SPLIT-STIRLING-CYCLE DISPLACER LINEAR-ELECTRIC DRIVE

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ABSTRACT

The retrofit of a 1/4-W split-Stirling cooler with a linear drive on the displacer was achieved and its performance characterized. The objective of this work was to demonstrate that a small linear motor could be designed to meet the existing envelope specifications of the cooler and that an electric linear drive on the displacer could improve the cooler's reliability and performance. The paper describes the characteristics of this motor and presents cooler test results.

INTRODUCTION

A recent in-house program at Mechanical Technology Incorporated (MTI) was directed toward retrofitting a 1/4-W split-Stirling-cooler displacer with a linear-electric drive. The cooler was supplied to MTI by the U.S. Army Chemical Systems Laboratory and the Honeywell Corporation with the objective of demonstrating the feasibility of adding a linear drive to the cooler. The in-house program involved:

- Designing a small linear motor to fit into the displacer bounce space
- Integrating the motor with the displacer
- Developing the control circuitry and logic to control displacer motion
- Testing the displacer with a standard 1/4-W cooler compressor.

COOLER DESCRIPTION

The 1/4-W split-Stirling cooler (Figure 1) was developed at the Night Vision Electro-Optics Laboratory. The retrofit to the cooler was made by adding a linear-electric drive to the displacer. The drive was designed to be added without changing the thermodynamics of the cooler, and to use all existing hardware. To achieve this, the linear drive was added to the displacer bounce space and attached to the displacer rod.

A layout of the retrofitted displacer is shown in Figure 2. This retrofit was assembled with existing components (shown to the left of line A-A) and the linear drive components (shown to the right of A-A). The drive components consist of a permanent-magnet linear motor, a housing, and a displacer rod connection. The linear motor has a radially energized, moving permanent-magnet plunger (which is attached to the displacer), and a laminated stator containing several circular coils. The housing, which provides a hermetic case for the motor, was designed for effective cooling of the motor, and to provide a rear bearing for radial support of the plunger.

In this retrofitted design, the motor was used to control the displacer motion by monitoring the pressure wave and triggering the displacer motion from this control parameter. The flexibility of the control scheme is shown in Figure 3. Control consisted of the ability to vary the phasing between the pressure wave and displacer motion (ϕ_d), the duration between intake and exhaust strokes (ψ_d), pulse width (τ), and the amplitude of the displacer forcing function (I_m). Through these four parameters, the effect of displacer phasing and motion on cooler performance can be evaluated. The control circuit (Figure 4) consisted of a pressure transducer mounted at the compressor outlet, the phasing circuitry, and a motor power supply.

MOTOR CHARACTERISTICS

The retrofit displacer motor is one of a family of permanent-magnet ($SmCo_5$) linear motors under development at MTI*. Figure 5 schematically shows a section of the motor with the plunger in the center position. The motor consists of stationary outer electrical coils wound on a steel bobbin and an inner permanent-magnet plunger. The magnets are radially magnetized with alternate magnets having north polarity on the outside diameter and south polarity on the inside diameter. The design characteristics for the motor are given below.

Frequency:	25.0 Hz
Stroke:	1.9 mm (0.075 in.)
Size:	25-mm dia x 25-mm long (1 in. x 1 in.)
Weight:	0.07 kg (0.15 lb_m)
Static Force at 0.8 A:	10.2 N (2.3 lb_f)
Electrical Input Power:	<3.0 W

RESULTS OF MOTOR BENCH TESTING

STATIC RESPONSE TEST RESULTS

As a first step in characterizing the performance of the MTI displacer linear motor, static force tests were conducted. The purpose of these tests was to determine available static force capability of the motor as a function of input current and plunger position. This information is particularly relevant to the operation of the motor to overcome friction effects as cooler wear and contamination progress.

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*Bhate, S.K., "Linear-Oscillating Electric Machine with Permanent-Magnetic Excitation," U.S. Patent: 4,349,757, September 14, 1982, assigned to MTI, Latham, New York.

These tests were conducted with the apparatus shown in Figure 6. With this apparatus, the motor force is measured with a piezoelectric force transducer as a function of displacement measured with an LVDT and motor current. A plot of the motor force is given in Figure 7 for currents up to 1.6 A. An important characteristic defined by the force plot is the extraordinary force capability of this miniature motor. The motor can produce several pounds of force throughout the required stroke range, which is more than adequate to control the motion of the displacer.

DYNAMIC RESPONSE TEST RESULTS

A displacement test apparatus was used to measure the dynamic response of the motor to an alternating step-current input. This type of test is important because it determines the ability of the motor to quickly travel from one extreme stroke position to another. The data also provide the controls design team with dynamic response information necessary for the establishment of control system time constants and parameters. Figure 8 is a sketch of oscilloscope traces of a typical dynamic motor response test at 25 Hz. The plunger travels the stroke of 1.7 mm (0.065 in.) in approximately 3 ms*.

COOLER TEST RESULTS

Retrofitting of the cooler was recently completed. To determine cooler performance, preliminary tests with the following parameters were conducted:

- Operation of the cooler at a reduced stroke of 1.7 mm (0.065 in.) to determine control parameter settings
- Cool-down rate to 80 K
- Motor input power.

