R. V. Cottington
C. B. Pease

National Gas Turbine Establishment,
Pyestock,
Farnborough,
Hampshire, England

Dynamic Response Testing of Gas Turbines[1]

A knowledge of the dynamic behavior of a gas turbine has always been necessary for control system design and development. One of the chief problems is to measure this information from engine tests as comprehensively and accurately as possible in the minimum amount of time. A technique, based on an improved and generalized version of the pseudo-random binary noise (PRBN) method, is described which shows significant improvements compared to other methods of dynamic response testing. The technique involves the injection of a small PRBN or other random disturbance into the fuel flow or variable geometry actuator, the recording of the response of other engine parameters to that disturbance and the subsequent use of a computer to derive the frequency response. The requirements necessary for successful dynamic response testing are discussed and a comparison made between the improved PRBN technique and conventional sinewave testing from actual engine tests. A number of engines have been analyzed using the new method, some of the results from which are presented.

Introduction

A gas turbine is a dynamic machine. In the majority of applications it is required to respond rapidly and accurately to frequent changes in power demand. This is achieved by means of a control system suitably designed to extract the best possible performance from the engine in terms of steady-state stability and transient handling commensurate with safety and operating costs. The successful design of such a control system is dependent to a large extent on the availability of data describing the measured performance of the engine, both steady-state and transient. The latter yields information describing the rate of engine response both to large rapid changes in power demand to determine engine handling and also to small amplitude, continuous perturbations for stability measurement. The frequencies of these perturbations span the range DC to approximately 20 Hz, depending on the type of engine being tested. Such steady-state and transient data can be used directly in the control system design process or indirectly for validating an appropriate engine simulation.

However, while engines under development are subjected to extensive steady-state testing, considerably less attention has been given to dynamic testing. The reason for this is two-fold. Firstly, much greater emphasis is given to steady-state measurements for assessing basic performance and establishing customer guarantees. Secondly, dynamic response testing has traditionally been a very lengthy and tedious process in order to obtain accurate measurements. However, a method is available, known as the PRBN (Pseudo Random Binary Noise) technique, which has been used in its generalized form to provide a rapid means of accurately measuring the dynamic response of an engine. This paper describes the technique and the way in which it has been successfully applied to the gas turbine.

Techniques of Dynamic Response Testing

Traditional Methods. The earliest and simplest method consists of imposing a step or ramp change in power demand to the engine and measuring its rate of response. However, the main problem of this method stems from the fact that the dynamics of a gas turbine are very nonlinear. Response rates increase significantly with engine power. Thus in order to identify local (linear) dynamics about each operating point, the magnitude of power change must be limited. This inevitably introduces the problem of extracting measured response data from signals containing comparable levels of aerodynamic and electrical noise. Signal filtering can be employed but there is always a compromise to be made between improvement in signal-to-noise ratio and signal attenuation at higher frequencies. Averaging the data from several similar discrete power demand changes also improves the situation. However, this process tends to be rather awkward and there exists the difficulty of exactly reproducing the same maneuver each time.

The situation has now emerged where discrete changes in power demand are mostly confined to large transients in which the engine is made to undergo wide excursions from its normal steady-state working line. This provides information concerning the nonlinear dynamic behavior of the engine. Data measured from these tests possess high signal-to-noise ratios and present little difficulty in their analysis.

Measurement of linear dynamics is tackled in a different way. Because of the small amplitude of input demand changes with the inevitable low signal-to-noise ratio of the measured engine signals, some

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form of averaging must be employed. Rather than average over a number of discrete transients, for the reasons given above, a better way is to inject a continuous disturbance or perturbation and to use a correlation technique to extract the required data from the inherent noise. A particular perturbation signal commonly used is the sinewave. Its main feature is that it stimulates a single frequency in the engine and by correlating it with a measured output signal, a measure can be made of the attenuation and phase shift of the latter. Given sufficient time, very small signals contaminated by large amounts of noise can be accurately measured. Repeating this process at different frequencies results in the generation of a frequency response characteristic. This proves to be a very time consuming process taking typically between 15 and 30 minutes of engine running for a characteristic containing 15 frequency points. This then has to be repeated for each engine operating point at which frequency response characteristics are required. The reluctance to undertake this type of dynamic testing particularly on development engines can thus be appreciated.

