ANNUAL LETTER REPORT FOR FY 89

"Feedback Control of Combustion Instabilities: A Case Study in Active Adaptive Control of Complex Physical Systems"

Contract # N00014-89-C-0052

GE Research & Development Center
Schenectady, NY 12301

Period of Report: 1 Mar. 1989 - 30 Sept. 1989

Feedback Control of .... Complex Physical Systems
N00014-89-C-0052
Anil Gulati & George C. Goodman
GE Research & Development Center

The technical objectives of the program are:

- Study active control of combustion instability in a laboratory scale combustor based on fuel flow modulation or an alternative practical means of actuation.
- Develop a model of the plant taking into account the complex physical mechanisms responsible for screech in a liquid-fueled combustor to help design a robust controller. The model should also account for possible interactions between the controller and the plant.
- Design a controller to suppress screech based on open-loop frequency response data. Implement the controller and demonstrate active control of screech based on liquid fuel flow modulation. Determine the range of application of the controller in terms of flow rates and equivalence ratios.
- Assess feasibility of nonadaptive, scheduled and adaptive control strategies to design a robust controller to achieve full-envelope control of combustion instability. Develop a general design process applicable to a practical combustor operating over a wide range of input conditions. Identify promising approaches, select candidate strategies for implementation and test these on the existing combustor.
- Explore extension of active control to suppress transverse mode high frequency oscillations expected in afterburner screech. Identify performance limits of commercially available hardware and explore alternative means of actuation.

Technical approach:

A currently available premixed gas combustor will be modified to include liquid fuel capabilities. The combustor will be used to support longitudinal combustion instability modes of relatively low frequency. The screech map of the combustor will be developed in terms of the air flow and fuel flow rates. A fast reponse servo control valve will be used to modulate the fuel flow, though alternative means of actuation will also be explored. A physical model currently being used to study combustion instability and its suppression by loudspeaker based active control means in a gas premixed combustor will be extended to account for liquid fuel preparation dynamics including injection, entrainment, and mixing and the associated phase lag. The model includes a conventional "n-tau" model to account for interaction between unsteady heat release and velocity fluctuations and allows for possible interactions between the controller and the physical plant.

The design of the controller will draw upon the experience gained in designing a controller for the loudspeaker based active control system. An open-loop frequency response of the plant will be obtained at an operating point close to screech and the poles corresponding to the instability will be identified. These poles will than be assumed to be reflected about the imaginary axis to produce an unstable model suitable for control design. Classical theory and modern LQG/LTR techniques will be used to design the controller. Once the controller is implemented its range of operation will be determined by extensive experiments. To extend the range of the controller over full-envelope operation two alternative approaches will be pursued. The first approach will be based upon operating the controller at the fringe of its stability region and using system identification techniques to empirically obtain a proces model to use in the design of the next controller. A series of such controllers will be developed to cover the full operating range. A suitable measured parameter will then be used to schedule these several controllers. Alternatively, adaptive control techniques for on-line process identification and controller design will also be pursued. Either of these approaches may also make use of the physical model described above.

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The most significant accomplishments for this year are as follows:

1. Modified an existing laboratory scale premixed gas combustor to obtain longitudinal combustion oscillations with liquid fuel. Obtained screech map of the combustor.
2. Obtained and installed servo control valve for fuel flow modulation. Obtained detailed frequency reponse of the servo control valve and its associated control circuitry.
3. Obtained open-loop frequency response data of the stable plant for the design of a controller.

