Report No. NA-68-27
(DS-68-8)

FINAL REPORT

Project No. 520-003-01X

RECIPROCATING ENGINE AND EXHAUST VIBRATION AND TEMPERATURE LEVELS IN GENERAL AVIATION AIRCRAFT

JUNE 1968

DEPARTMENT OF TRANSPORTATION
FEDERAL AVIATION ADMINISTRATION
National Aviation Facilities Experimental Center
Atlantic City, New Jersey 08405

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for

AIRCRAFT DEVELOPMENT SERVICE

June 1968

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ABSTRACT

The engine and exhaust system vibration and exhaust gas and metal temperature levels were determined for flight and ground conditions on several single-engine aircraft for purposes of establishing exhaust system and heat exchanger design and test criteria. The temperature data were presented as a function of engine compression ratio and the vibration data were plotted against engine horsepower to foster the general utilization of the information.

Method of data presentation permits the estimation of exhaust gas temperatures for horizontally-opposed, reciprocating engines. Temperature measurements indicated uneven heating of the muffler outer wall (heat exchanger surface) reflecting uneven flow of the exhaust gases through and around the baffles and diffusers probably producing thermal stresses and contributing to failures. Baffles and diffusers within the mufflers of engines with compression ratios of 8.5:1 or higher are exposed to exhaust gas temperature levels under which standard construction materials (AISI 321 and AISI 347 stainless steels) become marginal with respect to high-temperature oxidation, carburization, and attack by lead compounds.

Vibration of general aviation aircraft engines was noted to increase with increased power rating and reached maximum intensities under takeoff conditions. The acceleration level of mufflers on engines of high power compared favorably with the MIL-STD-810A Vibration Test Specification for equipment mounted directly on aircraft engines. Recommended procedure for development of new exhaust system designs involved random vibration testing under operating thermal conditions.

TABLE OF CONTENTS

	Page
ABSTRACT	iii
INTRODUCTION	1
Purpose	1
Background	1
DISCUSSION	2
Description of Equipment and Procedures	2
General	2
In-Flight Tests	3
Ground Tests	3
Results and Analysis	6
Exhaust Gas Temperatures	6
Exhaust System Metal Temperatures	8
Engine Vibration Intensity	8
Muffler Vibration Intensity	14
Power and Vibration	20
Vibration Specification	20
CONCLUSIONS	27
RECOMMENDATIONS	28
REFERENCES	29
APPENDIX 1 Description of Instrumentation (4 pages)	1-1
APPENDIX 2 Basic Otto Engine Cycle Theory as Related to Exhaust Gas Temperature (6 pages)	2-1
APPENDIX 3 Engine Exhaust Gas and Metal Temperatures (8 pages)	3-1

LIST OF ILLUSTRATIONS

Figure		Page
1	Typical Temperature and Vibration Instrumentation, Engine and Exhaust System	4
2	Engine Stands, Ground Test	5
3	Engine Exhaust Gas Temperatures Within the Stack or Manifold Under Maximum Power Conditions	7
4	Engine Exhaust Gas Temperatures Within the Tailpipe Under Maximum Power Conditions	7
5	Stack Metal Temperatures Under Maximum Power Conditions	9
6	Manifold Metal Temperatures Under Maximum Power Conditions	9
7	Muffler Outer Wall Metal Temperatures Under Maximum Power Conditions	10
8	Tailpipe Metal Temperatures Under Maximum Power Conditions	10
9	History of Engine Broadband Vibration Intensity, Aircraft Code Model "B"	11
10	Vibration Wave Identification, Engine Crankshaft Speed 1306 RPM	13
11	Spectral Characteristics, Engine Vertical Vibration Intensity	15
12	Spectral Characteristics, Engine Lateral Vibration Intensity	16
13	Spectral Characteristics, Engine Longitudinal Vibration Intensity	17
14	Spectral Characteristics, Muffler Vertical Vibration Intensity, Separate Type Exhaust Systems	18
15	Spectral Characteristics, Muffler Vertical Vibration Intensity, Cantilevered Crossover Type Exhaust Systems	19

LIST OF ILLUSTRATIONS (continued)

Figure		Page
16	Engine Vertical Acceleration Level Versus Horsepower	21
17	Engine Lateral Acceleration Level Versus Horsepower	22
18	Engine Longitudinal Acceleration Level Versus Horsepower	23
19	Muffler Vertical Acceleration Level Versus Engine Horsepower	24
20	MIL-STD-810A, Vibration Test Specification for Equipment Mounted Directly on Aircraft Engines	25
1.1	Instrumentation Location, Cross-Over Type Exhaust System	1-2
1.2	Instrumentation Location, Separate Type Exhaust System	1-3
2.1	Pressure-Volume Diagram, Otto Engine Cycle	2-2
3.1	Exhaust Gas and Metal Temperatures, Aircraft Code Model "A"	3-2
3.2	Exhaust Gas and Metal Temperatures, Aircraft Code Model "B"	3-3
3.3	Exhaust Gas and Metal Temperatures, Aircraft Code Model "C"	3-4
3.4	Exhaust Gas and Metal Temperatures, Aircraft Code Model "D"	3-5
3.5	Exhaust Gas and Metal Temperatures, Aircraft Code Model "E"	3-6
3.6	Exhaust Gas and Metal Temperatures, Aircraft Code Model "F"	3-7
3.7	Exhaust Gas and Metal Temperatures, Aircraft Code Model "G"	3-8

INTRODUCTION

Purpose

The purpose of this project was to measure and analyze the engine and exhaust system vibration and exhaust temperature levels in general aviation aircraft for use in establishing exhaust and heat exchanger design and test criteria in aircraft certification.

Background

The Federal Aviation Administration was engaged in a program concerned with the safety and reliability of engine exhaust systems in light aircraft. The objectives of this program were: (a) to identify deficiencies in design and construction of engine exhaust systems which compromise safety through possible carbon monoxide poisoning, in-flight fire and power loss; (b) to develop an exhaust system qualification test and procedure suitable for use by manufacturers as a requirement for certification to enhance the reliability and integrity of these exhaust systems and to reduce the hazards associated with failures; (c) to investigate and develop cabin heaters designed to eliminate or minimize the carbon monoxide hazard; and (d) to evaluate low-cost carbon monoxide indicators to determine their performance and suitability for use in general aviation aircraft.

Published results of the program include technical reports listed under References 1, 2, and 3. The results reported here were directed toward identification of the operating environment.

The severe conditions under which engine exhaust systems and exhaust heat exchangers operate have been responsible for a large number of failures, some of which have resulted in fatal accidents. Malfunctions and defects in the exhaust system can create three separate hazards to flight safety: (a) fractures in the heat exchanger surface (muffler outer wall) may result in contamination of the cabin with exhaust gases containing carbon monoxide; (b) failed muffler baffles may restrict the exhaust gas path and effect engine power loss by creating excessive exhaust back pressure; and (c) when ruptured, the exhaust manifold or stacks may induce a fire hazard by failure to contain the exhaust flames.

The continual vibration under corrosive and high-thermal operating conditions most likely will cause fatigue fractures, particularly following deterioration of the metal by carburization, high-temperature oxidation, attack by lead compounds, and metallurgical phase changes. Accurate information concerning exhaust system vibration intensities and exhaust temperature levels can be utilized as criteria by the designer for selection of the required material (alloy) and material thickness for a particular application. This information is also

needed for realistic simulation of the operating conditions when evaluating exhaust assemblies on thermal-vibration test equipment. Accurate information concerning engine vibration intensities and exhaust temperature levels is also beneficial and valuable to the engine manufacturers for many purposes.

DISCUSSION

Description of Equipment and Procedures

General

The project endeavor was concerned with single-engine, two through six-place, general aviation aircraft incorporating exhaust gas-to-air heat exchangers. Aircraft powerplants were four or six-cylinder, horizontally-opposed, reciprocating engines ranging from 100 to 260 hp. Engine compression ratios varied from 6.75:1 to 8.6:1. The aircraft and engines were models manufactured in relatively large quantities by two light-aircraft companies and two engine companies, respectively. Aircraft and engine specifications are listed in Table I.

TABLE I

AIRCRAFT AND ENGINE INFORMATION

Aircraft Code Model	Number of Places	Engine Rating (hp)	Number of Cylinders	Engine Displacement (cu in)	Engine Compression Ratio
A	4	250	6	540	8.5:1
B	6	260	6	470	8.6:1
C	4	180	4	360	8.5:1
D	4	145	6	300	7.0:1
E	2	100	4	200	7.0:1
F	2	108	4	235	6.75:1
G	4	160	4	320	8.5:1

The program consisted of two types of testing: (a) involving operating aircraft; and (b) testing on the ground involving aircraft engines and parts installed on engine stands.

The instrumentation for both types of testing was identical. The photograph of Figure 1 depicts typical engine and exhaust system instrumentation. A description of instrumentation is provided in Appendix 1.

Exhaust gas temperatures were measured within the stack or manifold and within the tailpipe. Metal temperatures were monitored at locations on the stack, manifold, tailpipe, and two places on the muffler outer wall (heat exchanger surface).

The engine vibration (required for testing exhaust systems) was measured (with accelerometers) in each of the three major axes of the engine at the exhaust flange locations or in proximity thereof. Vibration of the muffler or heat exchanger was recorded in the motion-sensitive direction or in most instances the vertical axis with two accelerometers.

In-Flight Tests

Five aircraft were tested in flight to measure the vibration and the temperature levels of the engine and the exhaust system. Measurements were recorded during the takeoff, beginning at the start of the roll and ending at the altitude of 300 feet. Measurements were also recorded under stabilized engine speed conditions at altitudes of 4000 to 7000 feet. Transient measurements were recorded during changes of engine rpm under similar altitude conditions.

Ground Tests

Testing on the ground was accomplished on each of six engine installations mounted on stands, incorporating aircraft parts and configuration forward of the firewall, as shown in Figure 2. The engines were mounted on the aircraft vibration isolators and supported in cantilevered fashion from the firewall with the standard aircraft engine mount assembly.

Engine power was absorbed by the identical two-blade propellers as utilized in flight. The cowling and baffles were standard with the exception that the top cowling was modified for incorporation of air scoops to provide additional engine-cooling air from the flow induced by the propeller. Large oil coolers were placed in the propeller slip stream for cooling the engine oil as required for running the engines on the ground.