Methods exist for speeding up the acquisition of frequency response data, for example, by means of sweeping the input sinewave through a range of frequencies [1, 2].[2] As an alternative to this approach, the input perturbation can comprise some form of random signal which, by definition, contains a wide range of frequencies. It is this particular approach that forms the basis of the dynamic testing technique described in this paper.

PRBN (Pseudo Random Binary Noise) Technique. A convenient form of random signal is PRBN. For a number of years, effort has been spent on the development of a dynamic testing technique that uses this signal as the input perturbation [3, 4 and 5]. The principal feature of this technique is that a range of frequencies over the required bandwidth is injected simultaneously into the dynamic system compared with one at a time as with sinewave testing.

A PRBN sequence is illustrated in Fig. 1. It can possess one of two values and may switch from one value to the other at time intervals Δt, determined by a clock. Whether or not such a switch occurs is predetermined by the sequence generator. Because of its binary nature, PRBN is easily generated, either by a feedback shift register or by a simple computer program. Given an N-bit shift register, the first stage is fed with the modulo 2 sum (i.e., $1 \oplus 1 = 0 \oplus 0 = 0$ and $1 \oplus 0 = 0 \oplus 1 = 1$) of the output of the last stage and the outputs of one or more of the other stages. A particular property of PRBN is that it is periodic, repeating every $2^N - 1$ clock intervals.

Its frequency spectrum is shown in Fig. 2. It is seen that the spectrum possesses a lower frequency limit, $f_{\min}$, and an upper frequency, f_p, at which the amplitude first falls to zero. It can be shown [5] that

$$f_p = \frac{1}{\Delta t}\,\text{Hz}$$

and

$$f_{\min} = \frac{1}{\Delta t(2^N - 1)}\,\text{Hz}$$

Δt is the clock period in seconds. Thus $f_{\min}$ and f_p determine the frequency range of excitation, which must span the engine frequencies to be measured. The realistic upper frequency limit might be considered to be of the order of $2/3 \times f_p$. The frequency range is determined solely by the value of N. Using a 9 bit shift register gives a ratio, $f_p/f_{\min}$, of 511, which represents a realistic frequency range of approximately two and one-half decades. This range has proved adequate for gas turbines. Δt can be adjusted to move this frequency range up or down according to engine type and operating condition. For example, as an engine comes down its power range, it becomes less responsive . Δt should thus be increased to reduce both $f_{\min}$ and f_p.

[2] Numbers in brackets designate References at end of paper.

Having superimposed a small amplitude PRBN signal onto a steady engine input, the means by which a frequency response characteristic is obtained is by correlating it with an engine output and applying a Fourier transformation. The elegance of this procedure is that the computation is very simple due to the binary nature of the PRBN signal. Therefore the computing requirements are relatively modest. Thus in the example shown in Fig. 3, the response is obtained between demanded fuel flow, W_{fD}, and engine speed, N. If the response between actual fuel W_{fA} and speed is required, the response of the fuel flow actuator must be subtracted. This subtraction process, although simple mathematically, has sometimes been the cause of poor results. Actuators are notorious for exhibiting a whole range of non-linearities such as stiction, hysteresis, etc., producing a marked degree of scatter in the measured frequency responses. Consequently, subtracting two characteristics of this nature results in a response of even poorer quality.

