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METHODS FOR THE ANALYSIS AND PREDICTION OF COOLANT FLOW INSTABILITIES IN BOILER SYSTEMS

by

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SUMMARY

One of the safety problems associated with the operation of nuclear and conventional boiler systems is the stability of the coolant flow through the heated channels. This paper describes various methods which may be used to predict the onset of coolant flow instabilities from measurement of selected boiling channel parameters, and how statistical analysis of the random fluctuations in these parameters enable the transient behaviour of the boiling channel to be determined. Particular emphasis is given to the use of cross spectral noise analysis methods for the identification of the dominant instability mechanisms, and data is presented from experiments carried out recently by the author on a low pressure test rig which uses Freon 113 as the primary coolant. The relative merits and limitations of various analytical methods are discussed with reference to their application as on-line diagnostic tools for assessing the transient behaviour of boiling channels during normal boiler operation.

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1. INTRODUCTION

The efficient operation of nuclear and conventional steam boilers is dependent on the heat transfer of thermal energy to the coolant flowing through the boiler channels. It is well known from research and operational experience (1) that static or dynamic coolant flow instabilities may reduce heat transfer efficiency and lead to control and/or safety problems. Static instabilities (principally flow excursion or Ledinegg instabilities) can be eliminated by appropriate design procedures, but the onset of dynamic instabilities (principally coolant flow or density wave oscillations) are more difficult to predict in complex boiler systems.

Dynamic instabilities are caused by multiple regenerative feedback mechanisms between the channel flow rate, vapour generation rate and pressure drop, and these in turn are complex functions of the channel geometry and operating conditions. The purpose of this paper is to describe some practical test methods which may be used to determine the onset of dynamic flow instabilities and the transient behaviour of boiler channels.

2. ANALYSIS OBJECTIVES AND CLASSIFICATION OF METHODS

Steam boilers normally operate at some nominal steady state in which there are small random fluctuations ('noise') in the various operating parameters (pressures, temperatures, flow rates, etc.). The measurement and analysis of these random fluctuations will give a variety of information about the dynamics of the boiler channel, and the method of analysis adopted will depend on the information required. One of the principal parameters of interest in boiler design and operation is the power level at which coolant flow instabilities occur, that is the 'instability threshold power' (ITP). This information can be obtained using relatively simple methods, whereas more detailed information, such as the time and frequency response behaviour of the boiler channel, requires more sophisticated analysis procedures. This latter information is particularly useful for the verification of theoretical models (e.g. 2,3) for boiler design and assessment purposes.

The various analytical procedures presented in the following sections can be broadly classified as either 'empirical' or 'statistical' methods, and can be listed in order of complexity as follows:

(i) Empirical

Analysis of the real time visual record of the flowmeter noise measured at the channel inlet.

(ii) Statistical

(a) Inverse variance analysis of the inlet flowmeter noise.
(b) Autocorrelation and power spectral analysis of inlet flowmeter noise.
(c) Cross correlation and cross spectral analysis of inlet flowmeter noise and channel pressure drop noise.

The real time visual record can be made using a standard pen recorder, and as the ITP is approached the recorded flow rate should show distinct oscillatory behaviour. This change will also be reflected in the computed variance in which the signal is squared and averaged after removal of the steady state (or d.c.) component. It has been shown (4) that when the inverse variance is plotted as a function of channel power, the relationship is approximately linear as the ITP is approached. Both these methods are sufficiently simple to give on-line information for operational purposes.

The autocorrelation and power spectral method gives qualitative estimates of the channel transient response, and requires a special purpose correlator and Fourier transform unit, or a minicomputer, to perform the computations. As shown in (4), the autocorrelation function also gives the variance and log decrement information from which the ITP can be obtained.