A 3"x3" premixed gas combustor available from an earlier study was modified to include liquid fuel capabilities as shown in Fig. 1 by adding (1) an electric pre-heater in the inlet section to preheat air at temperatures up to 600 °F, and (2) a fuel pump capable of delivering 0.5 gpm of kerosene at up to 3000 psi. A fast response Moog servo control valve has also been installed for regulating the liquid fuel flow and modulating it in real time for active control. Various axial locations upstream of the flameholder are available for fuel injection via a conventional burner nozzle which acts as a point source. For a given air flow it was found that the combustor resulted in significant oscillations over a wide range of equivalence ratios near stoichiometric. Figure 2 shows a typical power spectrum obtained during screech by recording the dynamic pressure just upstream of the flameholder. The spectrum shows a dominant frequency at 109 Hz corresponding to a longitudinal quarter-wave instability mode. This shows that the active control system comprising the sensor, controller and the actuator should have an overall bandwidth of 250 Hz or higher. Our past experience suggests that conventionally available sensors have a much higher bandwidth and it is fairly straightforward to design a controller with frequency response of up to 5 kHz. We believe, therefore, that the frequency response of the actuator may be the limiting factor in the design of the control system.

To determine the bandwidth limitations of the actuating devices readily available for liquid fuel modulation, a fast response Moog control valve was acquired. Figure 3 shows a frequency response obtained across the servo control valve and its associated control circuitry. As the figure shows, the valve has a relatively flat response up to 30 Hz which then starts falling rapidly and is lower by about 12 dB at 100 Hz and another 10 dB at 200 Hz. Even though local feedback control could improve the response of the valve by extending the crossover point somewhat it is clear that the valve is unable to modulate the fuel flow in a significant manner above 250 Hz. The valve, therefore, is seen to have marginally adequate response characteristics for this study. Alternative means of actuation also need to be explored.

There are two alternative approaches to designing a controller for suppressing the oscillations shown in the power spectrum of Fig. 2. One is to obtain a rigorous physical model of the complex unsteady combustion-acoustic interactions in the combustor and design a controller based on such a parametric representation. To do this a currently available model will be extended to include liquid fuel preparation dynamics and the associated time lags. An alternative approach is to base the controller design on standard numerical identification techniques applied to open-loop transfer function data obtained in the combustor. Fig. 4 shows such a frequency response (between the input to the servo control valve and the sensor in the combustor) obtained at a stable operating point of the combustor just below its screech limit. The frequency response data shows the existence of a stable pole pair at the dominant frequency corresponding to the instability. By reflecting that pole pair through the imaginary axis into the right half-plane, we can obtain an unstable model suitable for control design. Work is currently in progress to design such a controller and implement it in the control system.