The oscillograph tracing presented in Figure 9 shows the system pressure motor current time history. For the run depicted, phasing between the pressure wave and displacer intake motion (positive current pulse) was 10 ms (approximately 48°), pulse width was 2 ms, and current amplitude was 0.8 A. Because of the limited testing conducted to date, sufficient data has not been taken to verify that these are the optimum control settings. However, the cooler did achieve the cool-down specification of 80 K in less than 10 min even at a reduced stroke. It is anticipated that in future testing at a design stroke of 1.9 mm (0.075 in.), the motor will enable the cooler to show a significant improvement over the cool-down specification.

The following analysis presents the motor power for the operating point described.

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*Comparing favorably with a typical travel time of 6-8 ms in a pneumatically driven system.

Assumptions:

I_m - Displacer Motor Current = 0.8 A
R - Motor Coil Resistance = 27 Ω
F_f - Plunger Friction Force = 1.78 N (0.4 lb_f)
Δx - Motor Stroke = 1.7 mm (0.065 in.)
Δt - Plunger Travel Time = 0.002 s
F_A - Acceleration Force = 4.89 N (1.1 lb_f) (Assume $\ddot{x}$ constant over travel)

Peak Motor Power Calculation:

$$
\begin{aligned}
P_{peak} &= \text{Heating Loss} + \text{Friction Loss} + \text{Acceleration Power} \\
&= I_m{}^2 R + (F_f \times \Delta x)/\Delta t + (F_A \times \Delta x)/\Delta t \\
&= (0.8^2 \times 27) + \left[(0.4 + 1.1)\left(\frac{0.065}{0.002} \times \frac{1\ \text{ft}}{12\ \text{in.}} \times \frac{1\ \text{W}}{0.74\ \text{ft-lb}_f/\text{sec}}\right)\right] \\
&= (0.8^2 \times 27) + [(0.4 + 1.1)(3.67)] = 17.3 + 5.5 = 22.8\ \text{W}
\end{aligned}
$$

Average Motor Power Calculation:

$$P_{avg} = P_{peak} \times \text{Duty Cycle}^{*} = (22.8\ \text{W})(0.13) = 3.0\ \text{W}$$

This analysis shows that because the duty cycle is low, average displacer motor power is approximately 3 W (about 10%) of the total power consumed by a typical 1/4-W cooler system. Ongoing tests indicate that further reduction in the power required to drive the displacer will be achieved by implementation of optimum control parameters. A displacer motor power reduction to less than 2 W in this prototype, and to approximately 1 W in an advanced design that eliminates the frictional rear bearing, is anticipated. Further, the flexibility gained in displacer control should lead to performance improvements through better selection of regenerator materials (now limited by displacer dynamics), displacer motion control, vibration elimination, and stroke modulation.

CONCLUSION

The conclusion reached from this work is that a small linear electric displacer drive can be developed for the 1/4 W split-Stirling cooler that will fit into the present cooler envelope. The benefits that will be gained from a linear drive are improvements in performance and reliability. Future work at MTI will be directed towards advancing the state of the art of linear coolers by building a linear drive compressor and coupling it with our retrofitted expander to demonstrate the feasibility of a total linear split-Stirling cooler.

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*Calculated from Figure 9.