The cross correlation and cross spectral method gives quantitative estimates of the channel transient response, and requires a special purpose correlator, and/or minicomputer, for performing the computations. The cross correlation function in terms of the system input random variable x(t) and the output random variable y(t) is defined in reference (5). The cross spectral density function is obtained by Fourier transformation of the cross correlation function. In practice, 'leakage' occurs in the Fourier transformation of discrete data, and this is minimised by the use of various 'lag windows'. Complete details of this and other refinement procedures for reducing the 'bias' in the transfer function estimates are given in reference (5). If x(t) is the measured channel inlet flow rate noise, and y(t) the channel pressure drop noise, then the system transfer function is a measure of the channel 'hydraulic impedance' (6), and should reflect the stability of the channel as power is increased. This is demonstrated by the results presented in Section 4.

3. DESCRIPTION OF TEST RIG AND ANALYSIS EQUIPMENT

A schematic diagram of the test rig and the associated analysis equipment is shown in Figure (1). A centrifugal pump with 4 ℓ/s capacity at 20 m head circulates the Freon 113 coolant around the primary circuit. The primary circuit consists of a test channel in parallel with a large bypass, and a vapour condenser and subcooler for condensing and cooling the Freon prior to returning to the pump inlet.

The test channel heater element comprises a 10 mm dia stainless steel tube which is electrically heated via a 400 A, 12 V a.c. power transformer. The outer tube of the test channel is made of Pyrex glass to enable visual observations. A Hall effect a.c. wattmeter is used for power measurements, and standard copper-constantan thermocouples are used for temperature measurements. High resolution piezoelectric differential pressure transducers are used for the flowmeter and channel pressure drop noise measurements. The output from a piezoelectric transducer is amplified using a charge sensitive amplifier and a preamplifier in series. The preamplifier output is connected to a band-pass filter for selection of the frequencies associated with the hydrodynamic phenomena of interest; the filter output is then connected to the various recording and processing equipment.

Visual recording of the flowmeter noise is made with a pen recorder, and both signals can be recorded simultaneously on magnetic tape for subsequent off-line analysis. The central processing unit for the statistical analysis is the on-line correlator (Hewlett Packard Model No. 3721A); this provides the correlation functions for Fourier transformation by the spectrum display unit (Hewlett Packard Model No.3720A) and for the transfer function calculations by the PDP11/10 minicomputer. A special software program has been written by the author in FOCAL 11 language for this purpose (7). The program control is via the teletype unit, which also produces a paper tape record of the correlation functions for further off-line analysis. The various statistical functions can also be plotted using the X-Y plotter.

4. RESULTS AND DISCUSSION

The pressure drop noise measurements obtained from the test rig were analysed using the methods described and the results are presented in Figures (2) to (5). The test procedure involved incrementing the heater power through a power range until pronounced flow oscillations were recorded and observed. All other controls, such as the bypass valve, were unaltered. Transfer function calculations and tape recordings were made at the power levels where the computed inverse variance-power relationship was judged to be linear (Figure (3)). It has been found that the hydrodynamic noise at power levels below this linear region of operation is contaminated by extraneous turbulent noise, particularly the two phase turbulence effects in the riser section. At power levels above this linear region, the nonlinear channel behaviour does not conform to the inherent linearity assumptions of noise analysis theory, and hence the correlation and spectral analysis methods become invalid. The hydrodynamic information of interest was expected to occur at frequencies below 1 Hz, and so the frequency bandwidth used in the present tests was confined to 0.1-1.0 Hz.

It is not possible, within the scope of this paper, to present in detail all the information that can be obtained using the various analytical methods, and so only the essential results are presented and discussed.

The visual real time record, Figure (2), shows the evolutionary development of the flow rate noise as the channel undergoes transition from stable to unstable behaviour. The same information is graphically demonstrated by the inverse variance - power map in Figure (3), from which an instability threshold power of 1.77 kW can be obtained by extrapolation to zero inverse variance. This result agrees with visual observations, and comparison of the two methods indicates that the inverse variance method is more accurate than the empirical method. The corresponding power spectra are shown in Figure (4), and were obtained by Fourier transformation of the flow noise autocorrelation functions using a Parzen lag window with a resolution bandwidth of 0.19 Hz.