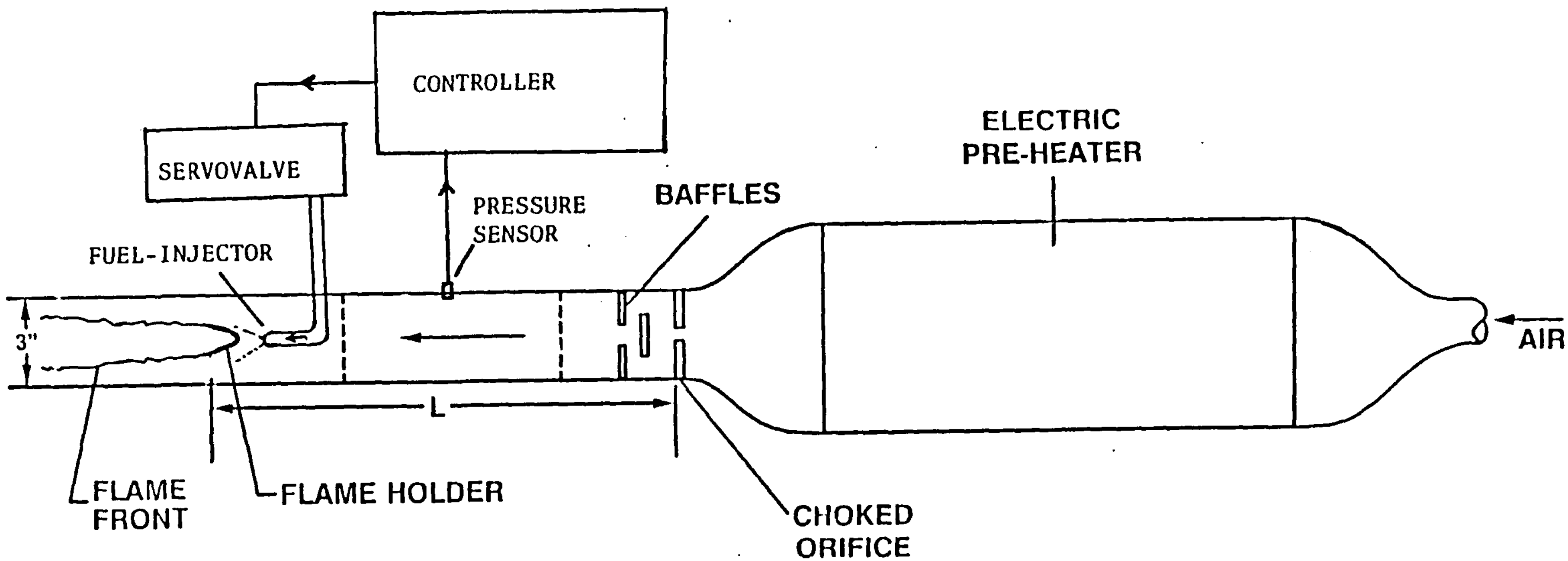
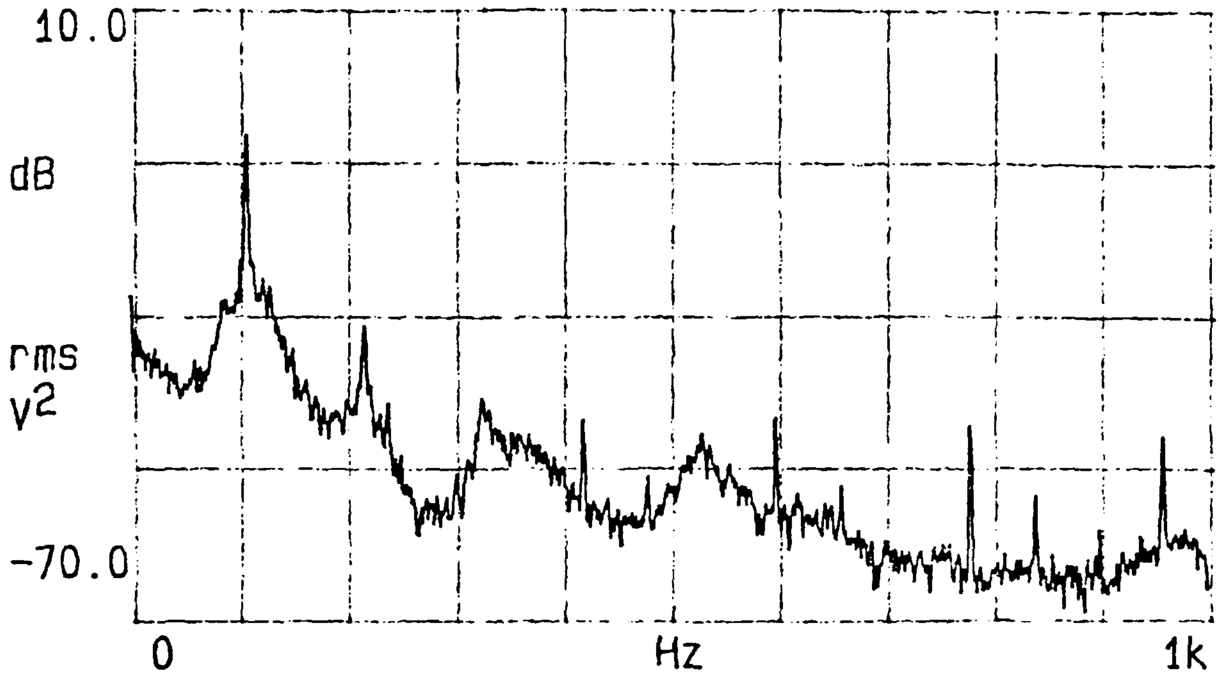


Fig. 1. Schematic of Combustor with Active Control System.