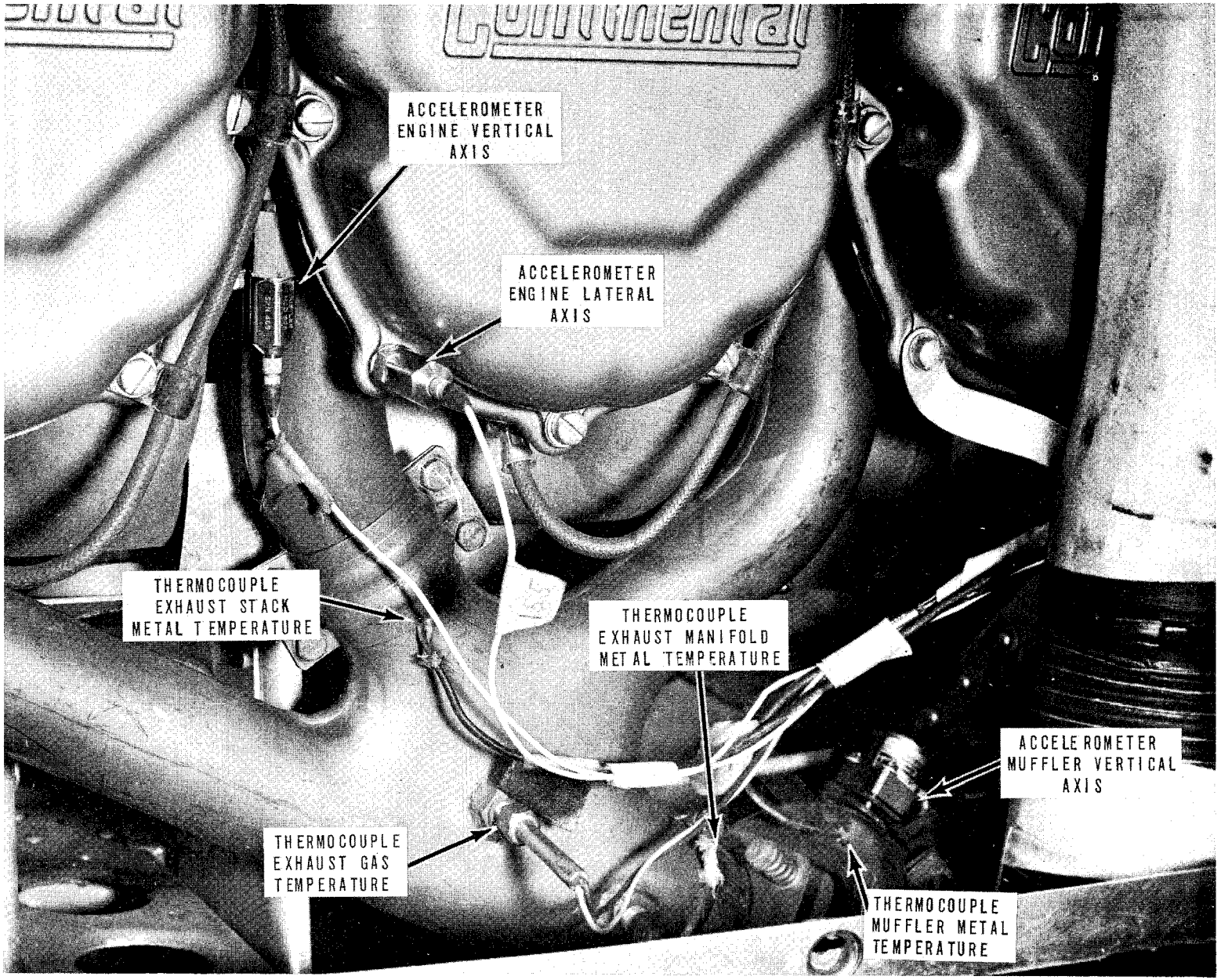

FIG. 1 TYPICAL TEMPERATURE AND VIBRATION INSTRUMENTATION, ENGINE AND EXHAUST SYSTEM

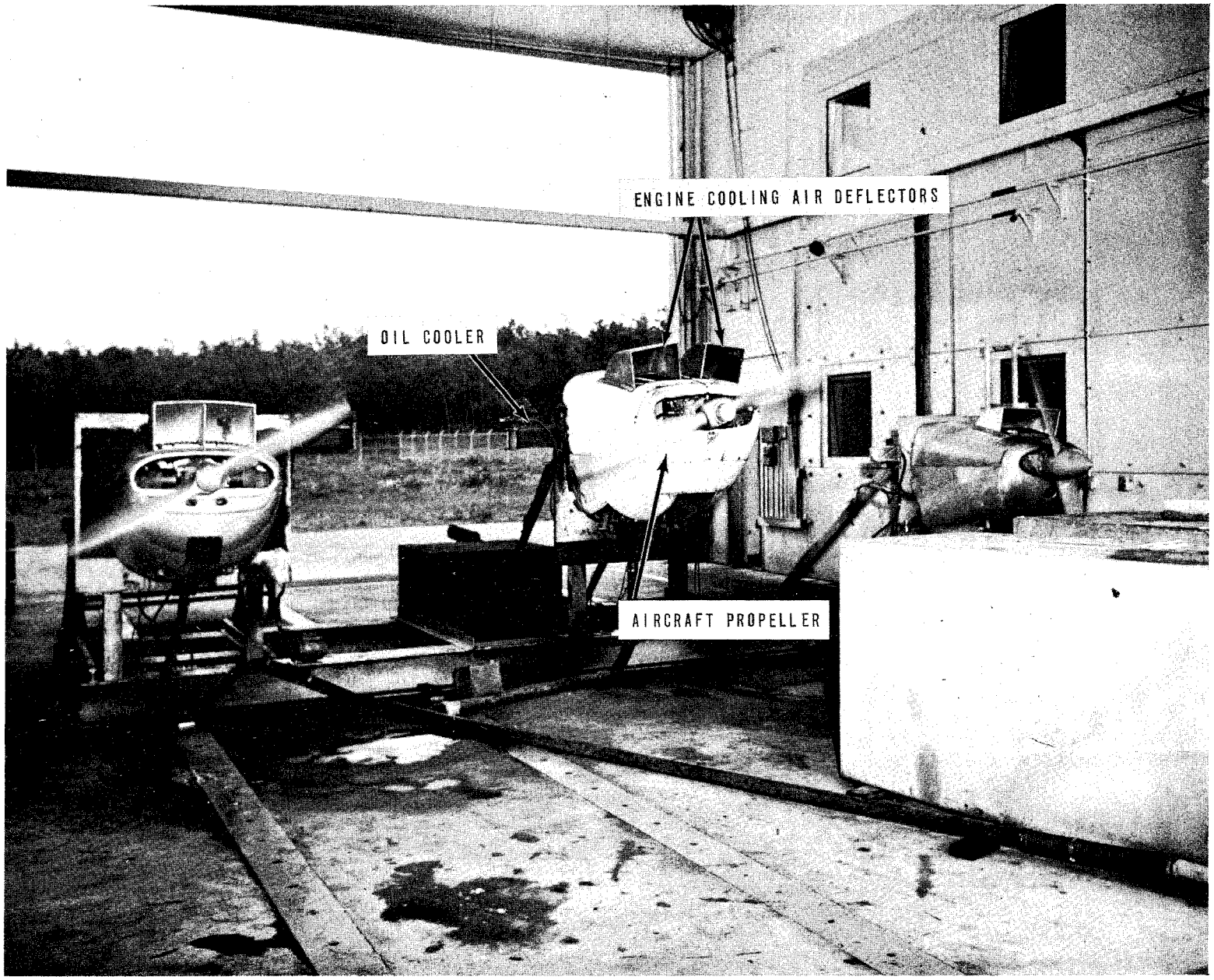

FIG. 2 ENGINE STANDS, GROUND TEST

Vibration measurements were recorded under both steady-state and transient conditions of engine speed. Inspection of the data revealed that the vibration waveform was composed of a large number of superimposed frequencies and a spectral analysis was performed for determination of vibration levels at discrete frequencies.

Information regarding the frequency and magnitude of acceleration was observed visually utilizing a vibration wave analyzer. The exhaust gas and metal temperatures were recorded from visual observations on a precision direct-reading potentiometer. A detailed description including the accuracy of the instrumentation systems is contained in Appendix 1.

Results and Analysis

Exhaust Gas Temperatures

Engine exhaust gas temperatures, measured within both the stack and tailpipe in various aircraft in flight and on the ground, were corrected to Standard Day conditions, and the corrected measurements at rated engine power were plotted against the engine compression ratio as depicted in Figures 3 and 4. Exhaust gas temperature is known to be a function of the fuel-to-air mixture and the engine compression ratio. The theory and the mathematical relationships concerning engine compression ratio as related to exhaust gas temperature are discussed in Appendix 2. Suffice to note here that the increase in exhaust gas temperature with compression ratio (Figures 3 and 4) reflects the heat of compression added when the gas was compressed to the higher pressures. The gas temperature information was prepared as a function of the engine compression ratio for presentation of the data in a form for generalized use. Maximum exhaust gas temperatures may be estimated for four-cycle, horizontally opposed, air-cooled engines when designed and constructed under present day state-of-the-art technology.

Exhaust gases within the stack, or downstream of the engine, approached temperature levels of 1600°F when engines with a compression ratio of 8.5:1 were operated at maximum power and lean fuel-to-air mixtures. When rich fuel-to-air mixtures were selected under similar conditions, the exhaust gas temperatures within the stack were reduced to somewhat less than 1500°F. Exhaust gases in the stacks or manifold of engines with a compression ratio of 7:1 and operated with lean mixtures were measured at temperature levels of 1480°F, and with rich mixtures, gas temperatures of 1380°F were indicated. The temperature of the exhaust gases in the tailpipe were 50 to 75°F less than the temperature of gases in the stack.

On a corrected basis and at maximum engine power, the exhaust gas temperature levels recorded on the ground were similar to the gas temperature levels recorded in flight. Exhaust gas temperature