The solution to this problem is to relate a measured parameter directly to the actual engine input, thus excluding actuator dynamics altogether. This can be achieved by means of cross-spectral analysis [6, 7]. The time histories of any two parameters (input and output) are subjectod to Fourier transformations. From these, the power spectrum of the input signal and the cross spectrum between both signals are calculated. Division of the latter by the former yields the frequency response between the input and output parameters. The calculation routines are no longer geared to PRBN specifically and are consequently more complex, but well within the capabilities of current computers. Although any form of continuous perturbation such as white noise can be used with this generalized method, PRBN remains a very convenient excitation signal since it has a flat frequency spectrum over most of the range of interest and is easy to

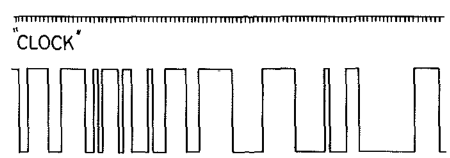

Fig. 1 PRBN time sequence

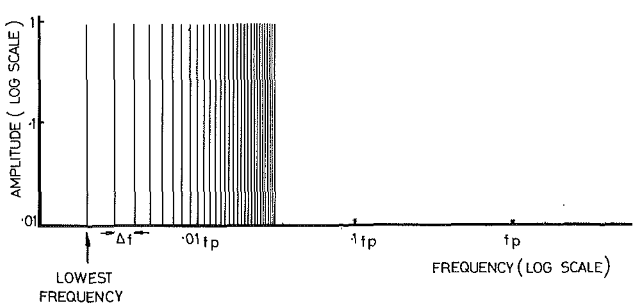

Fig. 2 PRBN frequency spectrum

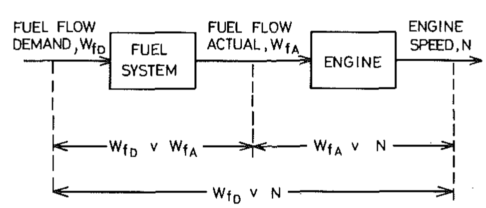

Fig. 3 Engine and fuel system transfer functions

generate. A prime requirement, however, is that the power spectrum of the actual input signal, e.g. measured fuel flow, is not too severely attenuated at the higher frequencies of the required frequency bandwidth; otherwise this will give a low degree of confidence in the frequency response at these frequencies where there is significant attenuation.

Comparison Between Sinewave and PRBN Testing

Before PRBN testing could be accepted as a routine dynamic analysis technique, confidence had to be attained in the results it produced compared with sinewave testing. Such a comparison was made in conjunction with Rolls-Royce on a two shaft turbofan engine installed on a sea level test bed. Fig. 4 shows diagrammatically the hardware layout used in the tests. Datum values of engine fuel flow and nozzle area were set up on potentiometers, depicted as pilot's levers in the diagram. Superimposed on these settings was the perturbation signal, which was switchable between either input. This signal consisted either of a sinewave or PRBN and passed through a common attenuator.

Both the sinewave and the PRBN signals were used in turn to perturb the engine fuel and then the nozzle area. Each test was repeated at three different amplitudes of the perturbing signal because, in any but a strictly linear system, this could influence the results. The largest amplitude resulted in engine shaft speed fluctuations of no more than ±2 percent of full scale, since this was considered to be the maximum permissible level from the point of view of engine wear. For the PRBN tests, a number of different clock intervals were used. The whole process was repeated at two different engine conditions, high power and flight idle. Seven different engine parameters, together with the input signals, were recorded on multi-channel magnetic tape. The sinewave tests were analyzed using a Solartron transfer function analyser and a special synchroniser to enable recorded data to be handled. The PRBN tests were analysed initially using the simple correlation technique producing frequency responses with respect to fuel flow and nozzle area demand (i.e. the actual PRBN input signal) and then using the cross-spectral method to produce responses directly related to actual measured fuel flow and nozzle area.

Frequency responses of the measured engine parameters with respect to fuel flow obtained from both the sinewave tests and the PRBN tests matched very closely. Figs. 5 and 6 typify the results obtained showing the responses of LP rotor speed and HP compressor delivery pressure respectively. This applies to where the input is either the demand signal itself or the measured input signal having subtracted the response of the actuator. The reason for this is that the fuel flow actuator is reasonably linear giving rise to smooth frequency response plots.