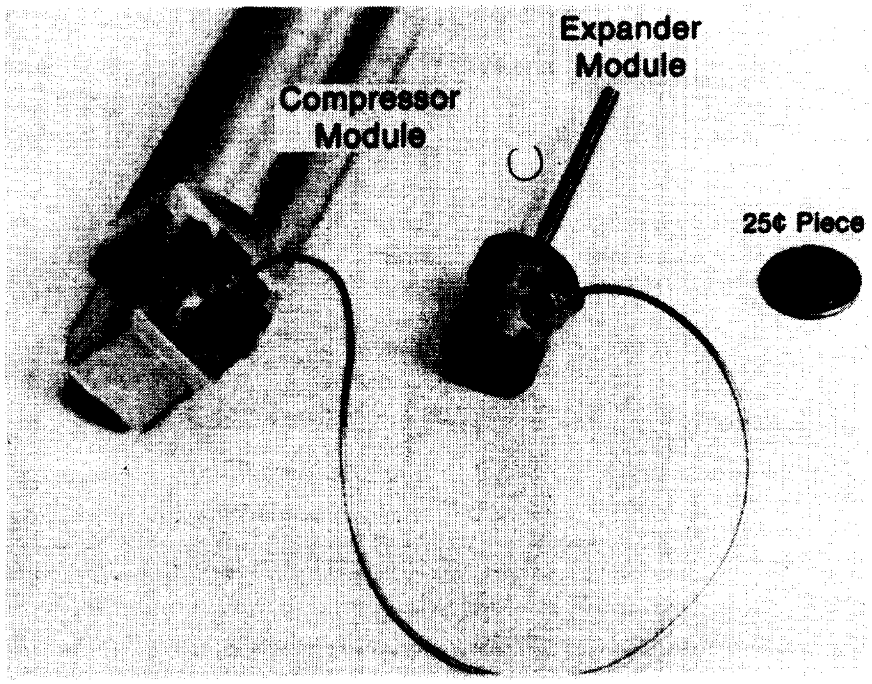

Figure 1 1/4-Watt Split-Stirling Cooler

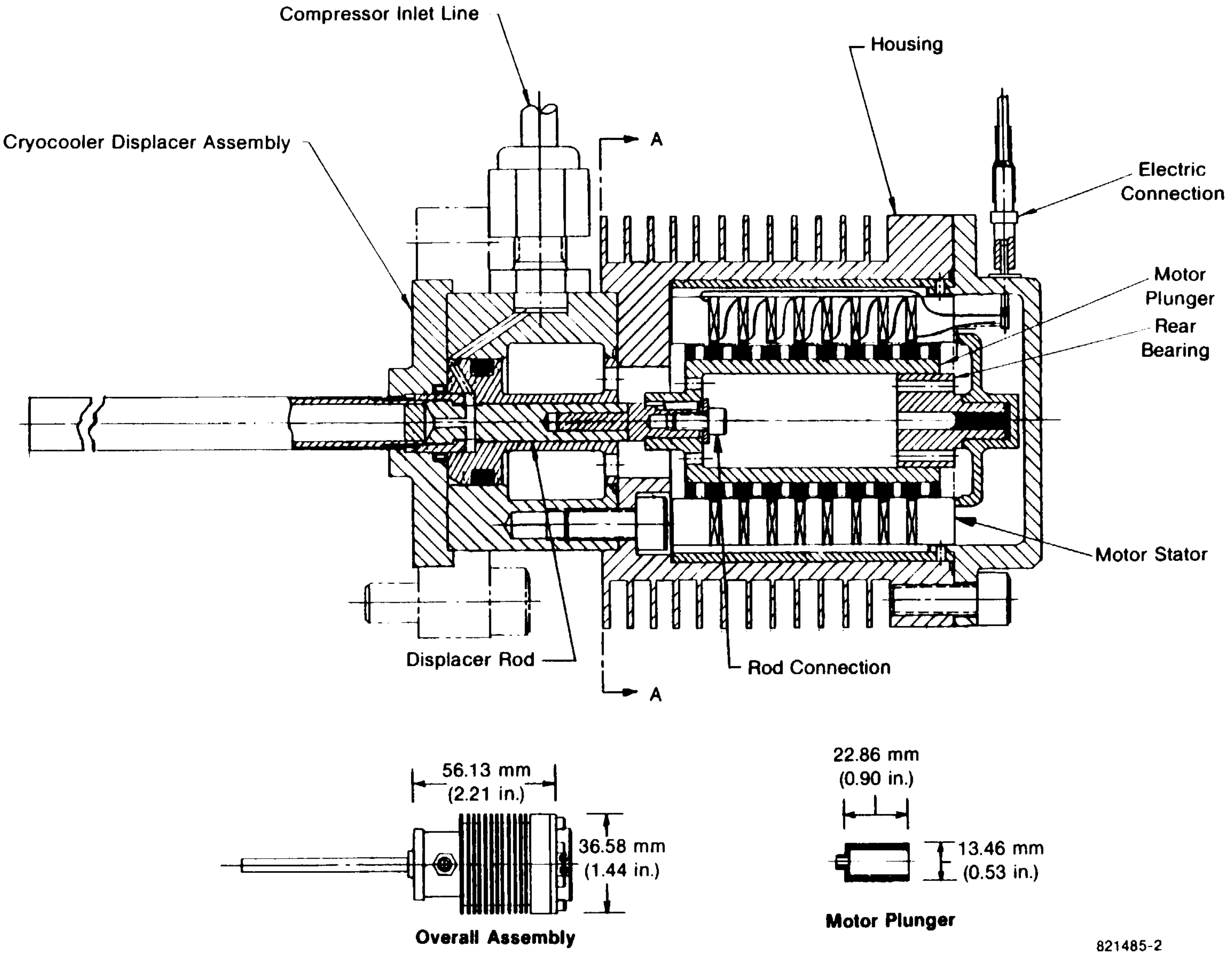

Figure 2 1/4-Watt Retrofit Cooler Displacer Design