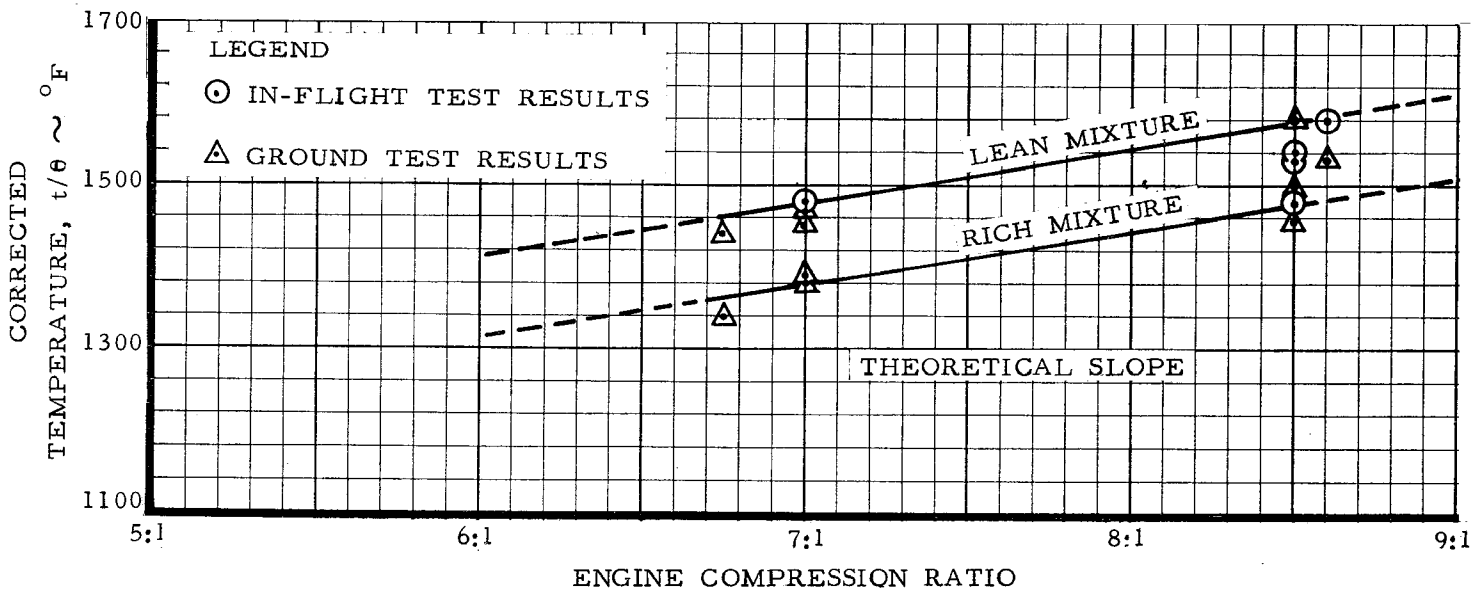

FIG. 3 ENGINE EXHAUST GAS TEMPERATURES WITHIN THE STACK OR MANIFOLD UNDER MAXIMUM POWER CONDITIONS

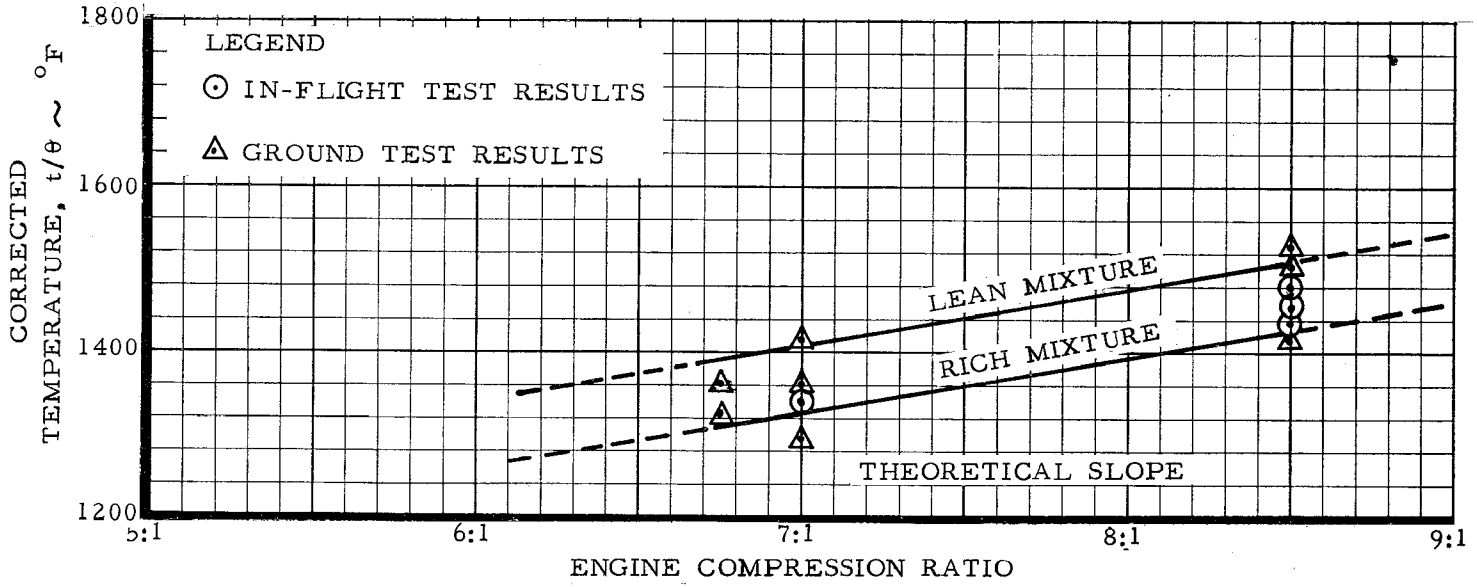

FIG. 4 ENGINE EXHAUST GAS TEMPERATURES WITHIN THE TAILPIPE UNDER MAXIMUM POWER CONDITIONS

as a function of engine crankshaft speed is presented in Appendix 3 for each aircraft in flight and engine installation on the ground.

Exhaust System Metal Temperatures

The metal temperatures of the stacks, manifolds, muffler wall, and tailpipe were corrected to Standard Day Conditions and were plotted as a function of the engine compression ratio in Figures 5 through 8. The spread in the data is in part attributed to the temperature extremes of rich and lean fuel-to-air mixtures. The stack metal temperatures were also affected by local variations of engine-cooling air existing between aircraft at the instrumented location. The deviations in metal temperatures of the muffler outer wall (heat exchanger surface), Figure 7, reflect the uneven flow of exhaust gases around and through the baffles and diffusers within the muffler, effecting uneven heating. Inspection of the thermal data in detail revealed general temperature variations of 300 to 400°F on specific mufflers. The problem of heat exchanger distortion and cracking has been aggravated by uneven flow and local overheating (Reference 1). Metal temperatures of 1200°F (maximum hot spot) were prevalent for exhaust systems of engines with a compression ratio of 8.5 to 1 when operated under maximum engine power. Exhaust systems of engines with a compression ratio of 7:1 operated at maximum temperatures of 1100°F. Metal temperatures were only slightly lower at downstream locations. Metal temperature measurements plotted as a function of engine crankshaft speed are included in Appendix 3.

Although metal temperatures of 1200°F maximum were measured on the outer surfaces of the exhaust system, the temperature of the baffles and diffusers inside the muffler were probably approaching the temperature of the gas. Since the baffles and diffusers are in contact with the exhaust gases and they are without the benefit of cooling, it was believed that their operating metal temperatures approximate 1500 to 1600°F on engines with a compression ratio of 8.5 to 1. Oxidation resistance of standard materials utilized in exhaust systems (AISI type 321 and type 347 stainless steels) become marginal for periods of extended operation at temperatures of 1500 to 1600°F. The standard material at these temperatures is subject to scaling and weight loss produced by severe oxidation and a combination of high-temperature carburization and attack by the products of combustion, particularly lead compounds. Type 310 (25 percent chromium 20 percent nickel) or Incoloy (21 percent chromium 34 percent nickel), with Incoloy perferred, was suggested for the parts that are exposed to high temperatures and the products of combustion (Reference 1).

Engine Vibration Intensity

Typical histories of broadband acceleration level and waveform for each of the three major axes of the engine are presented in Figure 9. Vibration intensity and waveform at maximum engine power is compared under conditions of: takeoff, in-flight, and ground test. A record of vibration under conditions of reduced engine power