In the case of the nozzle perturbations, there was considerable scatter in the points comprising the resulting frequency response plots. This was due to the presence of nonlinearities, i.e. stiction, backlash and hysteresis, in the nozzle actuator. While Fig. 7 shows the clean input power spectrum, Fig. 8 shows the effect of these nonlinearities on measured nozzle area. This noise is then perpetuated "downstream" into the analysis of measured engine parameters, such

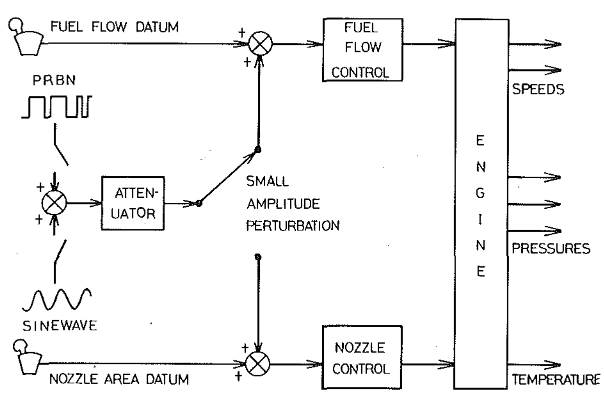

Fig. 4 Hardware layout for comparing PRBN with sinewave testing

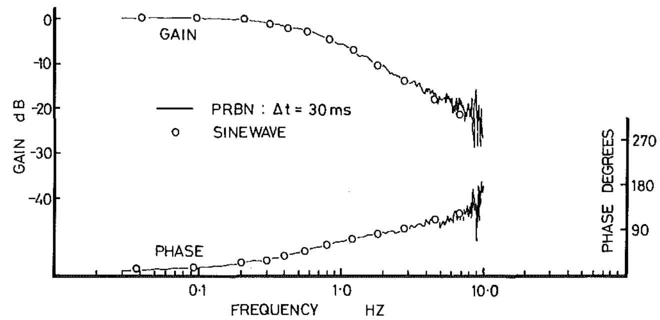

Fig. 5 Frequency response of LP rotor speed to actual fuel flow

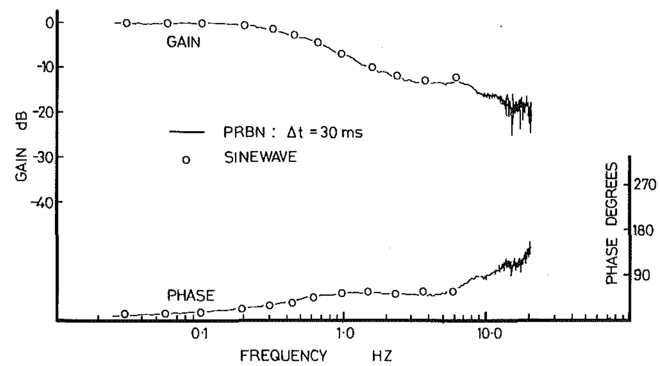

Fig. 6 Frequency response of HP compressor delivery pressure to actual fuel flow

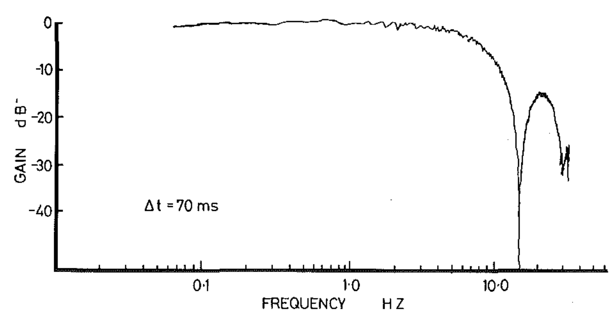

Fig. 7 Power spectrum of nozzle input signal

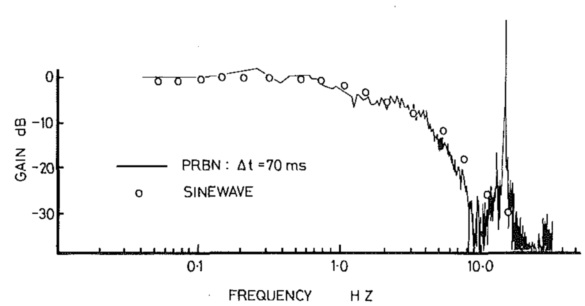

Fig. 8 Frequency response of measured nozzle area to PRBN

as jet pipe pressure (Fig. 9). The difficulty in subtracting the response in Fig. 8 from the response in Fig. 9 is now apparent. Superimposed onto Figs. 8 and 9 are corresponding results from the sinewave tests to illustrate that, despite the noisy PRBN results, the agreement is good. Fig. 10 shows the frequency response of jet pipe pressure with respect to measured nozzle area generated by the cross-spectral method. The result is a plot with much less scatter, of course, which was obtained in only one computational step.

The effect of increasing the amplitude of the input perturbation was to improve the quality of the frequency response plate in terms of scatter. Apart from this, there was no detectable change in the overall shapes of the responses, indicating that the engine perturbation was confined to its linear region of operation.

The outcome of this comparison was to demonstrate the ability of the generalized PRBN technique to produce frequency response characteristics between any two measured signals considerably quicker in terms of both testing time and analysis time than sinewave testing. This then led to the design and construction of suitable equipment to fully exploit the potential of PRBN testing in terms of obtaining maximum dynamic information from an engine in the shortest possible time.

Nonlinearities

Nonlinear elements in a dynamic system generally introduce harmonics into the system outputs that are not present in the input. A sinewave analysis, which is a correlation of an output signal with a single input frequency, represents in effect, a narrow band filter tuned to that frequency. It therefore filters out these harmonics and the degree of scatter of the resulting frequency response is generally unaffected.

