information to answer these questions so that engines can be operated safely and confidently without excessive maintenance requirements.

Aircraft gas turbine engines, however, have been developed to a high level of operational refinement in a relatively limited period of time. The factors limiting the performance, availability, and service life of these engines are not well understood. In addition, it is difficult to diagnose engine malfunctions with existing instrumentation. Therefore, the desire for more accurate, complete, and detailed information beyond that furnished *by* engine log sheets and cockpit instruments is to be expected.

This being the case, it would be most useful to find a combination of parameters which, when measured and analyzed, will not only be indicative of the present condition of each engine hut will be predictive of its future performance.

Of the many engine parameters suggested for measurement, engine pressure ratio (EPR), exhaust gas temperature (EGT), and rotational speed (RPM), along with fuel flow are considered of prime importance for detecting engine malfunctions or deterioration: EPR because it is the prime factor in measuring thrust on most jet engines; EGT because of its important effect on engine life; and RPM because it is a measure of centrifugal forces and the stresses imposed on the rotor in combination with high temperatures.

Engine pressure ratio is commonly (but not universally) instrumented for most types of turbojet engines. In those cases in which EPR is not instrumented, a gas generator curve can be plotted to show engine pressure ratio, exhaust gas temperature, and fuel flow as a function of rotational speed with values being corrected to standard inlet pressure and temperature by the inlet condition measurements. If engine pressure ratio is available, corrected values of fuel flow, rotational speed and exhaust gas temperatures can be plotted as a function of the engine pressure ratio.

Many single compressor turbojet engines employ compressor RPM as an indication of engine thrust; however, many complications arise when RPM is utilized as the controlling variable for dual compressor engines. As the high pressure compressor RPM is governed by the fuel control, RPM does not provide an accurate means of measuring changes which may occur in engine propulsion efficiency. **Also,** the RPM for any given thrust condition will vary slightly between engines, depending upon the speed to which the engine has been trimmed. The fuel control in each engine is adjusted to provide the high pressure compressor RPM at which the engine develops its rated thrust. This RPM variation must be taken into consideration when RPM is used to measure the thrust being developed by the engine. Also RPM does not vary in direct proportion to the thrust being produced by the engine over the entire thrust range as does turbine discharge pressure. Lastly, one percent variation of RPM results in approximately five percent variation in thrust at the higher power settings, whereas, one percent variation in turbine discharge pressure results in only one and one-half percent variation in thrust in both dual and single compressor engines. Therefore, the use-of turbine discharge pressure as the engine operation variable is not only much simpler but considerably more accurate.

Since the J79 series engines are considered constant RPM engines, EPR becomes less significant than RPM and EGT because variations in thrust are accomplished by means of the variable nozzle. However, under <u>known</u> conditions and non-transient schedules of inlet guide vanes and nozzle area, EPR may be used in the J79 series for performance comparison purposes. Because the thrust developed by the engine is proportional to the difference in pressure or to the pressure ratio between the engine air inlet pressure (Pt2) and the turbine discharge pressure (Pt7, or Pt5 in single compressor engines), turbine discharge pressure by itself is not an accurate indication of engine output.

Once a desired thrust condition has been set up for the climb or cruise, the fuel control will maintain an approximate constant percent of thrust output with a fixed power level position, even though turbine discharge pressure will decrease as altitude is gained. Engine pressure ratio that varies with Compressor inlet temperature will increase **as** the temperature becomes lower at the higher altitudes.

The importance of accurate monitoring of exhaust gas temperature (EGT) and rotational speed (RPM) cannot be overemphasized. Experience has shown that a definite relationship exists between exhaust gas temperature and premature engine removals. The fuel control is designed in such a manner that exhaust gas temperatures will normally be maintained within safe margins. However, the fuel control cannot compensate for operational malpractices. Furthermore, under extreme flight conditions or in the event of malfunction, the regulations of the engine internal temperatures can be marginal or above desired limits.

Gas turbine engines are subjected to high rotational speeds, high temperatures, and high pressures. Because of these stresses, turbine blades tend to change pitch with continued use, straightening toward low pitch, and nozzle guide vanes have a tendency to "bow" under high pressure and temperatures, decreasing the effective turbine pressure. Each instance is associated with a resultant loss of turbine efficiency. Turbine blades, also, undergo a distortion or lengthening process known as "creep" when subjected to high temperatures and rotational speeds. **This** slow deformation of metal under stress causes weakening of the blades and after a period of time can cause a rubbing of the blades on the turbine case.