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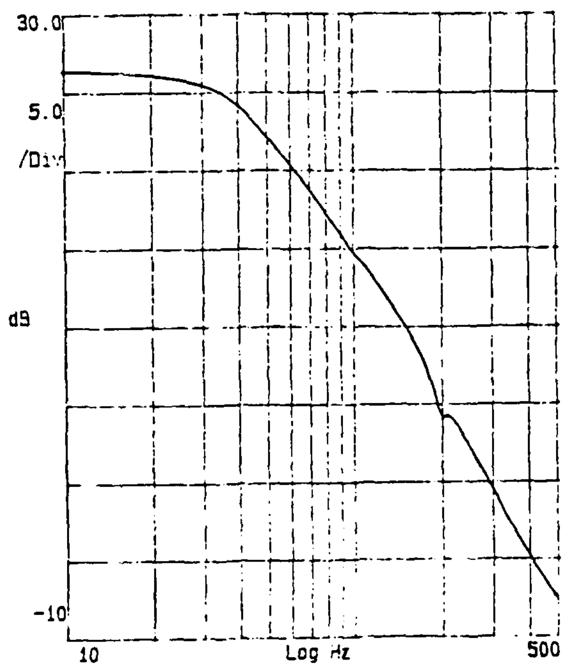

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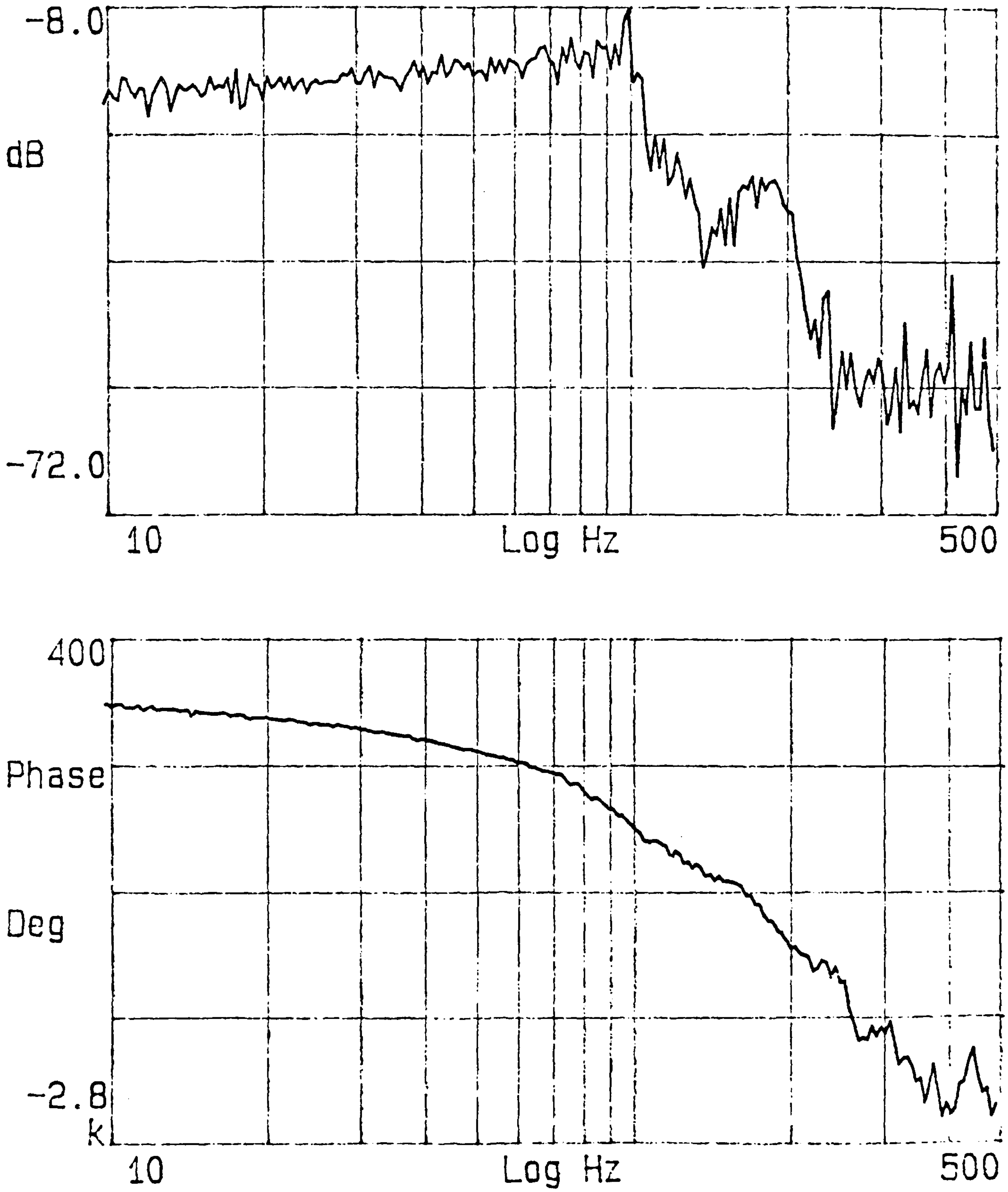