Any kind of random noise technique will be affected differently. It will not be able to distinguish between that part of the output signal, at a certain frequency, that is due to the input signal at the same frequency and that part which is a harmonic of a lower frequency. Therefore the effect of a nonlinear element on this kind of analysis will be to introduce scatter into the resulting frequency response characteristics. This has already been observed in Figs. 8 and 9. However, unlike normal uncorrelated noise, that introduced by a nonlinearity will repeat itself faithfully each time the stimulus is repeated. Therefore averaging over a longer period of time will be of no benefit. What will have an effect is the level of the excitation signal. Nonlinearities such as stiction and backlash have limiting values and so their effects can be reduced by increasing the amplitude of perturbation.

During PRBN analysis, should a particular frequency response characteristic exhibit significant scatter, it generally reveals the presence of a nonlinearity either in the actuator or in the sensing system. Experience has shown that a closer examination of the hardware indicates the type of nonlinearity present which can then be measured by means of simple experiment, e.g., actually measuring the magnitude of a hysteresis loop by increasing and decreasing the input signal and noting when the output first begins to move.

PRBN Testing

Because of the considerable amount of computation required in cross-spectral analysis, it is not practical to undertake this on line during actual PRBN testing when a number of parameters are to be analyzed. For the somewhat special case of a single output analysis, however, such as might be required for tuning the response of a control loop, there does exist commercial equipment which can perform this on line. Consequently measured engine data are recorded on magnetic tape and analysed off line. Thus there are two distinct phases in deriving the dynamic response of an engine: data acquisition and data analysis.

Data Acquisition. The apparatus used to acquire and record dynamic response data is shown in Fig. 11. The unit on the left hand side of the picture is used to generate a PRBN sequence that is repeated every 511 cycles of the driving clock, which gives a realistic frequency perturbation range of nearly two and one-half decades. The actual frequency range and the voltage amplitude of the signal are adjustable. Should the engine actuation system not be electrical, means must be engineered for converting the electrical input signal into a hydraulic, pneumatic, or mechanical form, whichever is appropriate to perturb the engine.