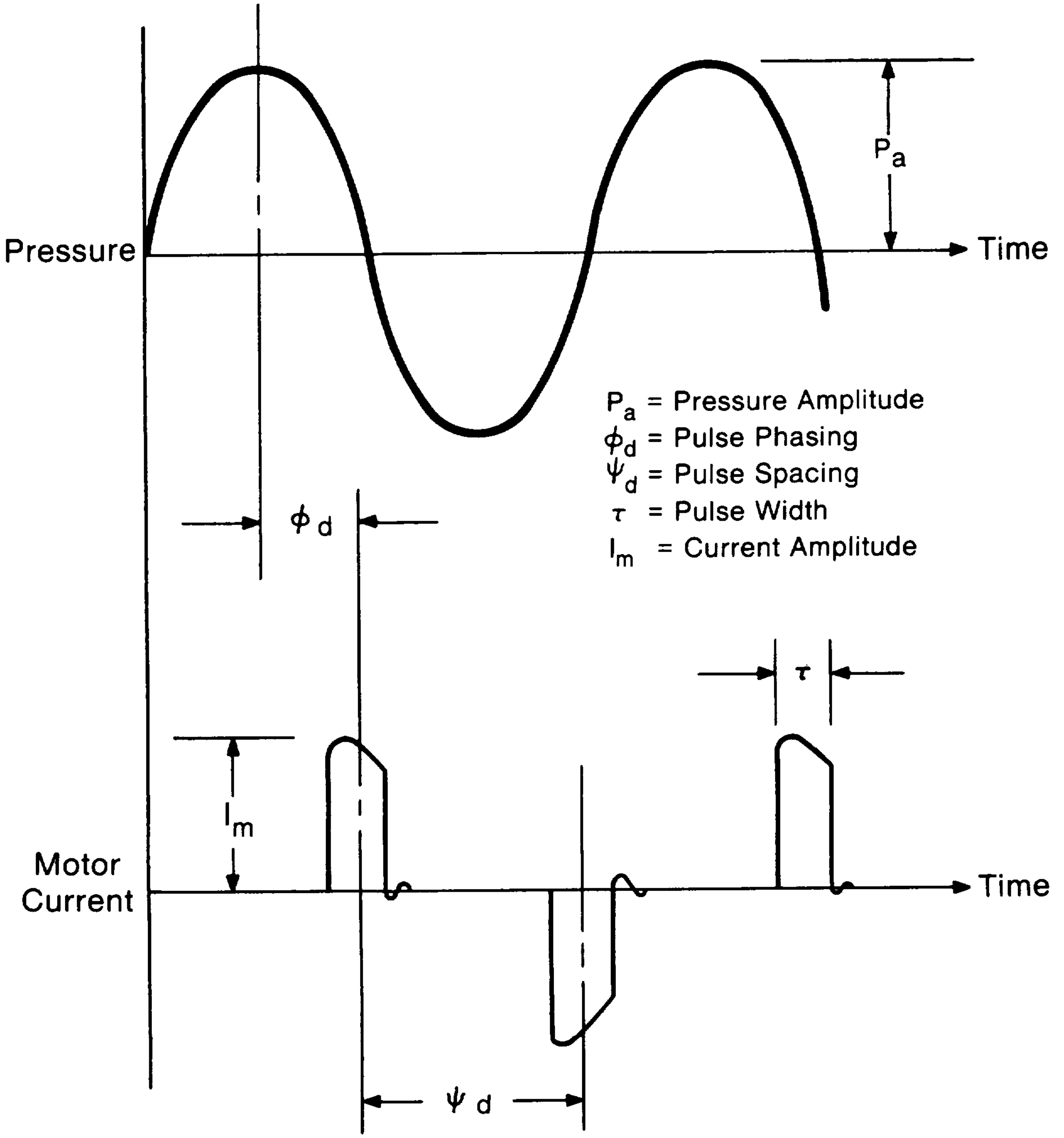

Figure 3 Displacer Motor Current Control Variables

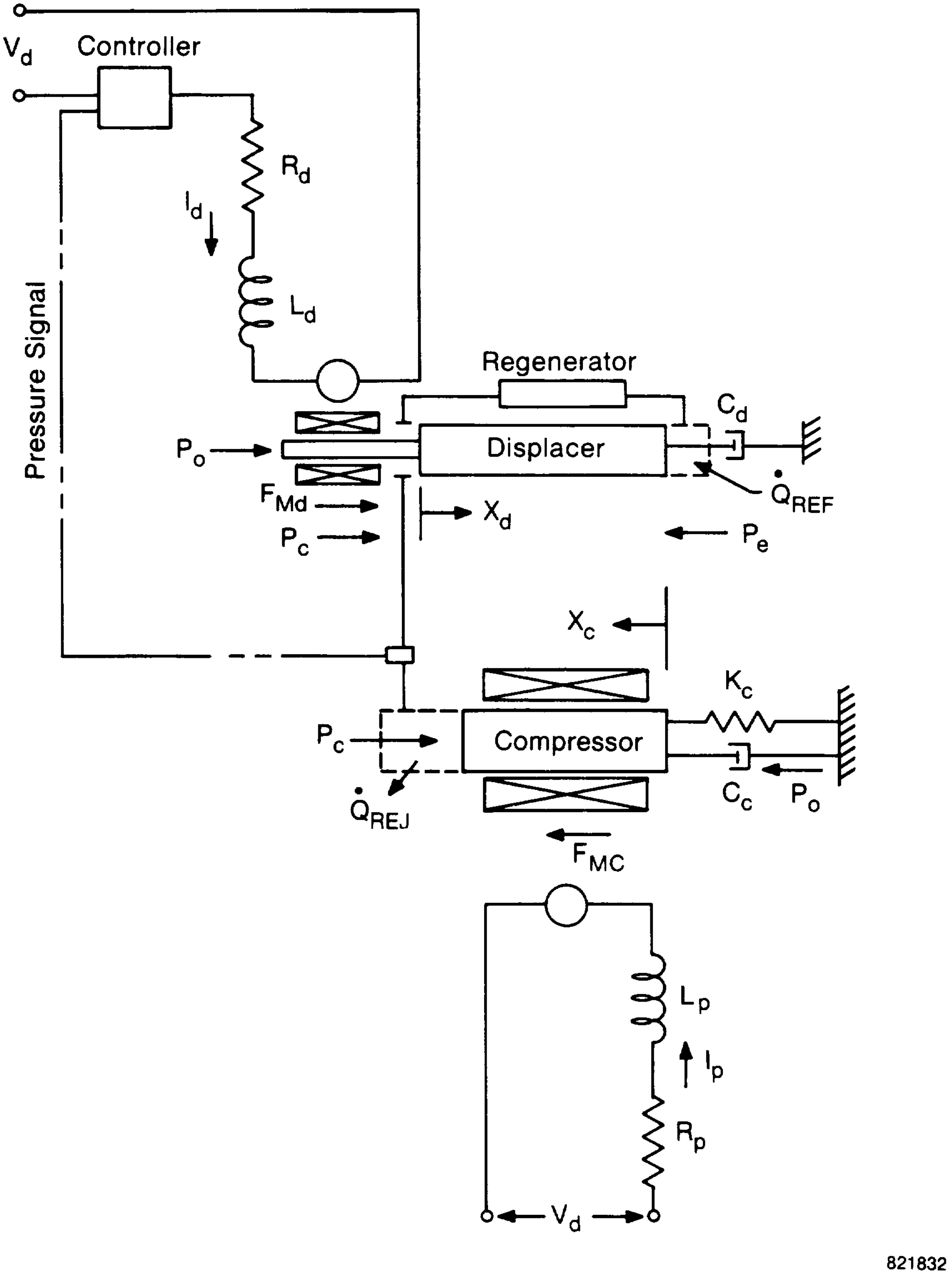