In a gas turbine engine, high load and high temperature are usually experienced at the same time. The loading on the turbine and compressor blades is principally the combined result of centrifugal force, associated with RPM, and some gas or air load, associated with engine internal pressure. When the turbine discharge pressure, which is indicative of other internal pressure, is high, so also will be the exhaust gas temperature. This means that when the turbine blades are subjected to their heaviest loads, the material of which they are constructed will be at its weakest.

In addition to the engine performance parameters discussed above, there are many other parameters that should be monitored to give a better, overall picture of engine condition and performance trends. They are:

a) Bleed valve operation or inlet guide vane position

b) **A/B** nozzle area or position

c) Engine oil breather pressure

d) Anti-Icing switch

e) Bearing sump pressure

f) Oil temperature

g) Oil pressure

h) Nacelle ambient

i) Turbine vibration

j) Water injection operation

I have gone into considerable detail in discussing aircraft engine parameters. The jet engine, the condition of which is prime in determining the mission readiness of the aircraft, serves as an excellent example for a discussion on selection of parameters to be used for in-flight recording.

When a maintenance recorder is to be considered as **an** integral part of an aircraft maintenance program, other aircraft systems should be included in the selected **parameters**. These are hydraulic, electrical, flight controls, autopilot, anti-ice, air conditioning, and electronics.

Structural loads should be considered by monitoring accelerations in the three major axes. As a reference for all systems functions, real time should be recorded, as well as altitude, airspeed and heading.

A diligent, intelligent selection and implementation of parameters for in-flight recording will provide the following advantages to the aircraft user.

1. Increase Aircraft Readiness

a. Component Overhaul - Component overhaul can be based on actual condition rather than on hours flown, or, in the event no parameters can be measured to indicate condition of component, overhaul can still be based on actual usage rather than on hours flown. At present, an aircraft shooting landings in three hours of pilot transition training, and a similar aircraft flying from Los Angeles to New York in three hours are regarded in the same manner with respect to maintenance requirements. It is obvious, however, that the aircraft shooting landings sustains far more wear to engines and structures than an aircraft that takes off from Los Angeles, climbs to altitude, cruises, and lands in New York Present maintenance procedures, unfortunately, make neither distinction nor concession for the particular flight conditions involved.

b. Premature Failures - Proper analysis of correct engine parameters provides a reliable indication of the engine's actual condition. Considerable savings are effected by reducing damage resulting from premature failures. Secondary damage to components nearby and/or related to the faulty unit are eliminated. As soon as the condition of a component is accurately known, inflight or in-service failure can be predicted and avoided. Maintenance ground time, thereby, is reduced, and scheduling (based on knowledge of actual conditions) becomes more efficient. Aircraft can be allocated to maintenance base for repair/replacement of components rather than accomplishing the work at any field at which the aircraft might happen to be at time of failure.

c. Routine Inspection - Maintenance data recording and analysis eliminate much of the unnecessary maintenance activity coincident with routine inspections. It also calls for immediate attention to affected areas that otherwise might pass unnoticed.

d. Ground Crew Decisions - The burden of making maintenance decisions on the current generation of complex aircraft is placed on the ground crew. Many years are required to produce a good mechanic, and continuing training and study programs are necessary to keep him abreast of the latest equipments and techniques. Many of the decision-making functions of the ground crew are accelerated and more accurately performed by using playback equipment to translate, process, and analyze stored data, and, where desirable, accomplish special analysis andinvestigation by supplemental use of a computer. Proper utilization of playback and flight analyzer equipment, supplemented by computers where necessary, drastically reduces the mass of papers, forms, and cards prepared during maintenance of civil and military aircraft.

e. Troubleshooting - A considerable portion of unscheduled maintenance cost may be attributed to the expensive practice of troubleshooting. When inflight malfunctions occur, the ground crew must take the report of the flight crew, and, with the evidence available on the ground, try to reconstruct what happened under the particular altitude and flight conditions. Inflight maintenance recording provides a complete history of the event including magnitudes reached by the applicable parameters, sequence of events, and the rates at which events occurred. Troubleshooting time, and thereby, ground time, is materially reduced.

2. Reduce Operational Costs

a. Fuel Management - Operational costs are reduced by proper airborne recording and analysis. Fuel management techniques are improved when correlated to the airborne maintenance data.

b. Inflight Failures - Inflight failures are minimized together with the coincident secondary damage to other systems.

c. Paperwork - Detailed scheduling information is available, and operational paperwork is reduced in a comparable manner as is maintenance paperwork.

d. Evaluation - Airborne-recorded maintenance data provide an excellent basis for mission and air crew evaluation.

3. Accident Investigation

Incorporation of a recorder designed to resist impact and fire conditions of an air disaster can provide considerable evidence in case of an accident. Such evidence would be invaluable in determination of the cause and in the prevention of future accidents.