It is desirable that the actuation systems possess good dynamic response over the required frequency range, otherwise the engine will not be adequately perturbed and the resulting frequency responses will be poor. Should the response not be adequate then use can be made of filter networks to shape the frequency spectrum of the PRBN signal to compensate for the deficiency in response.

Also of utmost importance is the accurate measurement of engine data with the minimum instrumentation time lag. Signals which are in the form of frequency output, e.g., rotor speeds and fuel flow, are processed through high response signal conditioning circuitry producing d-c signals with a time lag of only a few milliseconds. This is achieved as follows. The frequency is converted to a pulse of the same period which is then used to charge a capacitor to a reference voltage. The decay rate of the capacitor is controlled by appropriate circuitry

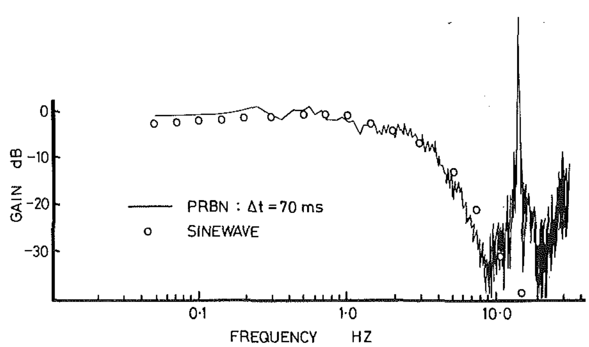

Fig. 9 Frequency response of jet pipe pressure to PRBN

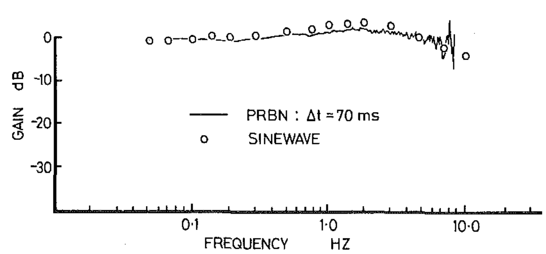

Fig. 10 Frequency response of jet pipe pressure to measured nozzle area

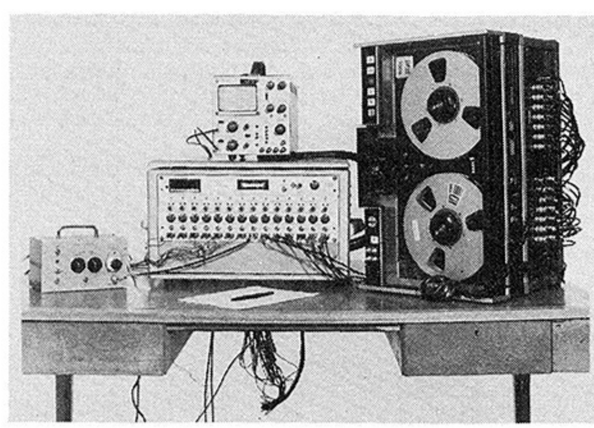

Fig. 11 Equipment used for PRBN testing

to accurately follow a hyperbolic trajectory (as opposed to the usual exponential trajectory). At the end of each pulse cycle, the voltage remaining on the capacitor is directly proportional to the input frequency and is retrieved by means of a sample and hold device.

Engine pressures are best measured by transducers mounted in temperature-controlled, water-cooled containers, situated as close to the sensing points as possible so as to minimize transducer pipe lengths and hence dynamic lags. Nonlinearities, such as backlash and hysteresis, must be avoided in mechanical devices measuring, for example, displacement, since their effect, as already discussed, is to introduce scatter into frequency response plots.

Care taken over the signal conditioning is also essential to the success of the overall technique. To accomplish this, a special purpose 14-channel signal conditioning unit (central item in Fig. 11) is used to back off the d-c level of all measured signals and then to amplify them before they are recorded on a 14-channel FM tape recorder (right hand unit in Fig. 11). This signal conditioning unit can be set up easily and quickly, a task readily accomplished during the time taken to measure the engine steady-state operating point.