Figure 4 Linear Cryogenic Refrigerator with Pressure Control

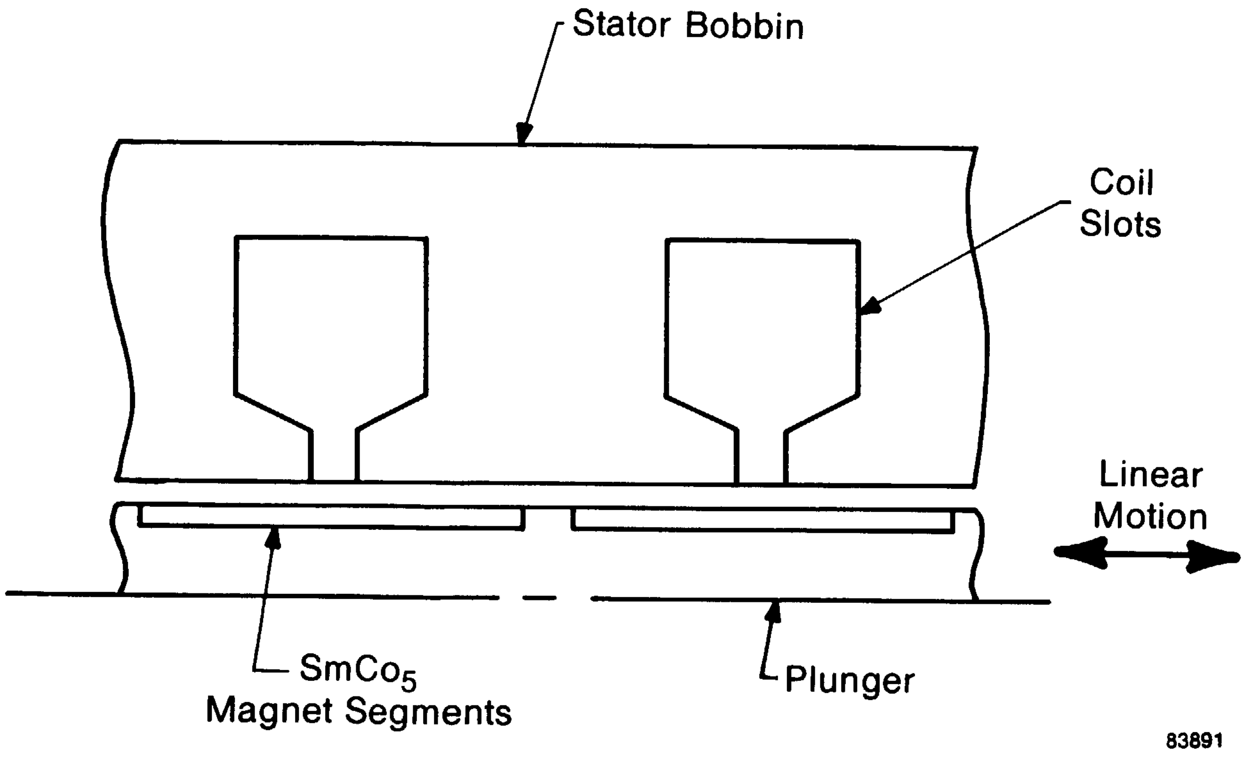

Figure 5 Schematic of Permanent Magnet Motor