Fig. 4. Measured Frequency Response of the Combustor and Servocontrol Valve obtained at an operating Point below the Screech Limit.

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Progress During FY'89 on a Related Project

Significant progress was made during the past year in increasing our understanding of combustion instability and its active control using a loudspeaker based on our study of a small 2"x2" gas premixed combustor as part of a related project. The following were the main accomplishments related to an improved model and an improved controller design:

- An active control system based on a simple constant gain controller of the type used by Candel et. al. was successfully implemented in a premixed gas combustor to suppress combustion-induced oscillations using a loudspeaker. It was, however, found that the constant gain controller had a limited range of application in terms of the flowrate through the combustor and the equivalence ratio. The active control system was found effective in suppressing screech only up to approximately 300 cc/sec of total flow and up to 0.7 equivalence ratio at that flowrate. The controller was also found to have a much narrower range of phase margin for successful control than expected.

- The combustor was found to have a very rich power spectrum which varied considerably as the flowrate and the equivalence ratio were varied. For some conditions the measured power spectra had numerous peaks adjacent to each other. It was also found that under some conditions as the controller gain was increased the dominant frequency of instability would correpondingly decrease significantly but an alternate mode/instability would get excited resulting in reduced effectiveness of the controller. This also suggested that the controller interacted significantly with the plant.

- A physical model of the combustion instability and its active control was developed based on an extension of the model used by Candel et. al.. A more detailed study of the model showed that it indeed predicted a narrower stability curve in terms of the allowable phase margin as observed in the experiment. The model showed that this is probably due to the controller interacting with the plant because in some cases it was found that as the controller gain was increased the dominant instability mode would be suppressed but in the process a formerly stable mode would get excited rendering it unstable. The model also showed that when the length of the combustor was cut in half (from 19" to 9.5") the dominant screech mode changed from the second mode to the first. This explains why in the shorter combustor the dominant screech frequency increased by only 20%. Finally, the model was extended to allow for observed axial variation of temperature in the downstream half of the combustor due to heat loss. Significant confidence in the physical model has been developed by showing that it correctly predicts most of the trends regarding the performance of the controller and its interaction with the plant. Work is in progress to refine the model even further.