The PRBN input perturbation is now applied, final adjustments made to the signal conditioning unit, and engine data recorded. The duration of the recording is determined by the period of the PRBN sequence and by the number of complete sequences injected to permit the averaging out of any noise that may be present. Typically a PRBN clock period of 30 ms gives a sequence duration of approximately 15 seconds. Although only two or three sequences were required to obtain good results where the signals were relatively noise-free, it was found desirable in practice to record up to ten sequences to ensure results of good quality. For the example quoted, this would take about two and one-half minutes of testing time. However, this length of time is directly proportional to the PRBN clock period and so for values greater than 30 ms, longer testing times are required. The value of the clock period selected is such that the analysis bandwidth conveniently spans the engine frequency range of interest and is determined from a few preliminary runs.

Data Analysis. The PRBN analysis procedure used to derive frequency response characteristics is based on a cross-spectral analysis of the appropriate input and output signals using a Fast Fourier Transform technique as previously explained. The procedure has been programmed onto an EAI PACER 600 hybrid computer. Dynamic response data stored on magnetic tape are passed through anti-aliasing filters on the analogue computer before they are digitized and stored on disk. An interactive digital program then enables a user to analyse these data and to generate appropriate frequency response characteristics on an incremental plotter. During this process, the user is able to monitor on a visual display screen the progress of the analysis and to select the number of PRBN sequences that he wishes to average over in order to reduce the effects of signal noise. The bandwidth of the anti-aliasing filters, the digitization process and analysis procedure are all matched to the bandwidth of the input PRBN signal.

Should engine dynamic response information be required in a mathematical form, then there exists a computer program that derives a transfer function from a frequency response characteristic. The method used is a hill climbing technique such that given the structure of the transfer function together with an initial guess for its coefficients, the latter are adjusted to minimize the difference between the frequency responses derived from the measured data and from the transfer function itself. This step, however, does introduce an element of subjectivity in that the correct form of transfer function must be known and the convergence of the program is to some extent dependent on the initial guess of the coefficients. Furthermore, there may be a number of transfer functions that would fit any experimental frequency response characteristic to within the accuracy of the measured data and the convergence criterion used by the hill climber. For these reasons, the preferred form of dynamic response presentation is a frequency response characteristic.

Applications. Extensive dynamic response analyses have been made of several gas turbine engines using the PRBN test procedure at NGTE. The initial experiments and comparison with sinewave testing were performed on an engine assigned for research and were thus without the pressure normally associated with development testing. Subsequently, tests have been performed on engines undergoing development testing at simulated altitude and forward speed conditions, including some with a supersonic intake installed. The latter included measuring the response of the engine to perturbations in intake variable geometry. Data derived from such tests were used to determine and assess control system stability and performance.

Marine gas turbines undergoing endurance trials under simulated marine conditions have also been subjected to PRBN testing. These engines currently have hydromechanical fuel control systems. Therefore it was necessary to introduce the input PRBN signal via an electrically operated servo valve specially fitted to the fuel system for this purpose.

Fig. 12 illustrates diagrammatically the system used. High pressure fuel is split between primary and main burners through a pressurizing valve. A Moog valve was installed in the primary line to function as a variable restrictor. Electrical actuation was so arranged that removal of the input signal caused the valve to open, thus restoring normal running conditions.

The resulting power spectrum of the fuel flow is shown in Fig. 13 and is reasonably flat up to about 10 Hz, indicating that all frequencies between DC and 10 Hz are being excited. The quality of a typical frequency response characteristic produced from subsequent analysis is shown in Fig. 14 and depicts the response of the LP shaft to fuel flow variations. Up to ten tests were performed on each engine from idle to full power with ten engine parameters being simultaneously recorded for subsequent analysis. The total engine running time to execute all ten tests was only three hours per engine including the time taken for the engine to settle between changes in operating condition. This again demonstrates the efficiency of the PRBN testing technique and the importance of having available instrumentation and signal conditioning equipment specially designed for the task.