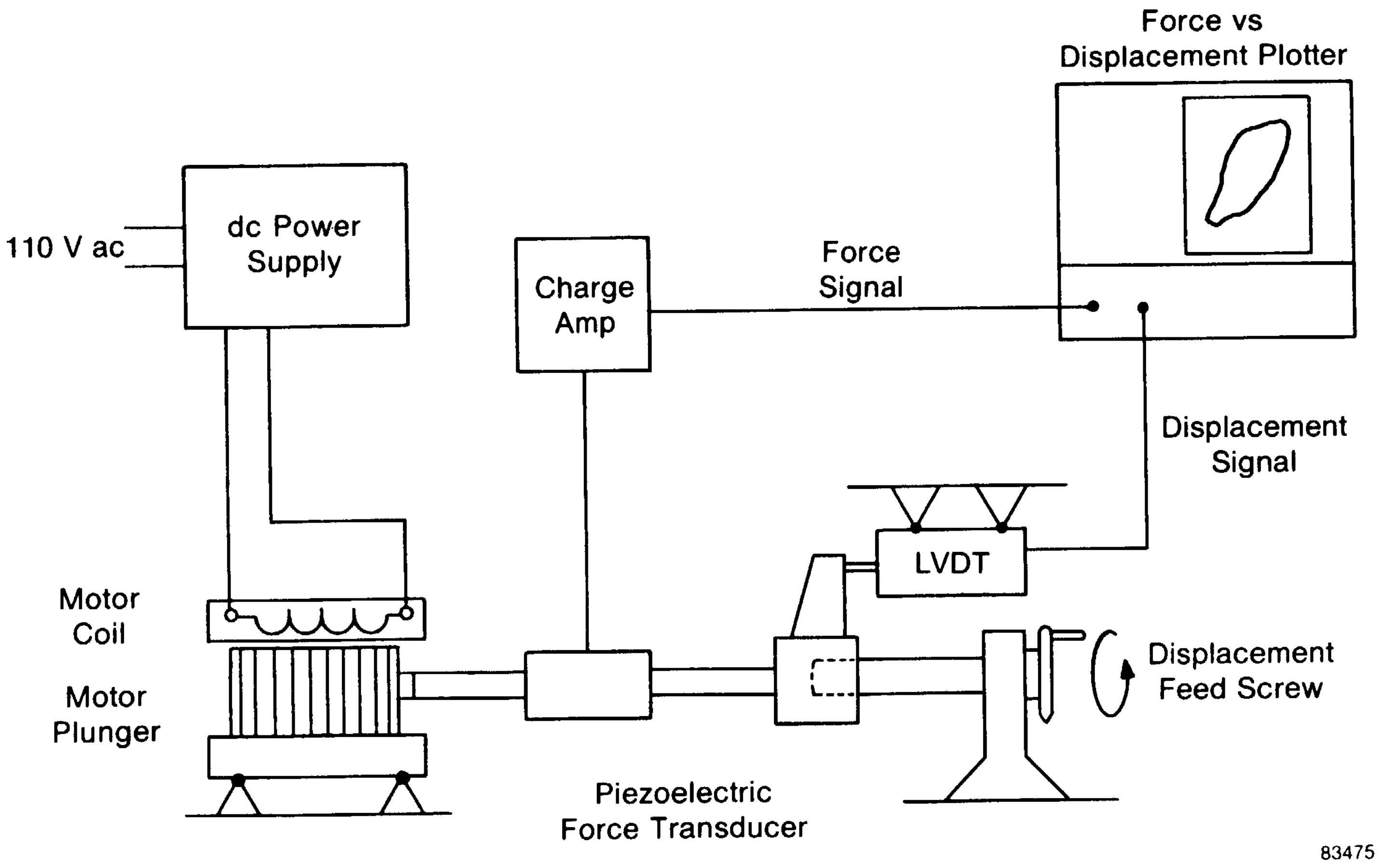

Figure 6 Displacer Motor Static Force vs Displacement Test Setup

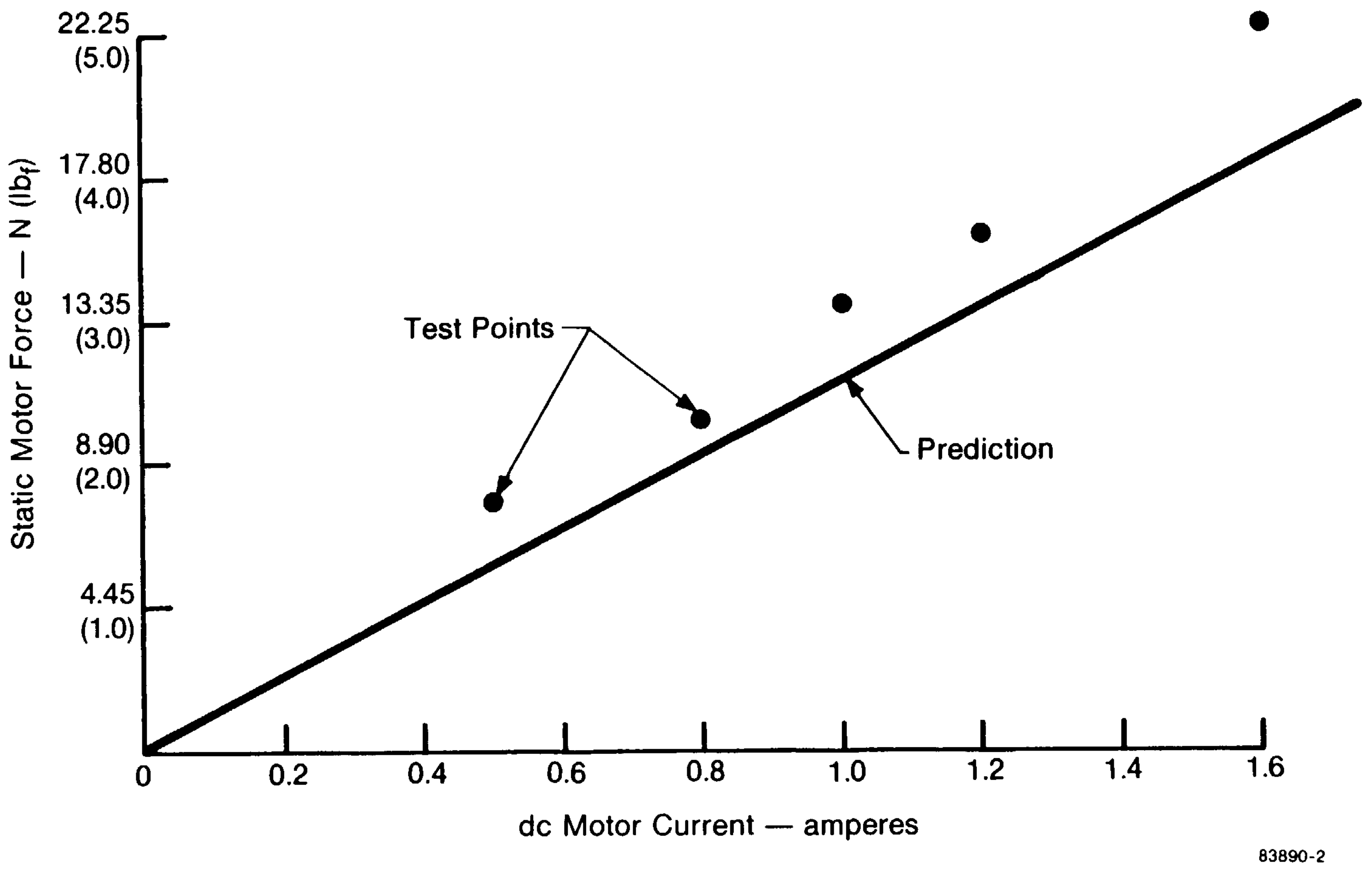

Figure 7 Comparison of Displacer