- A series of controllers were designed and implemented successfully to significantly improve the performance of the constant gain controller in terms of extending its effective range over wider inlet conditions and improving its performance throughout the effective range. The effective range of successful application of the controller was increased in terms of the equivalence ratio to 0.8 at a flowrate of 330 cc/sec. The improved controller was obtained by using classical, frequency domain design techniques as well as modern system identification and LQG/LTR design techniques, applied to the open-loop frequency response data obtained after stabilizing the system with the constant gain controller. The hierarchy of the controllers implemented was: (a) original constant gain controller, (b) controller incorporating an eighth order Butterworth filter, (c) controller with notch filter, and (d) eighteenth-order, LQG/LTR controller based on parametric representation of the transfer function of the plant. A generalized process to design a robust controller by bootstrapping controllers effective over overlapping regions of flow conditions has been identified and will be implemented shortly.

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George C. Goodman	Control Systems Engineer
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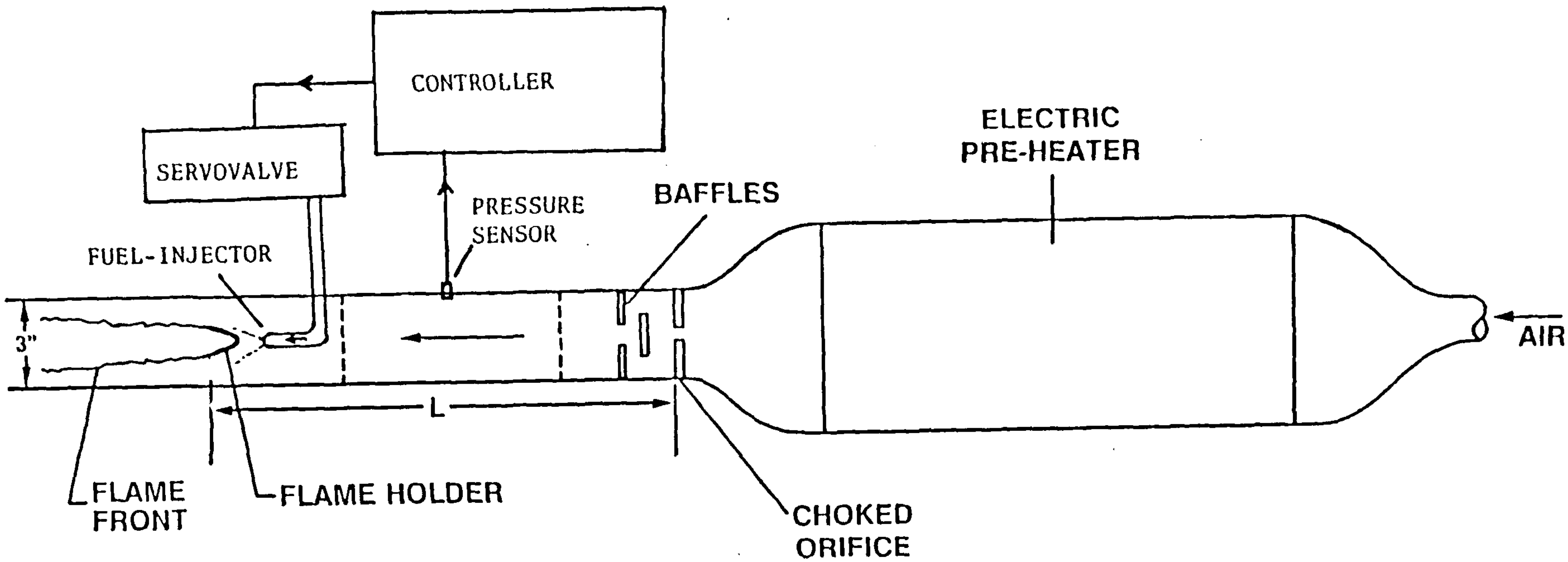