Perhaps the most significant results are the transfer function estimates relating the channel inlet flow rate and pressure drop noise measurements shown in Figure (5). The transition of the channel hydraulic behaviour from a stable one at low powers to a resonant one at high powers is clearly evident from the transfer function modulus plots, whilst the corresponding increase in phase lags reflects the increase in the transport delays between the channel flow rate and pressure drop noise through the two phase region of the channel.

The computation of cross spectral information between selected parameters is a logical extension of the power spectral method but, to the author's knowledge, this application of the inherent noise method has not been attempted previously.

5. CONCLUSIONS

This paper has demonstrated that the stability of the coolant flow through a boiler channel and its associated instability threshold power can be determined from the

(i) visual records of the inlet flowmeter noise;

(ii) inverse variance of the flowmeter noise versus power map;

(iii) autocorrelation and power spectral analysis of the flowmeter noise; and

(iv) cross correlation and cross spectral analysis of the flowmeter and channel pressure drop noise.

All the methods may be used satisfactorily as on-line diagnostic tools, but the method adopted will be determined by the information required. The cross spectral method gives the most detailed information on the transient behaviour of the boiler channel, and a logical extension of this method is to use multivariate cross spectral analysis (5) for more complete identification of the boiler dynamics process. Such analysis may considerably improve current methods for the optimal control of large conventional and nuclear boiler plants.

6. ACKNOWLEDGEMENTS

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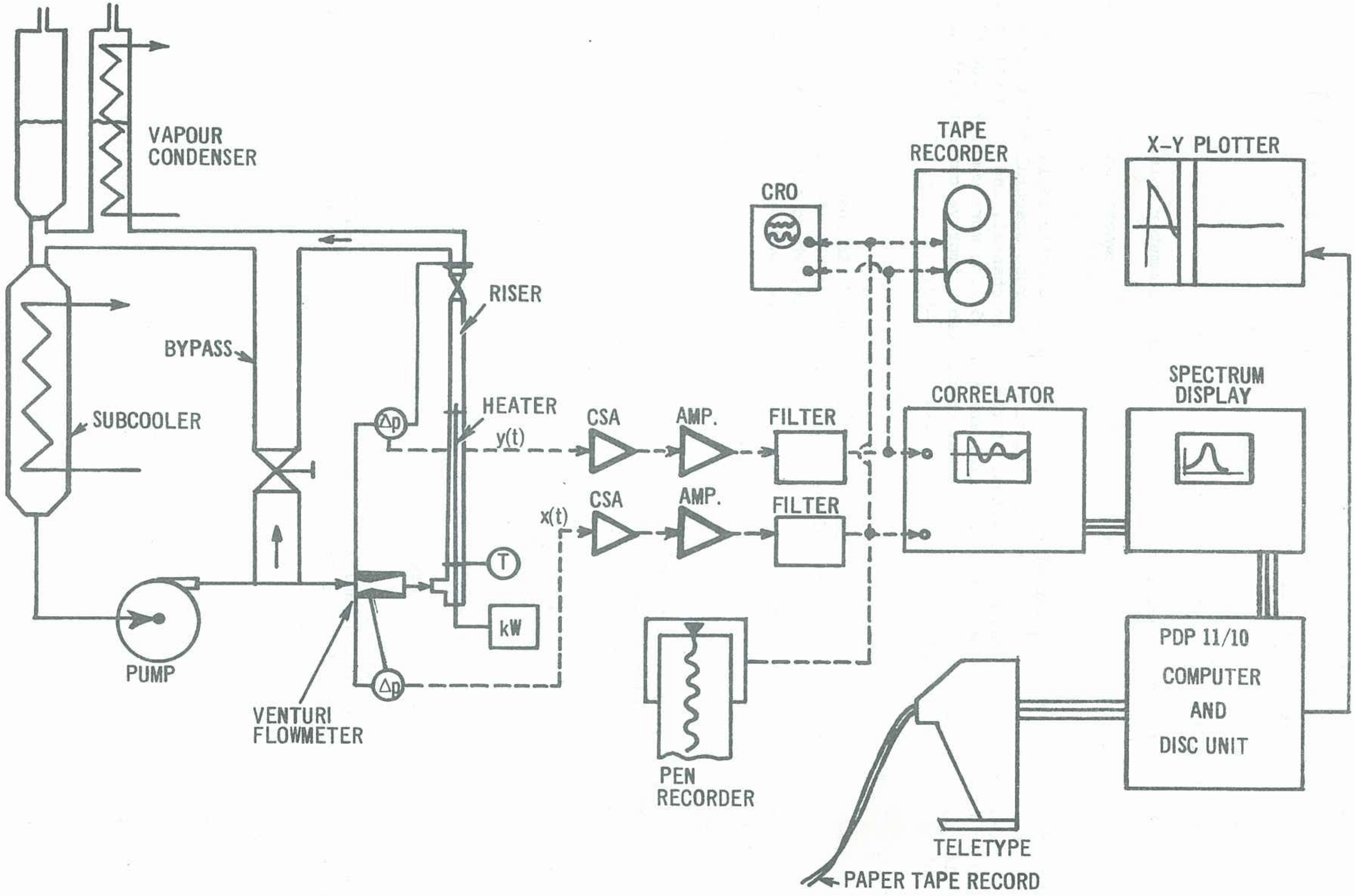