Motor Test Data with Predictions

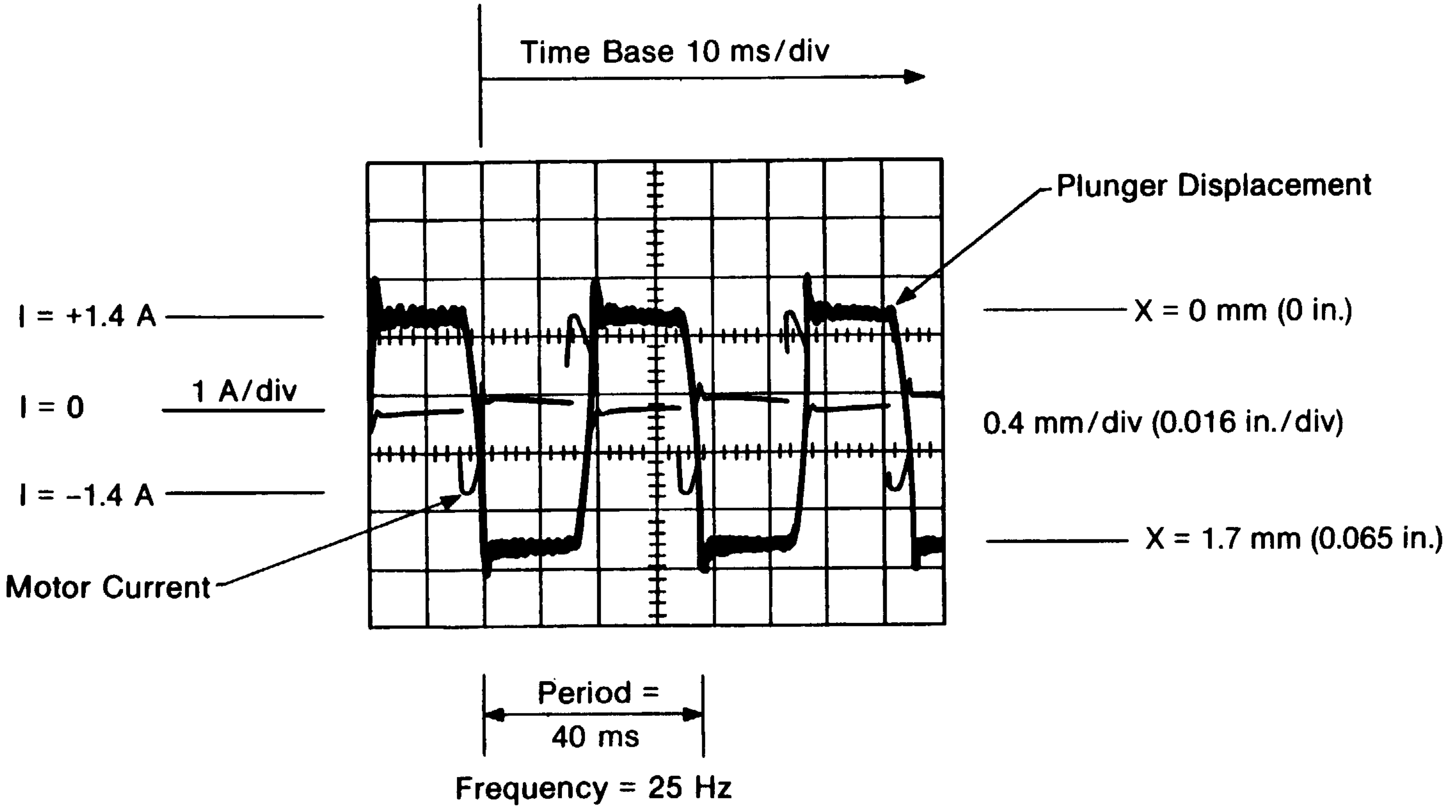

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Figure 8 25-Hz Operation of