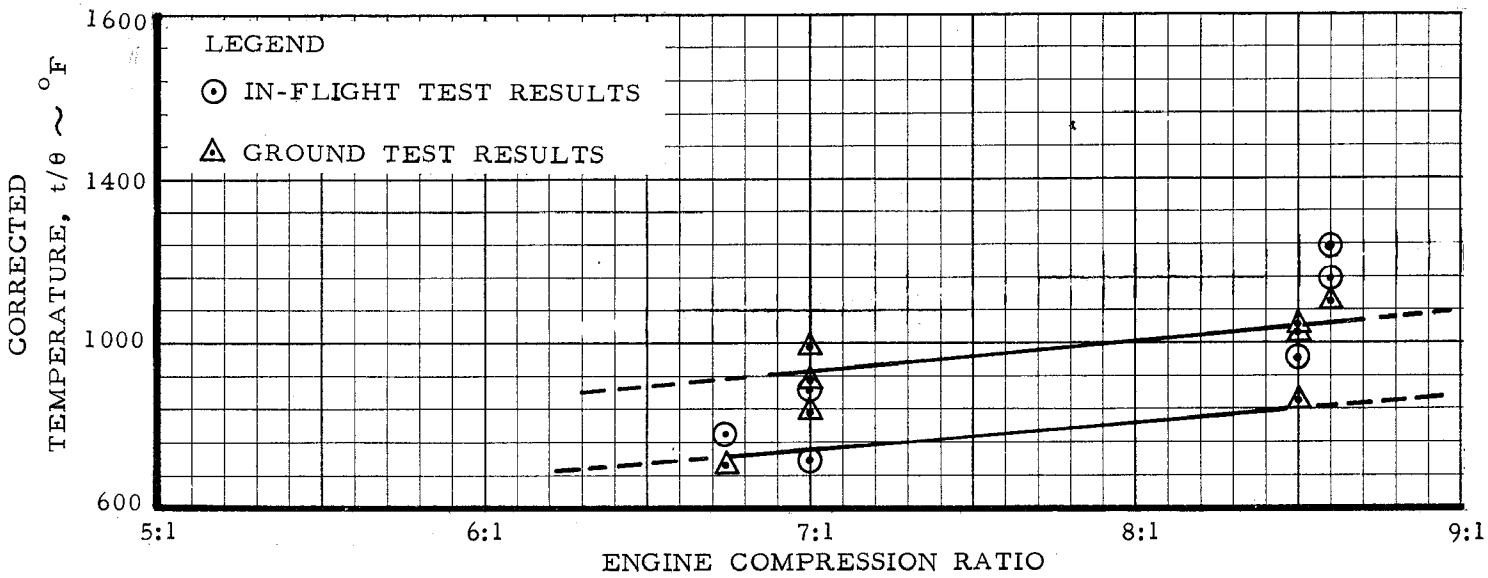

FIG. 5 STACK METAL TEMPERATURES UNDER MAXIMUM POWER CONDITIONS

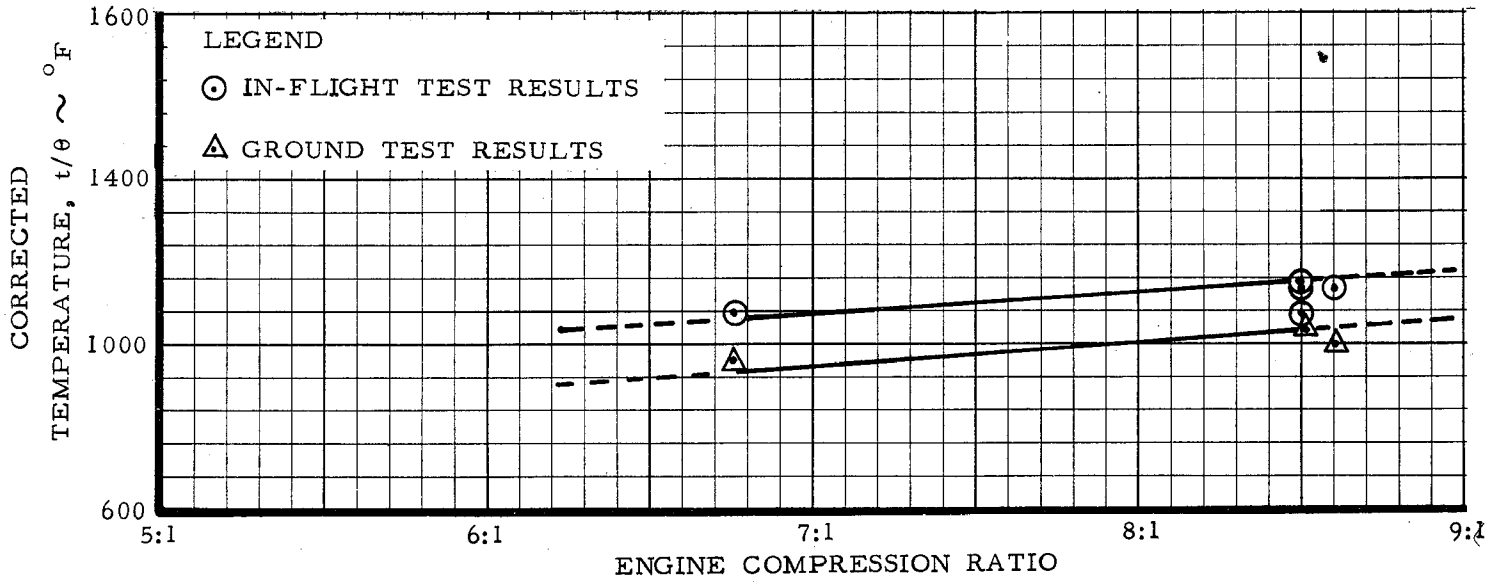

FIG. 6 MANIFOLD METAL TEMPERATURES UNDER MAXIMUM POWER CONDITIONS

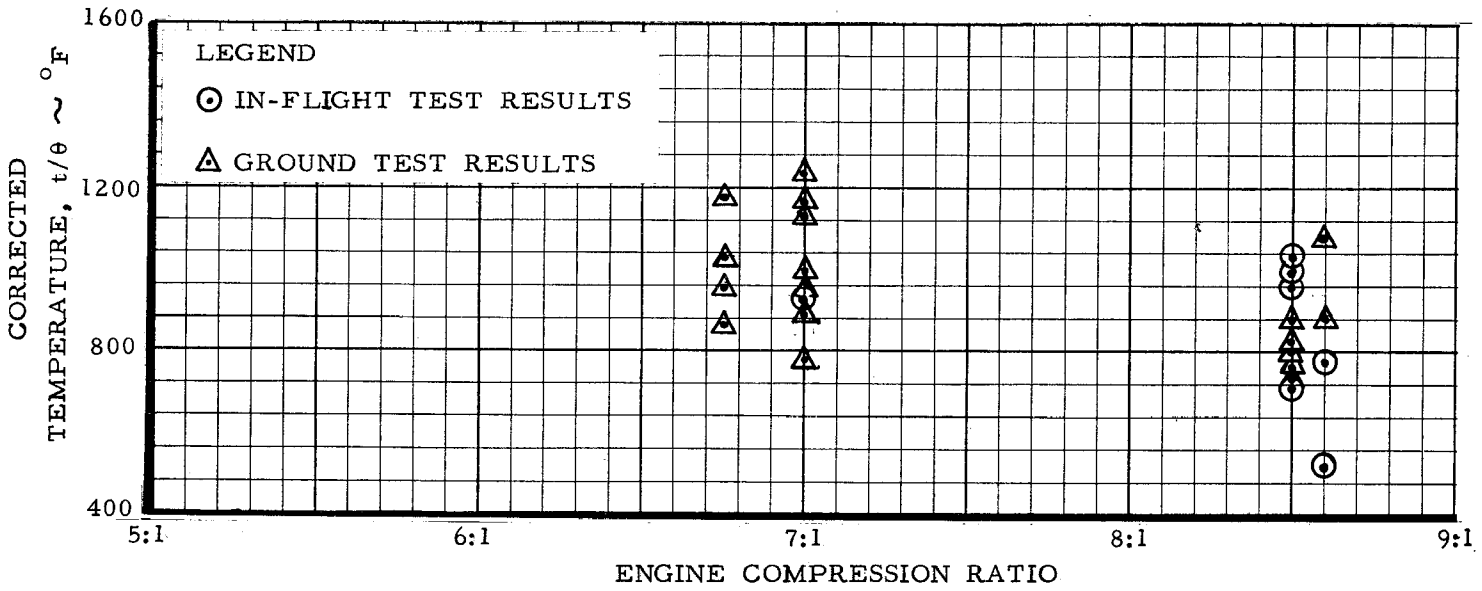

FIG. 7 MUFFLER OUTER WALL METAL TEMPERATURES UNDER MAXIMUM POWER CONDITIONS

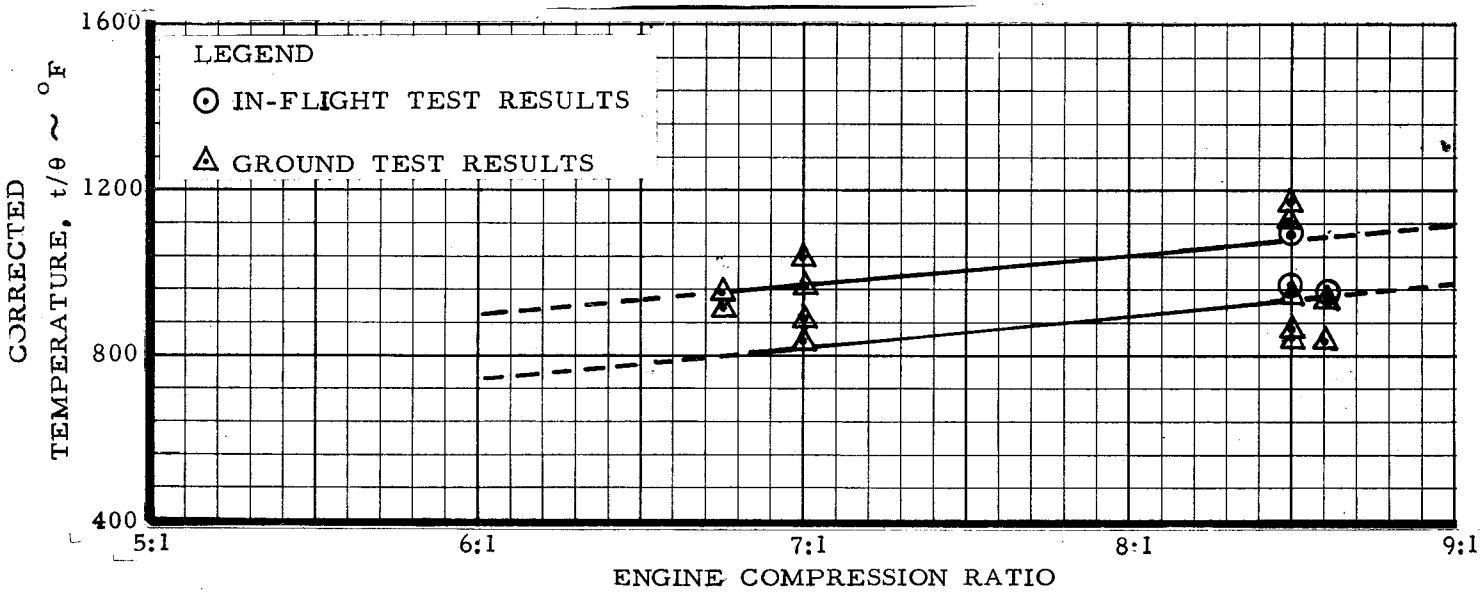

FIG. 8 TAILPIPE METAL TEMPERATURES UNDER MAXIMUM POWER CONDITIONS

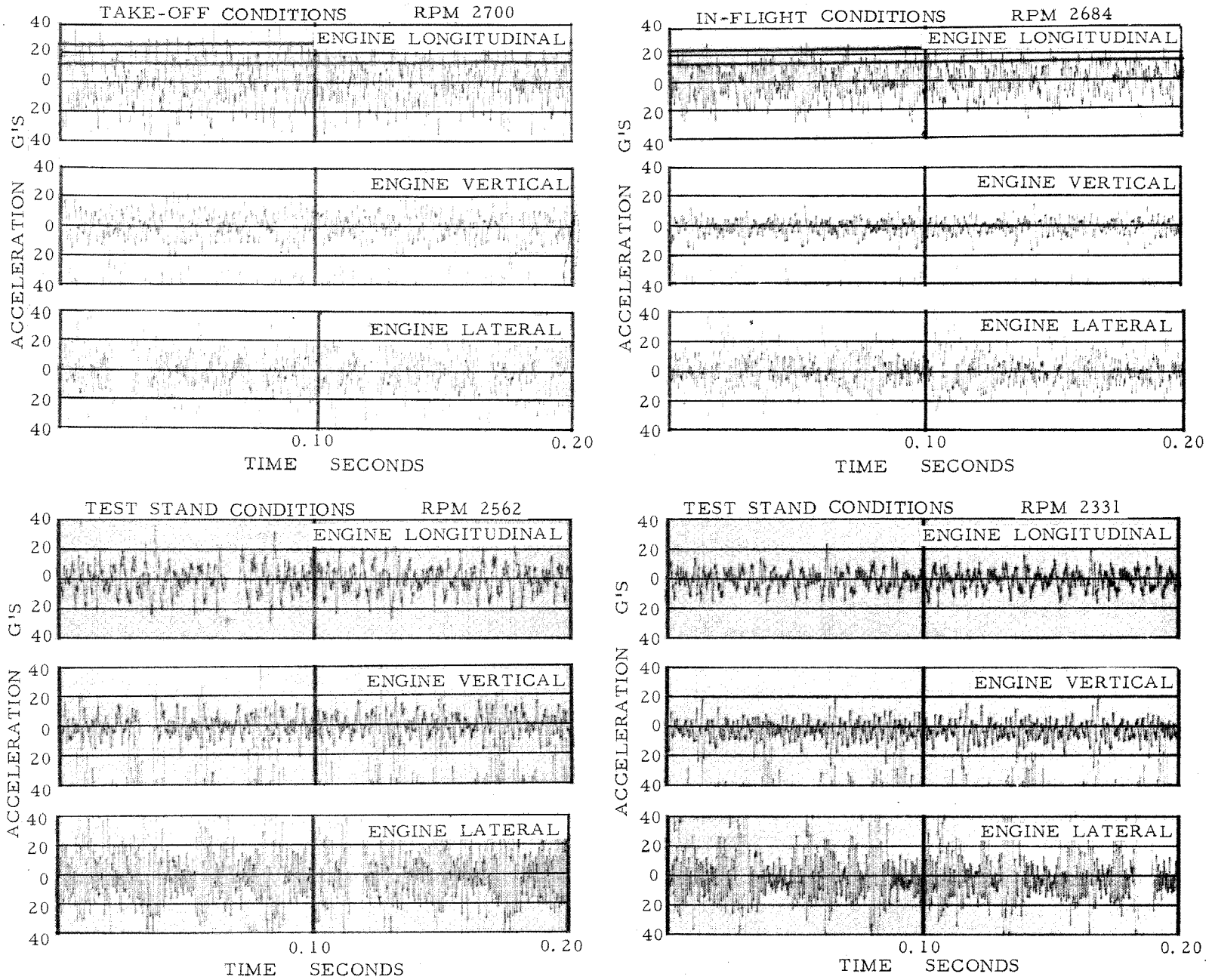

FIG. 9 HISTORY OF ENGINE BROADBAND VIBRATION INTENSITY, AIRCRAFT CODE MODEL "B"

for ground test is included for reference. Examination of these records showed that the vibration wave was periodic; however, the wave was complex and composed of a large number of superimposed frequencies.

In operating aircraft, engine vibration levels were indicated highest during conditions of takeoff at maximum engine power. Vibration intensity at maximum power in flight between altitudes of 5000 to 7000 feet was indicated to be significantly less than the levels recorded during takeoff although vibration waveform was similar. This result was attributed to the engines developing less power under altitude conditions. Although they were not tested, supercharged engines develop high power and may effect high-vibration levels under altitude conditions. During ground test at high engine power, vibration levels were indicated to be somewhat higher than the levels recorded during takeoff; waveform was generally similar.

To identify the component parts of the engine vibration wave, the speed of the record was increased and the engine crankshaft speed was decreased. This expanded record is reproduced in Figure 10 with wave identification noted. The maximum excitation pulse occurred during combustion of the power stroke. Minor excitation occurred in phase with the opening and closing of the valves. The engine vibration wave was repeated in cycles of two rpm engine crankshaft speed in phase with the events of the four-cycle engine. The vibration wave of each cylinder was phased in relation to the engine firing order. Thus the vibration of the cylinders at the exhaust flange location consisted of identical periodic, complex vibration waveforms, each out of phase with the other.

The complex wave with phase variance between cylinders effects a severe requirement for realistic vibration testing of engine exhaust systems. The simulation problem involves the use of a single vibration exciter with a rigid test fixture fastened to the exhaust flanges to support the exhaust system for vibration test. Random vibration testing may more closely simulate the actual conditions.

The following introductory paragraph on the definition of frequency spectrum was excerpted from Reference 4. "All signals can be thought of as existing in three dimensions. A sinewave is in reality an amplitude-time curve in the 'x-y' plane existing at some fixed point on the frequency axis 'z.' An examination or projection of the sinusoidal history on the amplitude-frequency 'x-z' plane would be a vertical line at the frequency 'f.' This is the true spectrum of a sinewave and can be viewed as the two-dimensional projection of a time function onto the amplitude-frequency plane. Such a projection of the frequency parameters of a time-amplitude waveform is called a spectrum or frequency analysis."