FIGURE 1 SCHEMATIC DIAGRAM OF TEST RIG AND ANALYSIS EQUIPMENT

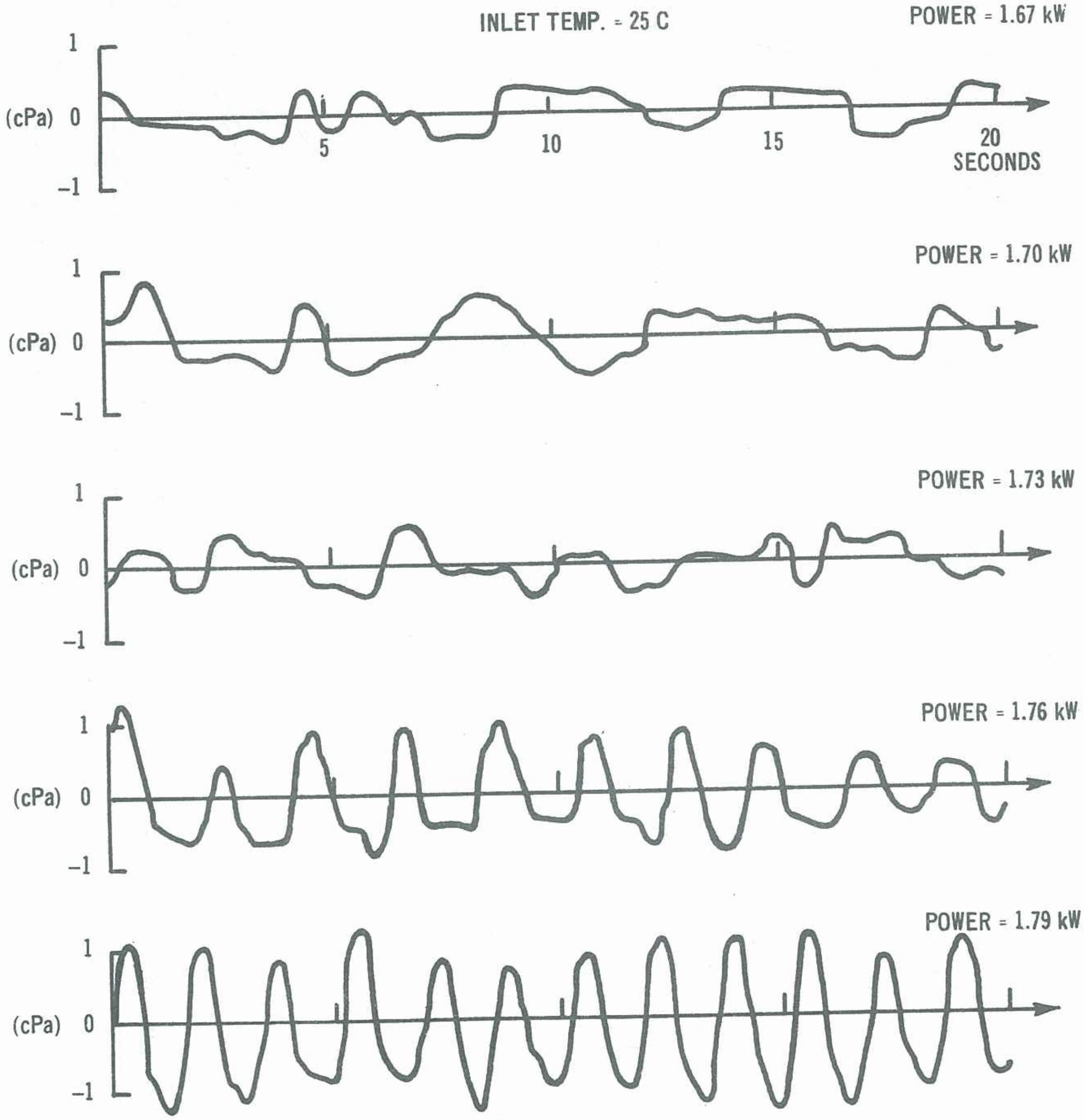

FIGURE 2 VISUAL RECORD OF