Split-Stirling Displacer Motor

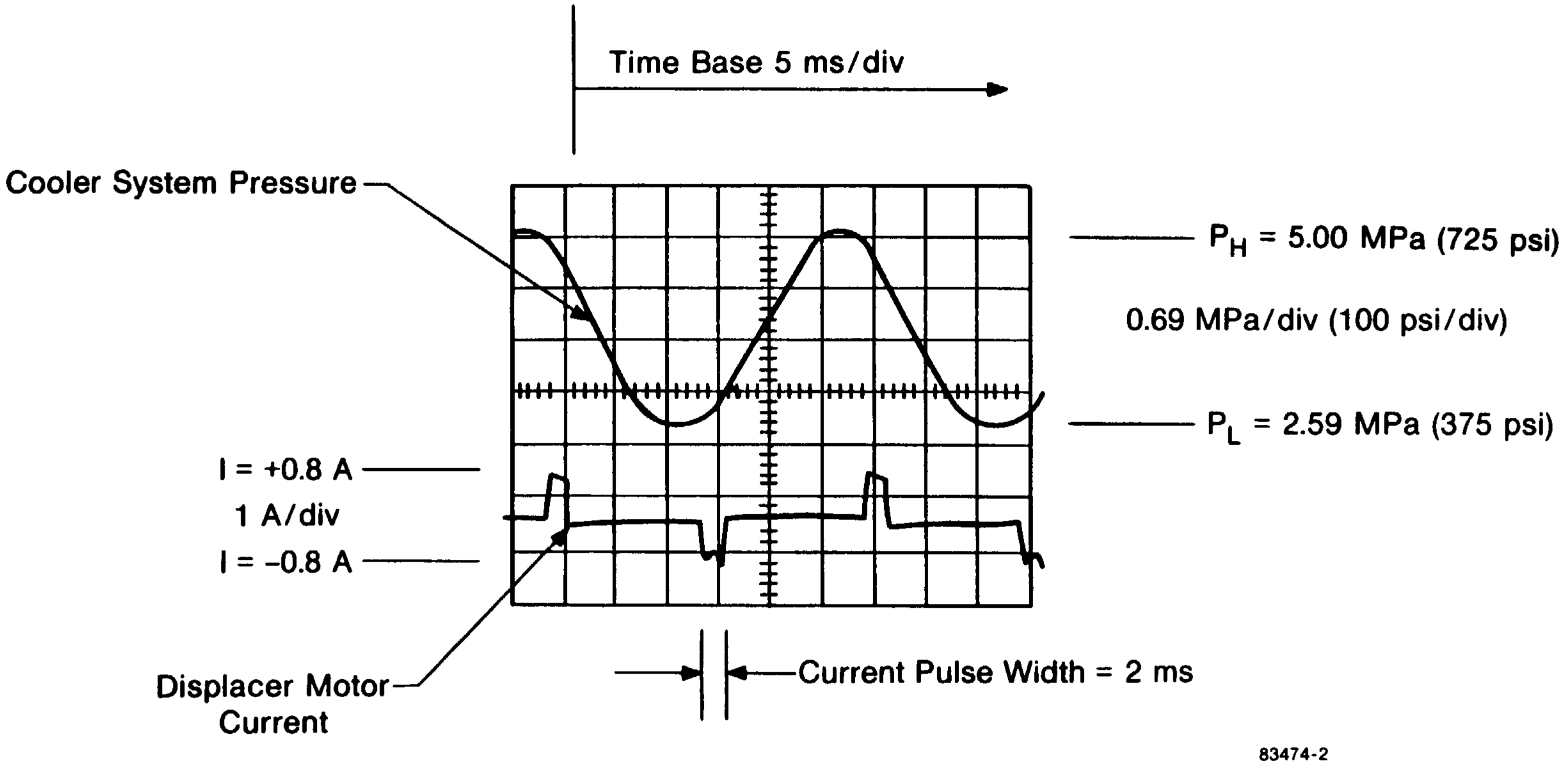

Figure 9 Cooler System Pressure/Displacer Motor Current Versus Time for Retrofit Cryocooler