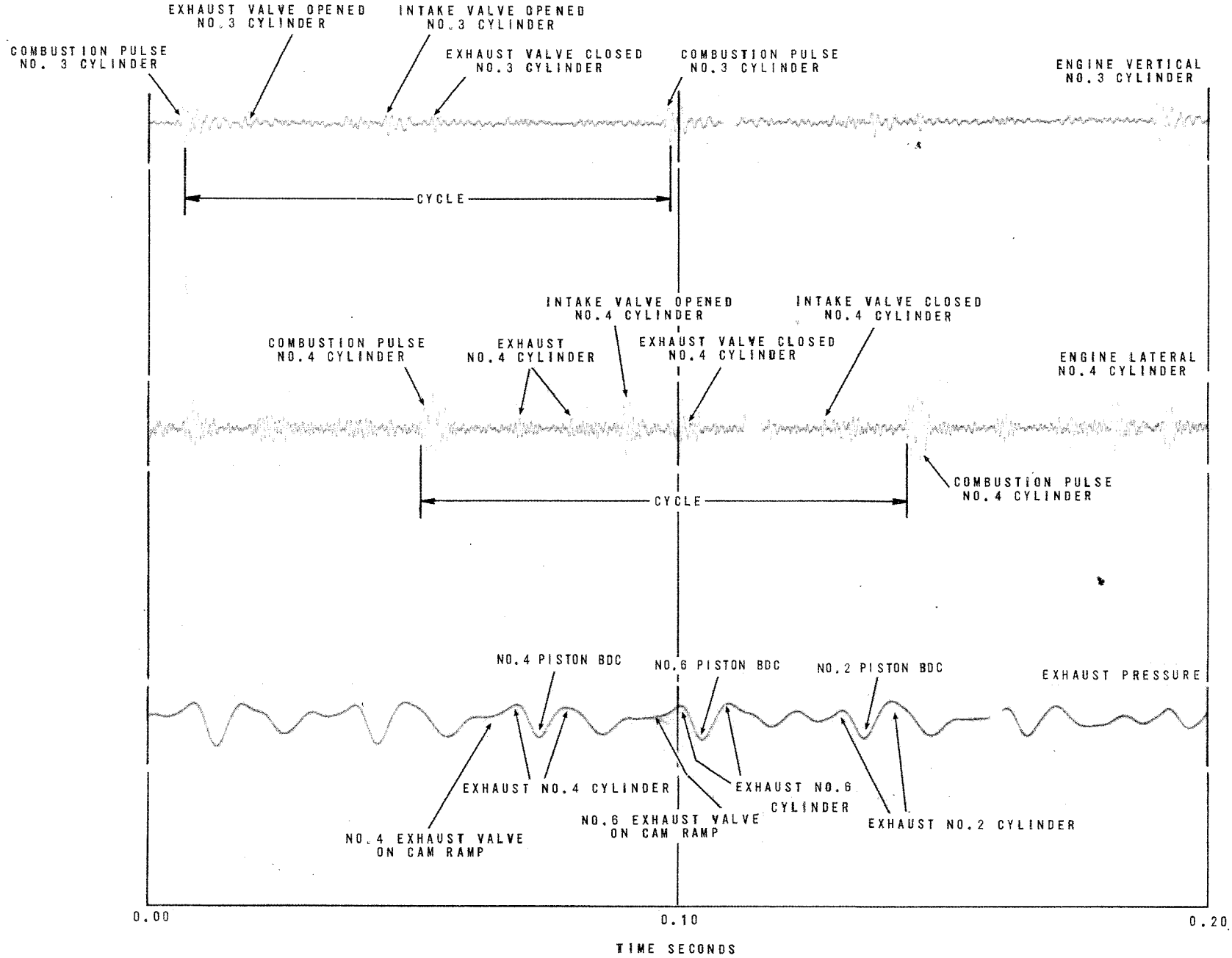

FIG. 10 VIBRATION WAVE IDENTIFICATION, ENGINE CRANKSHAFT SPEED 1306 RPM

Characteristics of the engine vibration spectrum are illustrated in Figures 11, 12 and 13. These data were recorded from visual observations using a vibration wave analyzer incorporating tuneable one-third and one-tenth octave filters. The one-third octave band divides each 10-to-1 tuning range into 10 bands. In each band, the ratio of the upper cutoff frequency to the lower cutoff frequency is 1.26 to 1. The narrow band (one-tenth octave) in effect divides the range into about three times as many bands. The bandwidths of the filters increase in cycles directly with the mean frequency of the band. Thus, as frequency increases, the bandwidth increases and acceleration amplitudes are indicated higher.

Waveform characteristics of engine vibration in the vertical axis were generally similar on each of five aircraft. Maximum acceleration amplitudes of the engines in the vertical axis were measured between 400 and 500 cps on each of four aircraft. The exact frequency is identified by the symbols denoting the center frequency of one-tenth octave filters, and is believed to be the natural frequency of the engine and mounting combination. Attention is called to the levels of acceleration measured with filters as opposed to the broadband levels. The indicated broadband vibration amplitudes were reduced significantly when the vibration signals were filtered.

Maximum acceleration of the engines in the lateral axis occurred between frequencies of 1300 to 1600 cps on five aircraft. The vibration was sensed in a direction parallel to both the piston and valve motion and the amplitude of acceleration was indicated higher. Further the natural frequency of the engine was increased significantly. Maximum acceleration levels of the engines in the longitudinal axis occurred between 1400 and 2000 cps. The high frequencies reflect the relative stiffness of the engine and mount assemblies in the longitudinal axis.

Muffler Vibration Intensity

Spectral characteristics of the muffler vertical vibration are depicted in Figure 14 for three separate or dual-type exhaust systems and in Figure 15 for two cantilevered crossover-type exhaust systems. Muffler vertical vibration of separate type exhaust systems reached a maximum acceleration level between 200 and 440 cps on each of three aircraft, the exact value depending on the particular configuration. Maximum acceleration amplitude was measured at approximately 10 g's rms on mufflers of engines developing 62.6 to 77 hp. Fourteen g's rms were indicated on a muffler of an engine developing 228 hp. A muffler of the cantilevered crossover-type exhaust system reached resonant conditions at a relative low frequency of 100 cps with a maximum rms acceleration of 15 g's. The engine was developing 214 hp when the data were recorded. Muffler vertical vibration levels, as measured with narrowband pass filters, were higher than the