CHANNEL INLET FLOWMETER NOISE

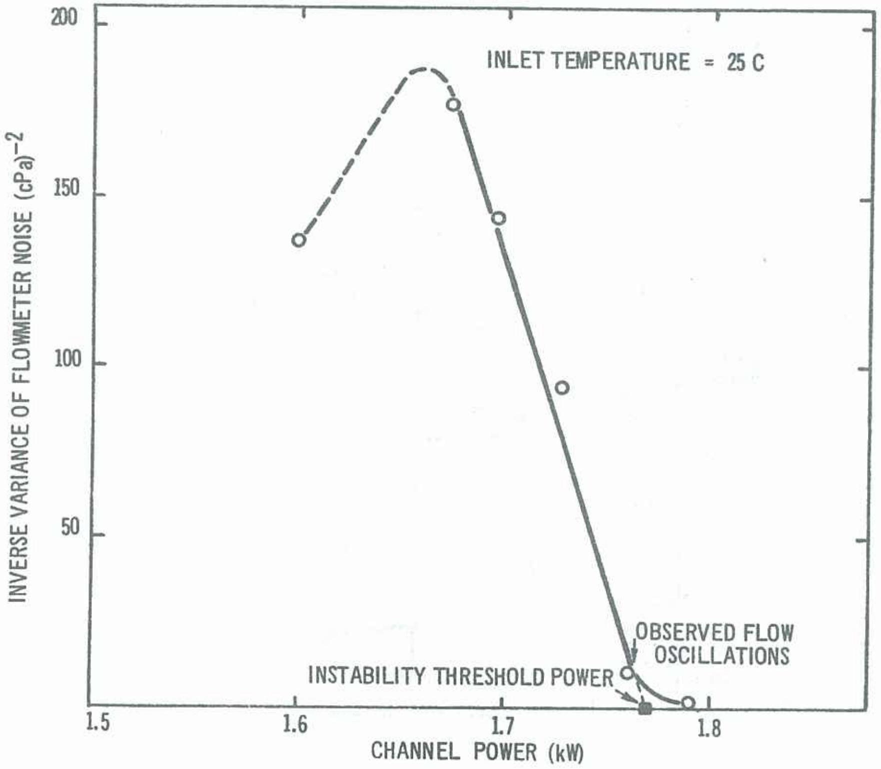

FIGURE 3 INVERSE VARIANCE OF FLOWMETER NOISE VERSUS CHANNEL POWER MAP