Conclusions

The PRBN technique of measuring dynamic response has been successfully applied to the gas turbine. Comparisons were made be-

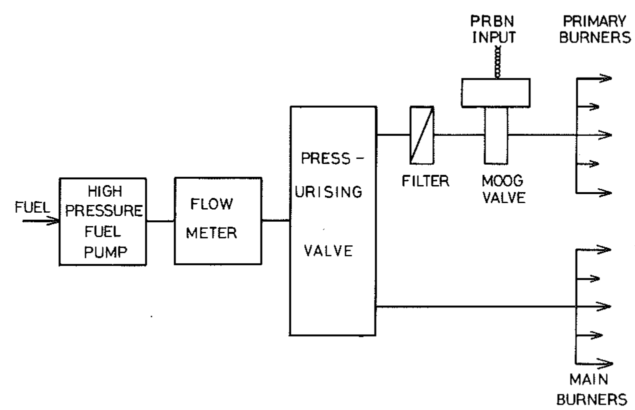

Fig. 12 Superimposing a PRBN input signal onto a hydromechanical fuel system

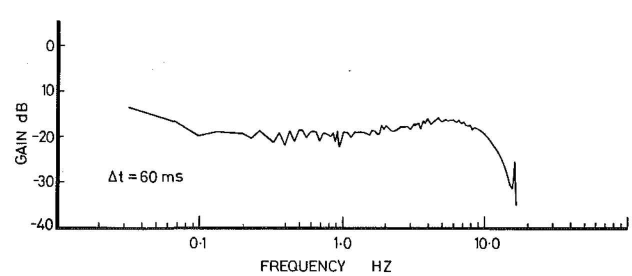

Fig. 13 Marine engine PRBN test—power spectrum of fuel flow

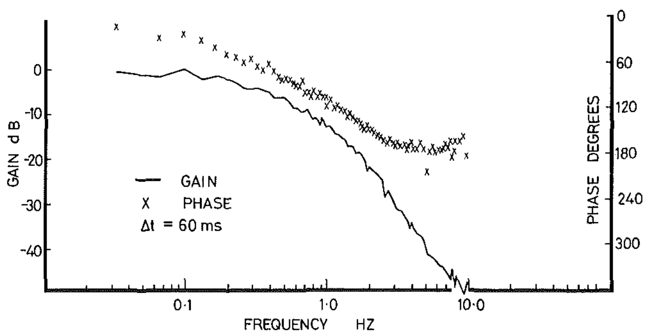

Fig. 14 Marine engine PRBN test—frequency response of LP rotor speed to fuel flow

tween frequency response characteristics derived from this new method and from the more conventional sinewave testing. Excellent agreement was achieved giving confidence in the use of the PRBN method.

The method was then used in a generalized form such that, instead of just relating the response of a measured engine parameter to the PRBN input signal, the frequency response between any two measured parameters can be derived directly. This is achieved by using a cross-spectral analysis technique. Although any random input noise source can be used, PRBN has proved convenient in that it is easy to generate and possesses a flat frequency spectrum over the frequency range of interest.

A test procedure has been evolved and suitable instrumentation and signal conditioning equipment developed to maximize the effectiveness of the technique by allowing dynamic data to be measured and recorded as rapidly and accurately as possible. Subsequent analysis to derive frequency response characteristics is undertaken off-line by an interactive program on a hydrid computer.

The key advantage that PRBN testing has over the more conventional forms, such as sinewave testing, is the speed in which it can be done—less than five minutes per test point compared with up to half an hour using sinewaves. This has elevated the process of dynamic response analysis of gas turbines from a position of being "the last item on the test schedule" to one which is quick and easy to accommodate without making excessive demands on the overall test program. Thus where it has been limited to only a few isolated instances during the history of engine development, it can become, and is becoming, a far more commonplace feature of development programs.

Acknowledgments

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