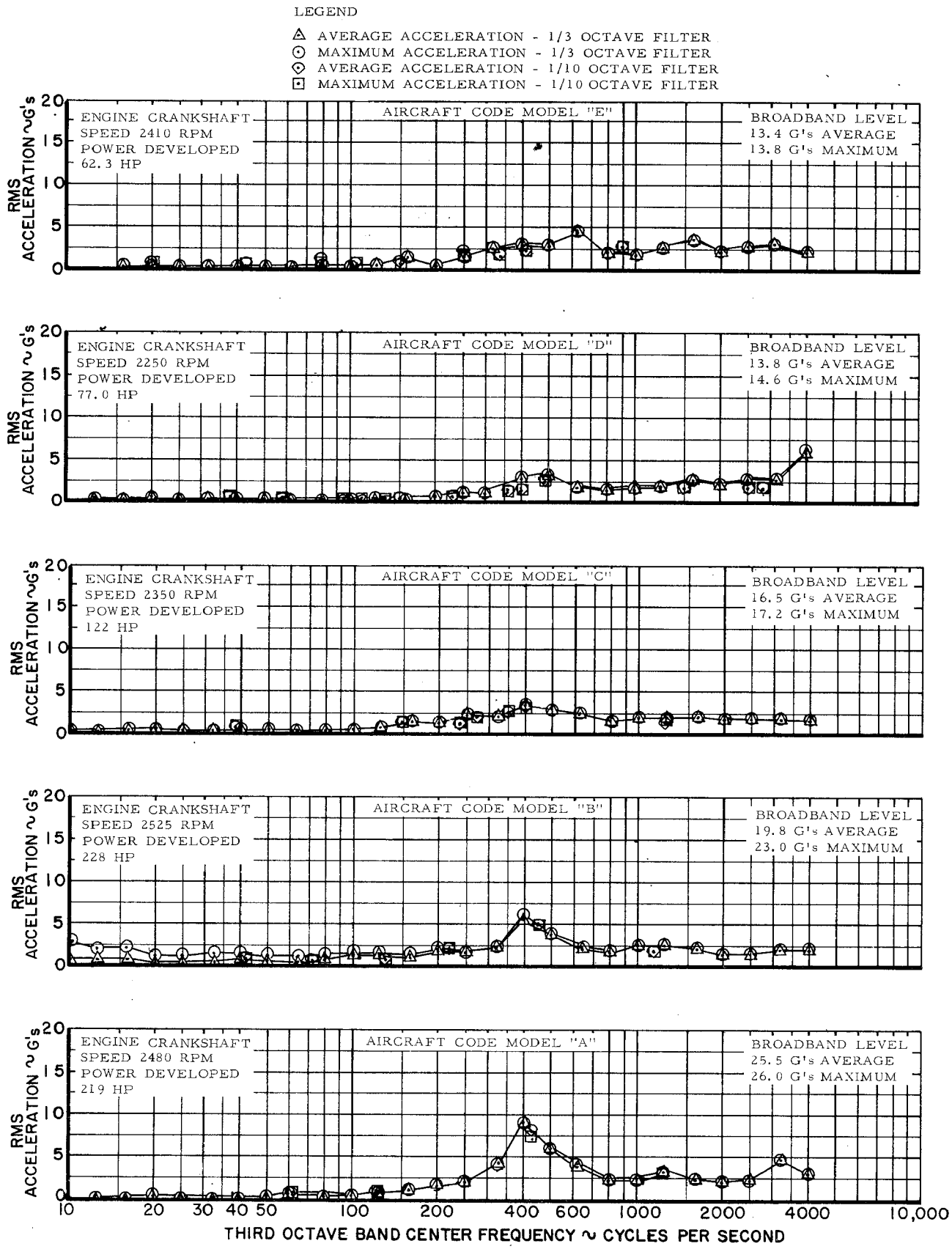

FIG. 11 SPECTRAL CHARACTERISTICS, ENGINE VERTICAL VIBRATION INTENSITY

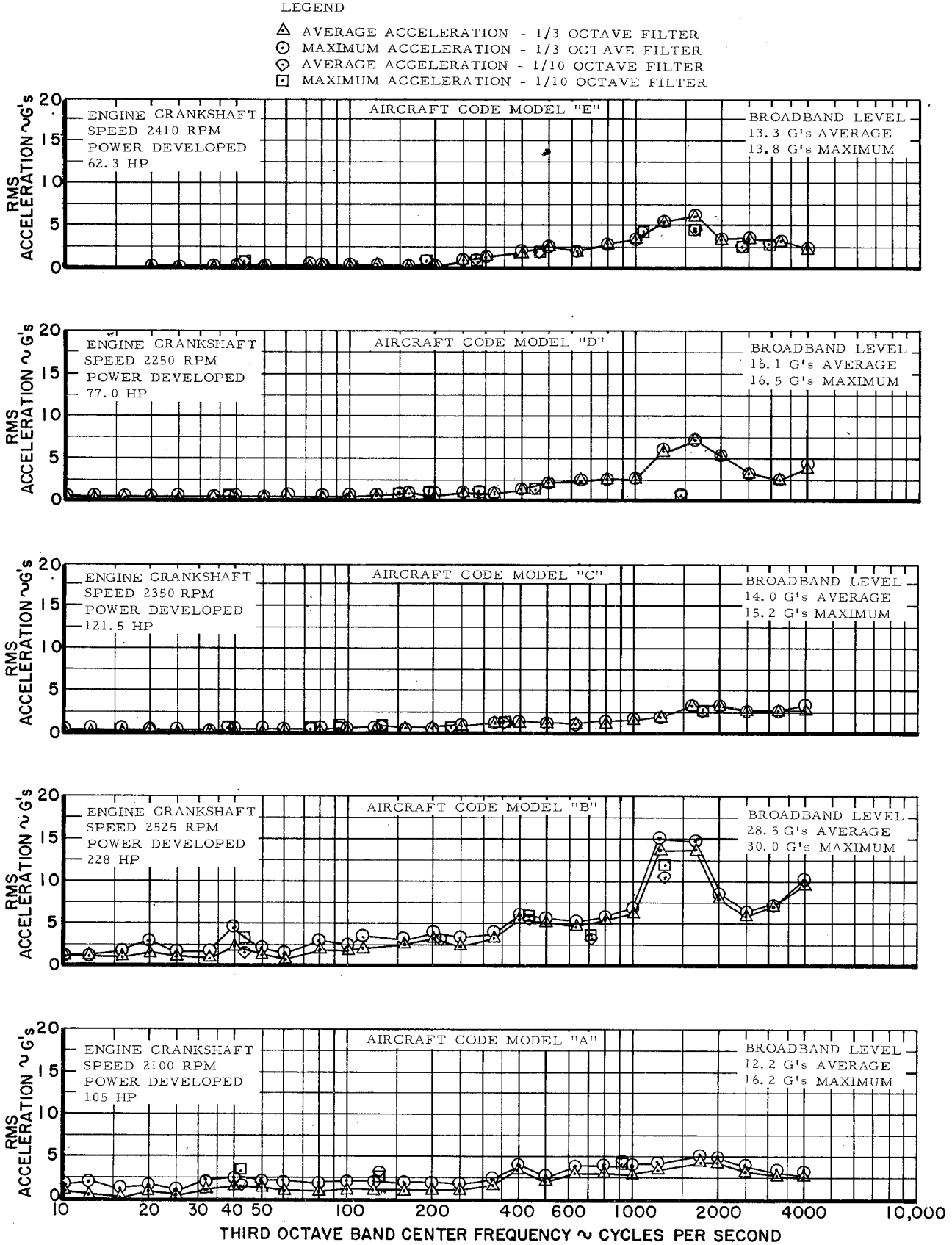

FIG. 12 SPECTRAL CHARACTERISTICS, ENGINE LATERAL VIBRATION INTENSITY

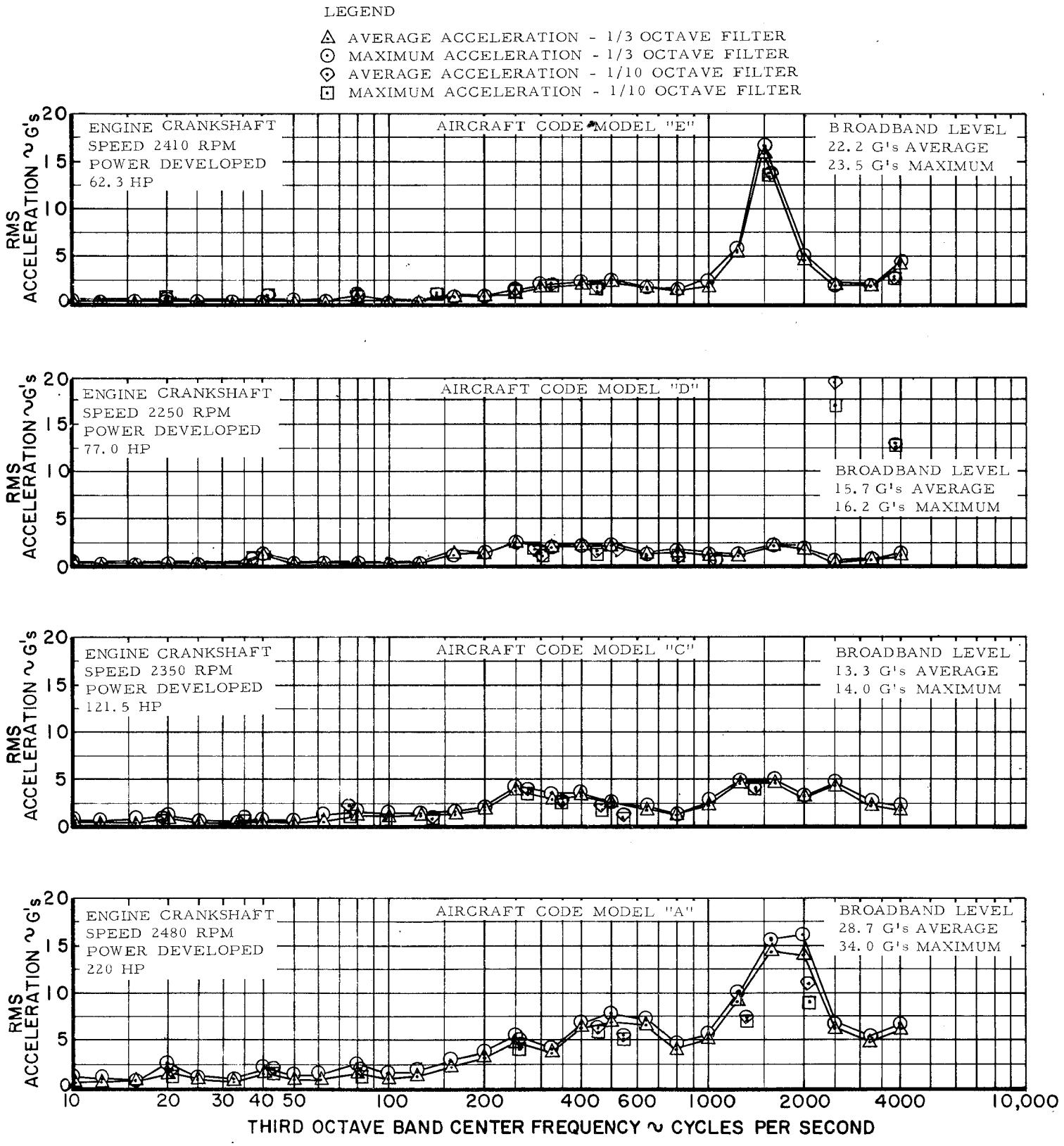

FIG. 13 SPECTRAL CHARACTERISTICS, ENGINE LONGITUDINAL VIBRATION INTENSITY

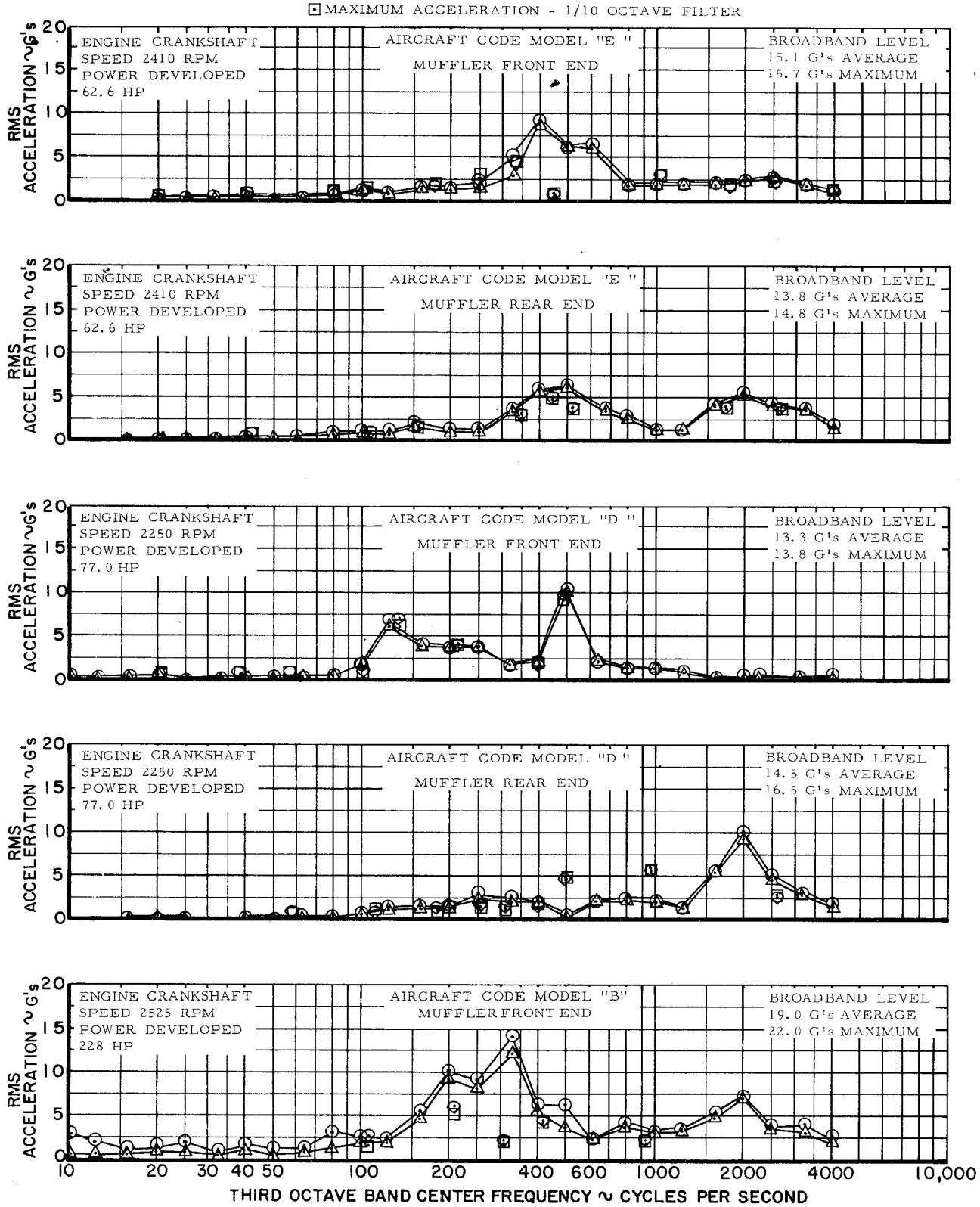

FIG. 14 SPECTRAL CHARACTERISTICS, MUFFLER VERTICAL VIBRATION INTENSITY, SEPARATE TYPE EXHAUST SYSTEMS

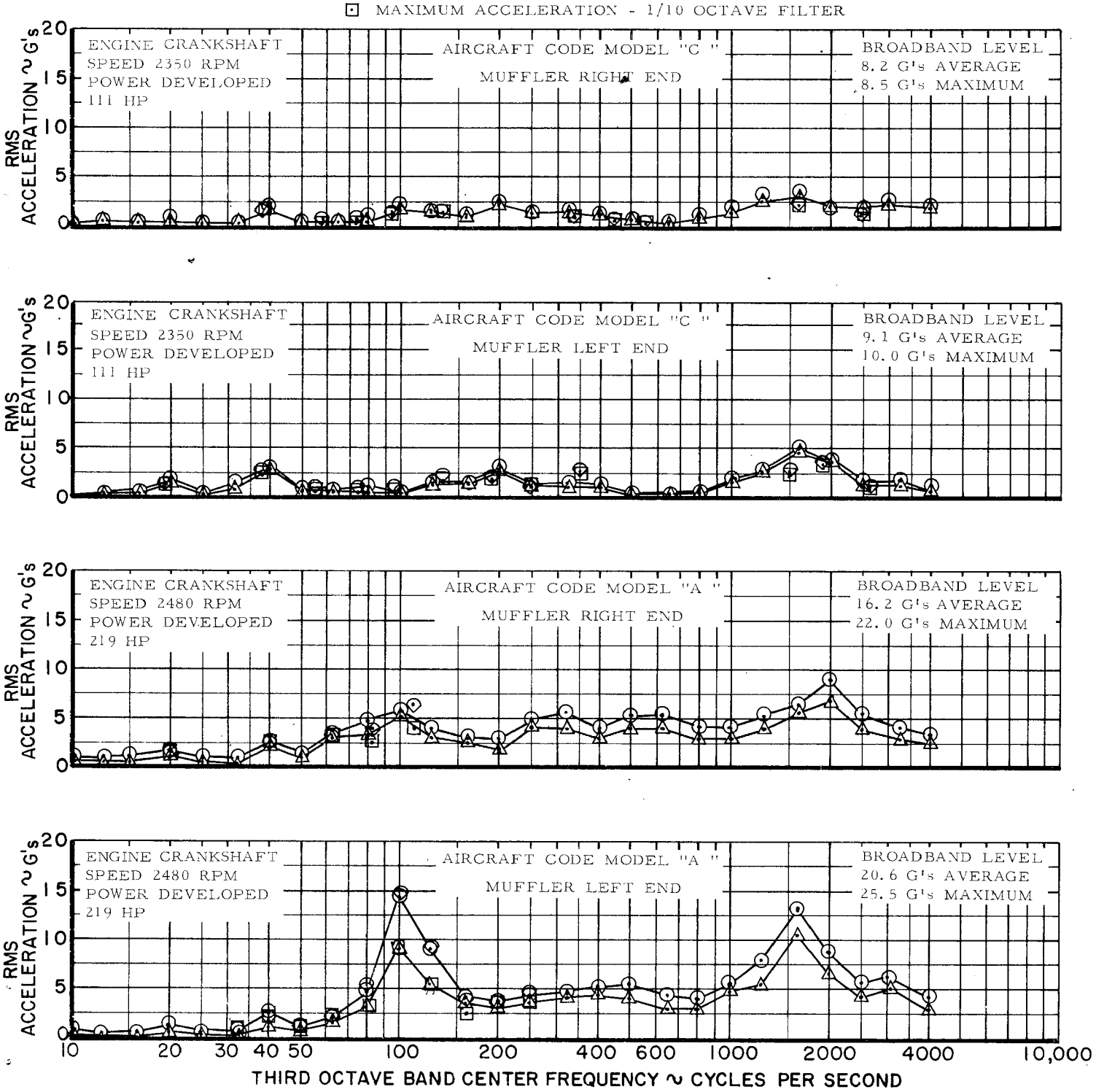

FIG. 15 SPECTRAL CHARACTERISTICS, MUFFLER VERTICAL VIBRATION INTENSITY, CANTILEVERED CROSSOVER TYPE EXHAUST SYSTEMS

corresponding engine vertical vibration levels. This increase was attributed to amplification effected by exhaust system resonance and probably excitation by the exhaust gas pressure pulsations.