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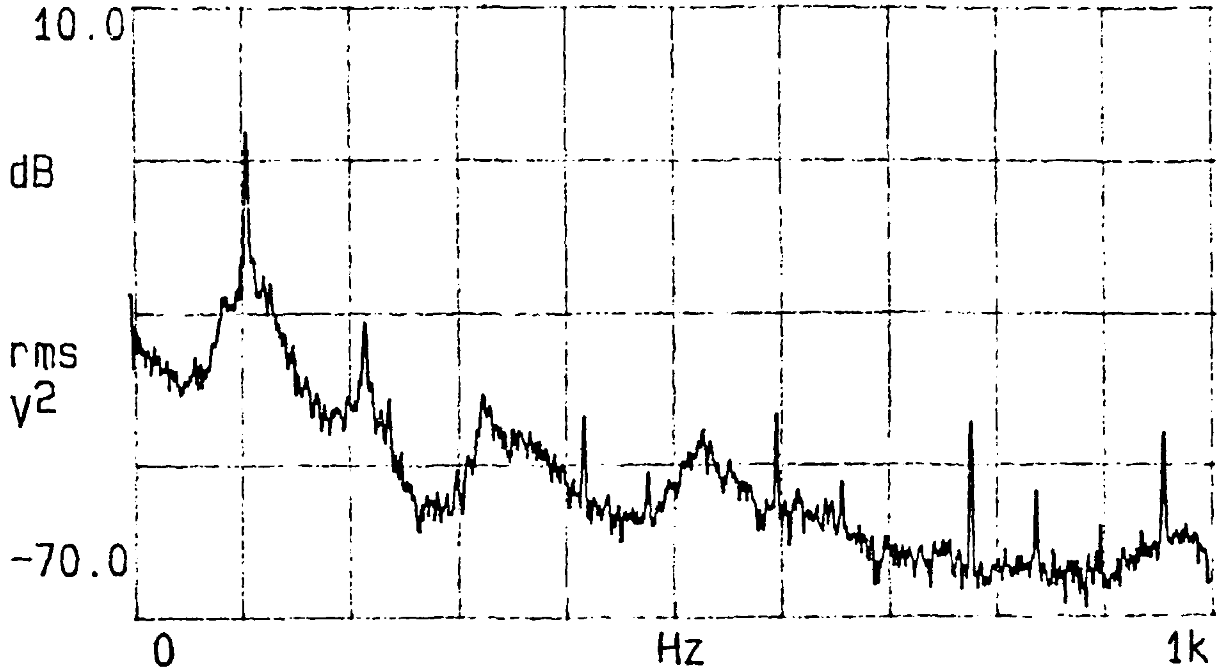

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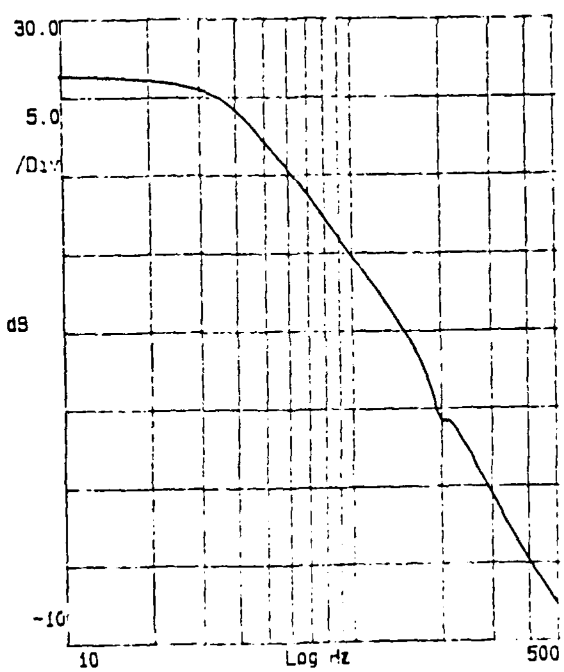