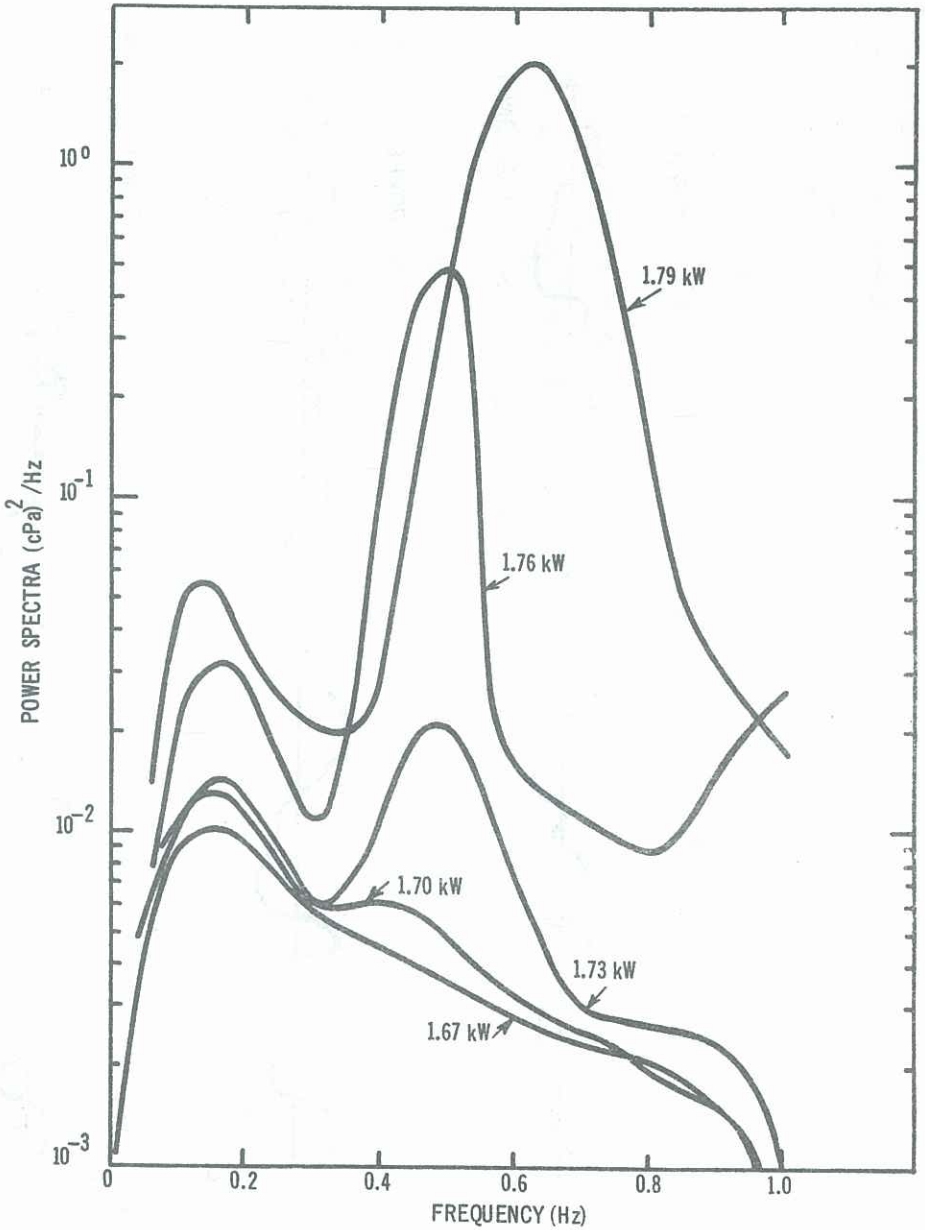

FIGURE 4 POWER SPECTRA OF FLOWMETER NOISE AT VARIOUS CHANNEL POWER LEVELS