Power and Vibration

Engine vibration intensity appeared to be a general function of the horsepower being developed at the time of observation as shown in Figures 16, 17 and 18. The illustrations show the broadband acceleration level, the maximum one-third octave band level, and the maximum one-tenth octave band level, all plotted against the horsepower developed by the various engines at the instant of data acquisition.

Narrowband vibration of engines in the vertical axis varied between 2 and 5 g's rms acceleration at 100 hp, while at 230 hp acceleration ranged from 5 to 9 g's rms. These data were maximum levels recorded with the center frequencies of one-tenth octave band filters tuned between 400 and 520 cps. The lateral acceleration level of engines developing 100 hp varied between 2 and 6 g's rms as measured with narrowband filters. Lateral vibration of engines developing 230 hp was indicated to be within limits of 5 to 12 g's rms. The data were recorded at maximum conditions observed with the filter center frequency tuned between 1300 and 1400 cps.

Considerable scatter of the data occurred when engine longitudinal acceleration was plotted as a function of horsepower. Factors such as resonance of the accelerometer mounting may have affected the results. The accelerometer was mounted on the flat of a special intake stud cap nut to sense longitudinal vibration.

Vibration Specification

Maximum acceleration amplitudes measured on the mufflers of seven aircraft were plotted regardless of design configuration in Figure 19 for purposes of forming a test specification. The top boundary of the envelope (one-tenth octave band pass filter) represents an indicated conventional vibration test specification wherein only one frequency exists at a given time, but wherein the frequency is varied progressively from the minimum to the maximum specified frequency.

When the rms levels were converted to peak acceleration, the indicated test specification compared favorably with the military standard for equipment mounted directly on aircraft engines (Figure 20). Test results indicated that the acceleration amplitudes and frequencies of MIL-STD-810A, Vibration Test Specification (Reference 5), were adequate for sinusoidal vibration testing of aircraft engine exhaust systems. Random vibration testing, however, is preferred, and broadband acceleration levels during vibration test should be comparable to those reported herein. It is suggested that the power spectral density relationships be shaped with peaks at the frequencies