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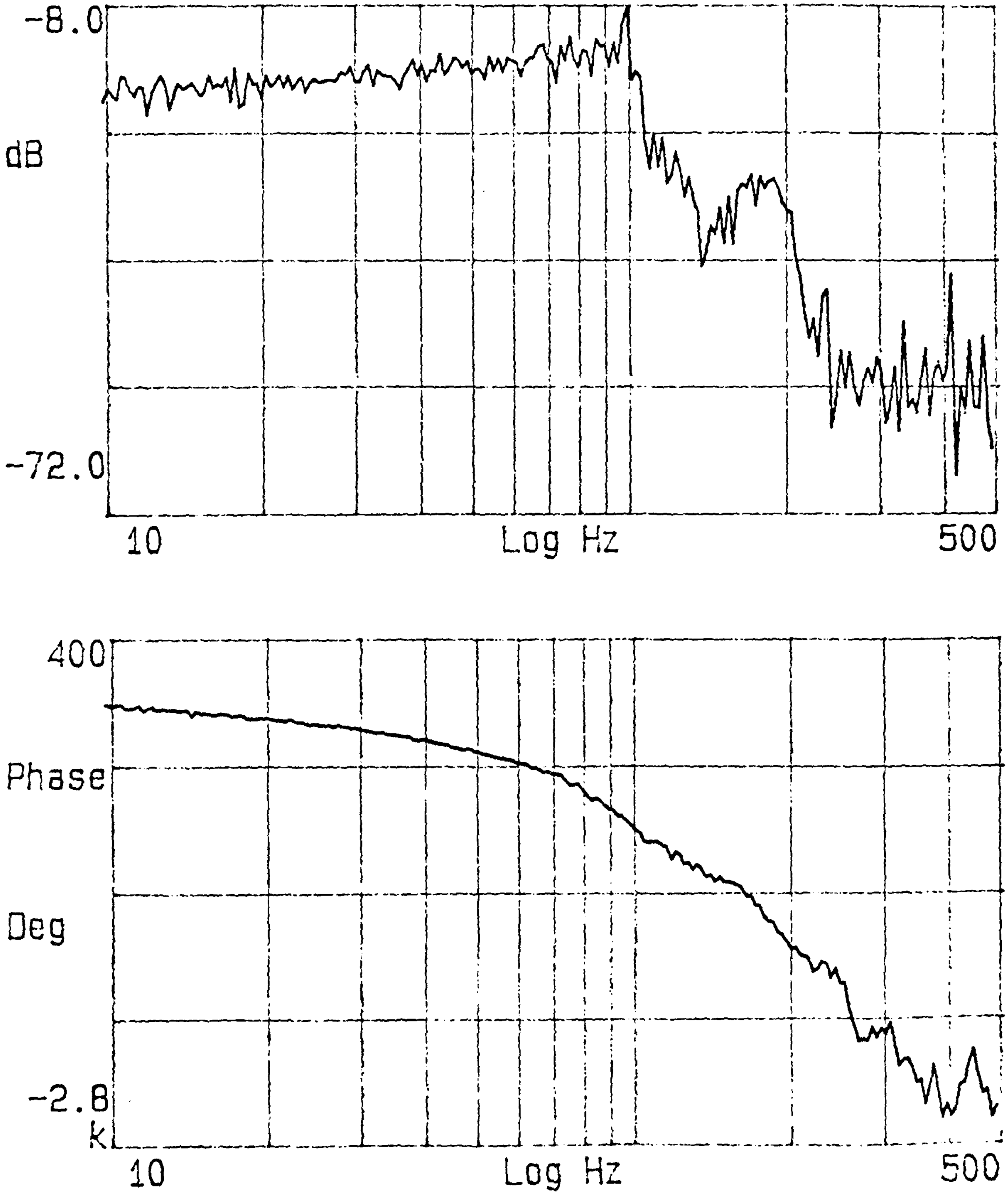

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