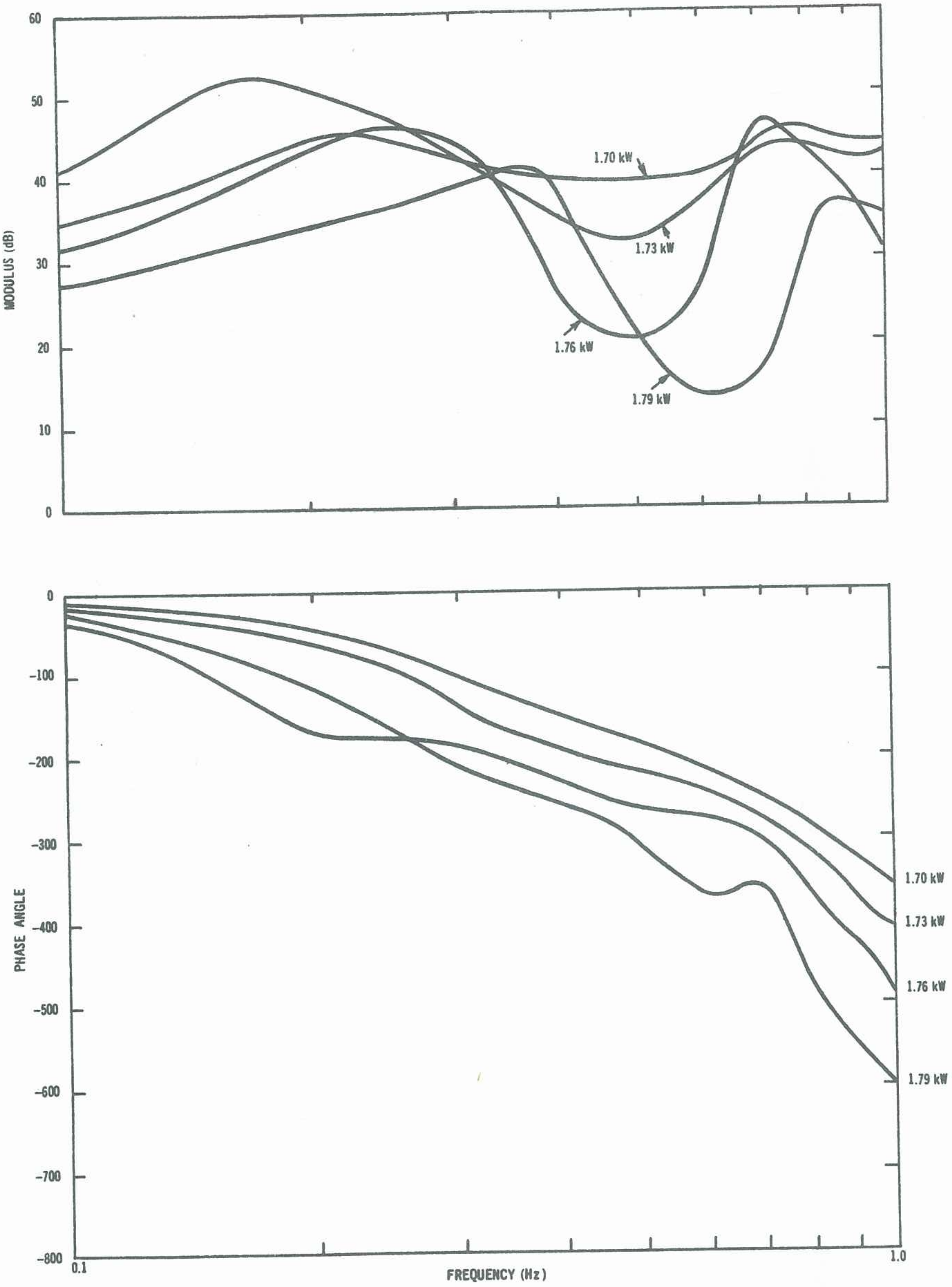

FIGURE 5 CHANNEL FLOW-PRESSURE DROP TRANSFER FUNCTION ESTIMATES AT VARIOUS POWER LEVELS