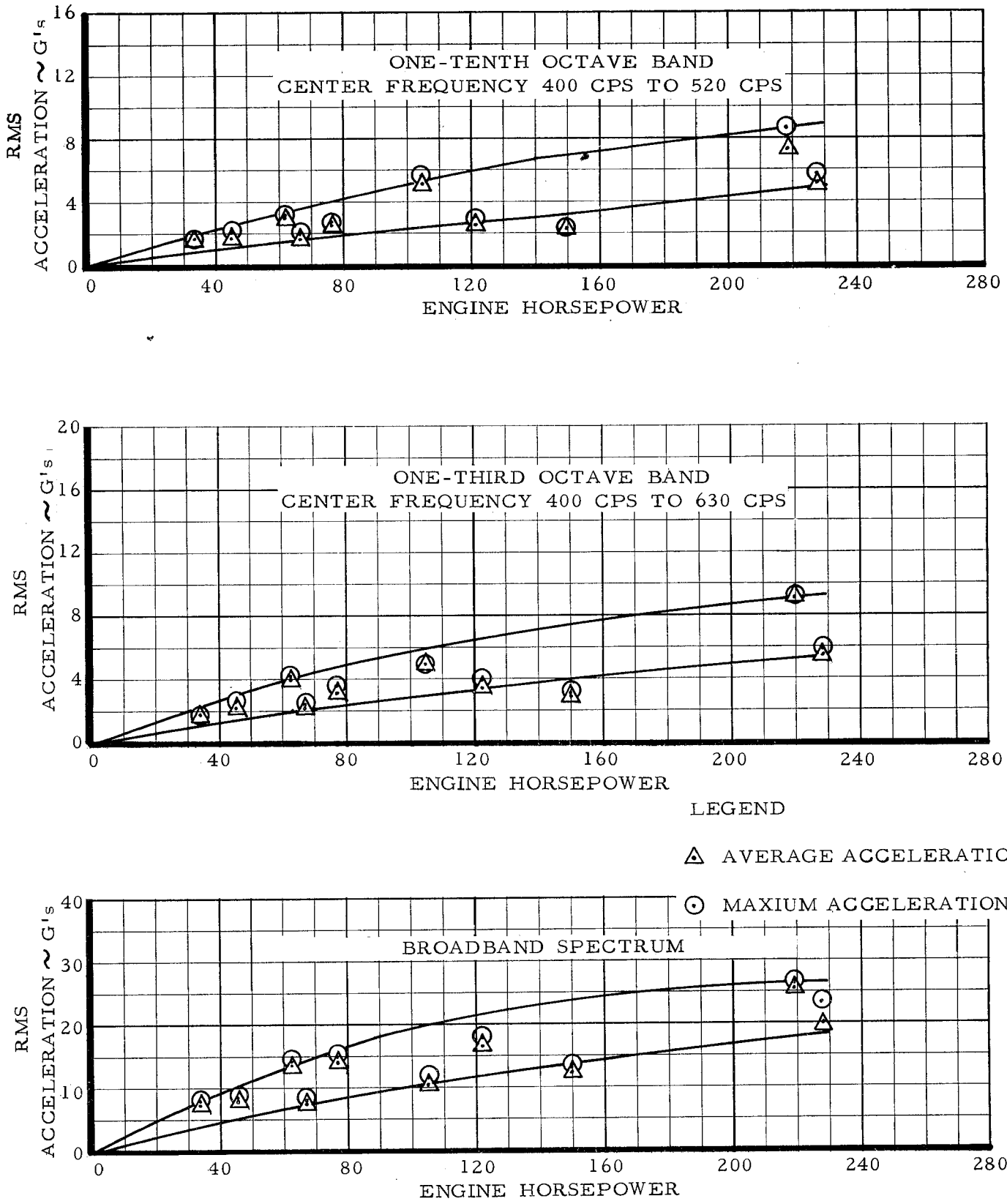

FIG. 16 ENGINE VERTICAL ACCELERATION LEVEL VERSUS HORSEPOWER

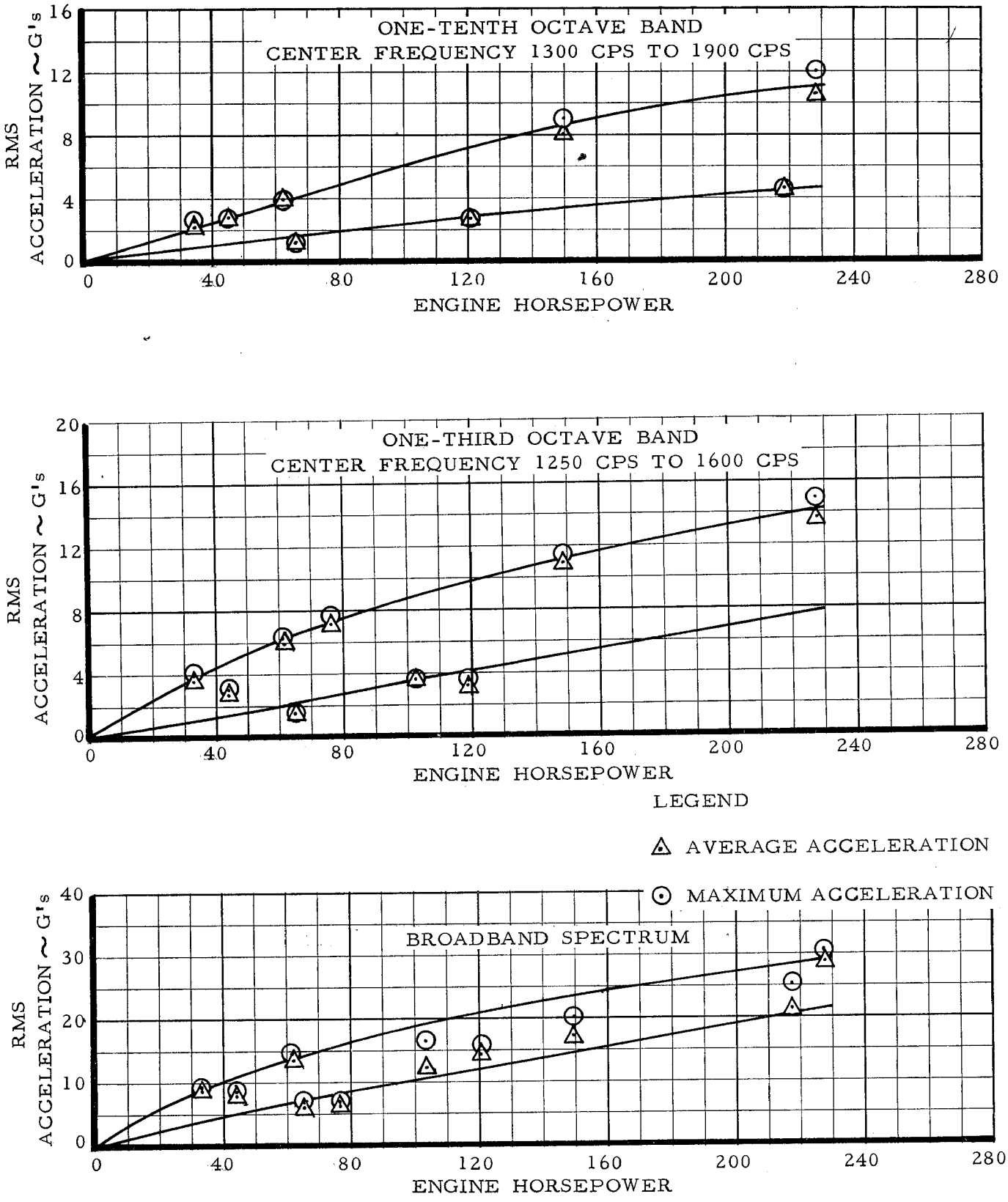

FIG. 17 ENGINE LATERAL ACCELERATION LEVEL VERSUS HORSEPOWER

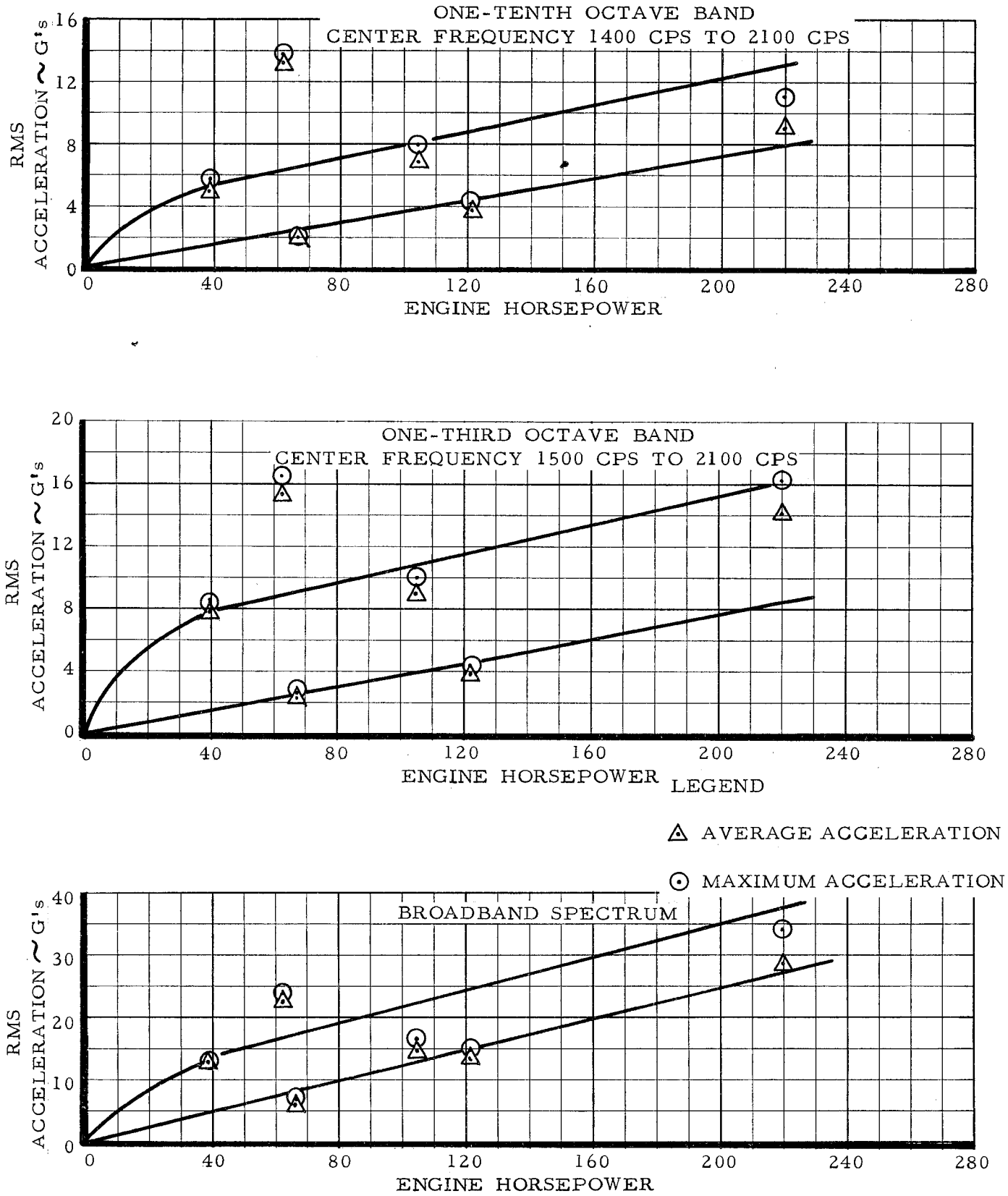

FIG. 18 ENGINE LONGITUDINAL ACCELERATION LEVEL VERSUS HORSEPOWER

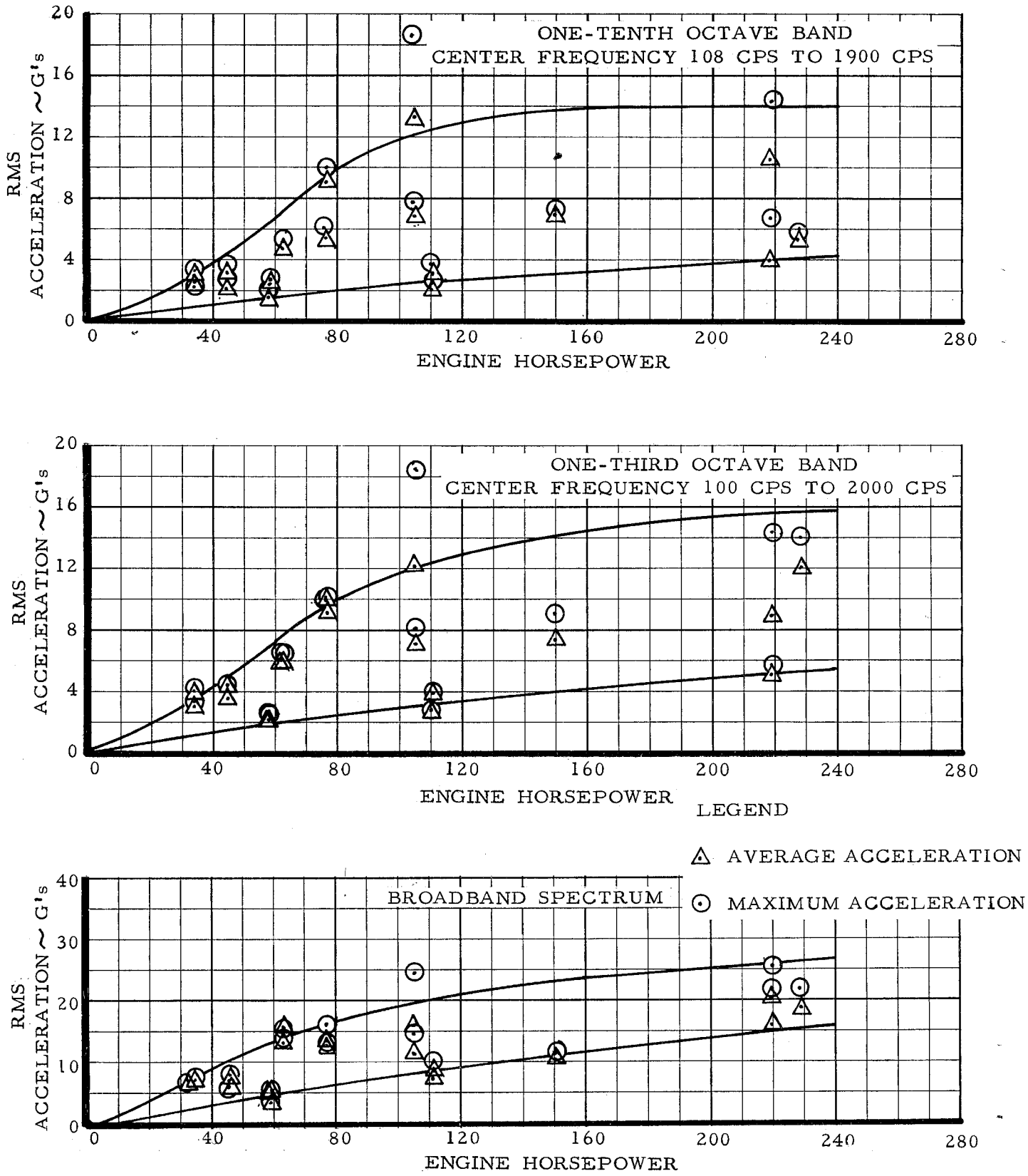

FIG. 19 MUFFLER VERTICAL ACCELERATION LEVEL VERSUS ENGINE HORSEPOWER

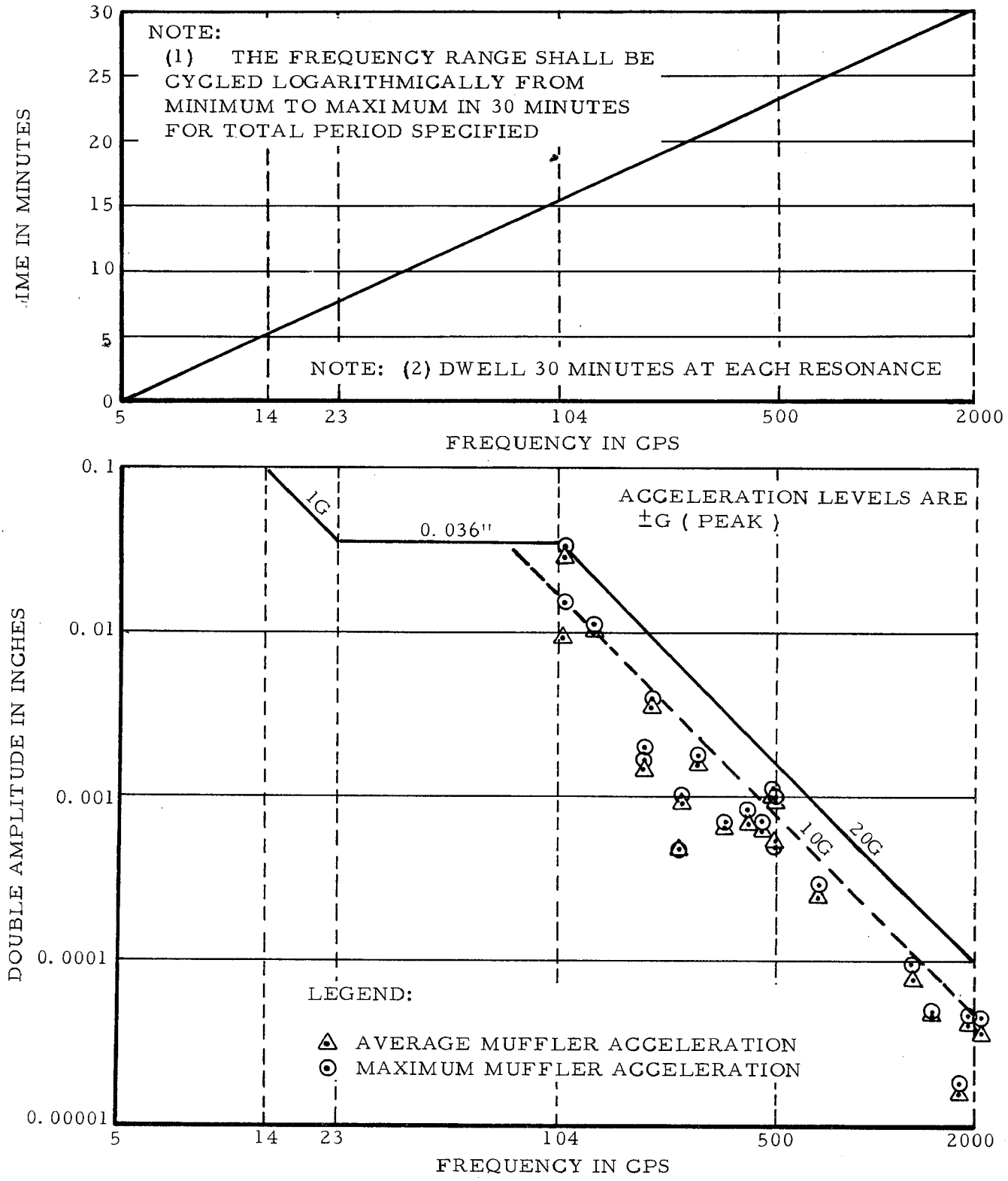

FIG. 20 MIL-STD-810A, VIBRATION TEST SPECIFICATION FOR EQUIPMENT MOUNTED DIRECTLY ON AIRCRAFT ENGINES

corresponding to the maximum measured accelerations. For effective sinusoidal or random vibration testing, it is necessary that the exhaust system be heated to maximum operating temperatures as defined in this report.

Although the vibration excitation of the engine with respect to the exhaust system at the mounting flange locations was defined as a stationary process; i.e., its statistical properties do not change with time, random type vibration testing of engine exhaust systems was preferred only for the feature of testing under a continuum of frequencies. The engine excitation of the exhaust system consisted of periodic complex vibration waveforms; the waveforms, however, were out of phase at the exhaust mounting flanges as they were phased by the firing order of the engine. Since a rigid test fixture was required for mounting the exhaust systems on the vibration exciter, testing under broadband frequencies was believed to be more realistic than testing only under a single discrete frequency and varying that frequency from minimum to maximum.

CONCLUSIONS

Based upon the results of in-flight tests and ground tests reported herein on four-cycle, horizontally-opposed, air cooled engines, it is concluded that:

1. Engine exhaust gas temperatures may be estimated by utilizing the temperature data and the theoretical effects of compression ratio as presented in this report.

2. Baffles and diffusers within the mufflers of engines with high compression ratios on the order of 8.5:1 are probably operating under maximum temperatures (1500°F to 1600°F) that are marginal with respect to producing high temperature oxidation of currently used materials.

3. Maximum temperature of the exhaust system components exposed to cooling air on their outer surfaces was measured at levels of 1200°F and below. Rapid high temperature oxidation of the materials (AISI 321 and 347 stainless steels) from which these components were fabricated is not expected at this temperature level.

4. The observed wide variation in metal temperatures of the muffler outer walls reflect uneven heating. This can effect high thermal stresses that contribute to the initiation of crack type failures.

5. Increased horsepower tends to increase engine vibration intensity.

6. The engine vibration waveform is periodic but consists of a complex, continuous frequency spectrum with significant amplitudes in certain narrowband frequency limits.

7. The MIL-STD-810A, Vibration Test Specification, for equipment mounted directly on aircraft engines is appropriate for sinusoidal vibration testing of engine exhaust systems in the vertical axis or critical motion sensitive direction.

8. The complex engine vibration wave with phase variations between cylinders imposes a severe requirement for realistic vibration testing of exhaust systems. These conditions would be more closely simulated by random-type vibration testing as opposed to sinusoidal testing.

RECOMMENDATIONS

Based upon the results of the in-flight tests and ground tests reported herein, it is recommended that:

1. A material more resistant than AISI 321 and 347 stainless steels to high temperatures and the products of combustion be used for the muffler baffles and diffusers.

2. The thermal and vibration data be utilized for calculating the requirements of material and material thickness for engine exhaust system applications.

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