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NOISE CONTROL IN INTERNAL COMBUSTION ENGINES —————

Edited by —————
DONALD E. BAXA

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*To Professor Ali A. Seireg
and
The Official Stamp*

PREFACE

This book is written for the individual responsible for solving noise control problems associated with internal combustion engines and their related components. Practicing noise control engineers in the internal combustion field will find here much practical information stemming from the authors' original research, their analysis of available literature, and their many years of experience. This compilation of state-of-the-art knowledge on noise control of internal combustion engines will be useful as well to persons who design, manufacture, and evaluate components for internal combustion engines and other manufactured products from which noise and vibration can be expected. In addition to the noise evaluation and control procedures outlined in the earlier chapters, several of the later chapters deal with noise control on a component-by-component basis.

The need for this book reflects the growing emphasis on controlling noise in our environment. Internal combustion engines are a major contributor to environmental noise; the growing demands for engine performance in an economically small package have increased the problems that currently exist. Consequently, the need for noise control measures is greater now than ever before. It is hoped that this book will provide the reader with insights and answers to the everyday problems faced in the field.

The material in this book assumes a basic understanding of the fundamentals of acoustics or practical knowledge of noise control. It provides a systematic methodology for investigating, evaluating, and designing controls for noise emanating from an internal combustion engine or arising from the addition of necessary components. Control at the source of the noise is the primary emphasis, although Chapter 9 considers control along the path of propagation. Diesel engines are most frequently cited in the noise source examples. Although gas engines have similar problems, diesel engines are typically more noisy and have been more closely scrutinized.

The first chapter presents the history of internal combustion engines, their evolution into current applications, and the general noise control measures and legislation that have arisen as a result. Chapters 2 to 4 set the stage for the remaining portion of the book. Chapter 2 examines the effects of various operating parameters on the noise level that an

engine can produce. Chapters 3 and 4 provide a comprehensive discussion of the instruments, facilities, and procedures utilized to measure and evaluate generated sound.

If a noise problem does exist, it is then necessary to determine the potential noise sources, transmission paths, and radiating surfaces that can contribute to the overall noise level, and to develop the appropriate solutions. Chapter 5 examines silencers as a means of noise control, and Chapter 6 considers both the noise-generating aspects of cooling systems and the various control measures that can be applied. Chapter 7 presents a comprehensive state-of-the-art review of damping and isolation treatments; Chapter 8 applies these treatments, together with procedures earlier discussed in the book, to sample modifications of engine structure.

Acoustical enclosures (Chapter 9) and noise control of additional components such as gears, bearings, and brakes (Chapter 10) are subjects necessarily treated in a comprehensive examination of noise control of internal combustion engines and related systems. The final chapter, on quality control, presents a noise and vibration monitoring methodology to meet design goals and quality standards consistently.

I would like to thank Peg Rickard for expertly preparing the manuscript and conscientiously coordinating the many details necessary for the book's completion; Dorothy Ingle for assisting with the proofing; Richard Dykstra for reviewing the manuscript in its entirety; Darrell Petska, without whose assistance this book would not have been possible; and my wife, Shirley, whose patience and understanding during the editing were greatly appreciated.

DONALD E. BAXA

*Madison, Wisconsin
January 1982*

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CHAPTER ONE

INTERNAL COMBUSTION ENGINES AND NOISE

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1. INTRODUCTION

The internal combustion engine has mechanized the world. Since the early 1900s it has been our prime source of mechanical power. Because of it, we have automobiles, buses, and airplanes for travel. We have earth scrapers, bulldozers, and loaders to shape our cities and provide highway links between them. We have tractors, reapers, trucks, and railways to increase farm productivity and distribute the produce. We have power mowers and tillers for tending our yards and gardens. We also have motorhomes, motorboats, and snowmobiles for leisure-time activities.

However, this progress has created new problems. The vast number of internal combustion engines in the world today has resulted in air pollution, concern about shortages of petroleum products to fuel the engines, and noise pollution. This book deals with the latter of the three major problems presently associated with internal combustion engines. Noise is no longer considered merely as a source of annoyance. Science has proven that excessive noise can have severe psychological and physiological effects on human beings as well. Some of the major physiological effects include hearing loss; cardiovascular, muscular, and gastric effects; and fatigue. This book investigates major sources of internal combustion engine noise, relates methods of evaluating the level and impact of those noise sources, and discusses procedures for reducing the subject noise levels.

2. HISTORY OF THE INTERNAL COMBUSTION ENGINE

An internal combustion engine burns fuel in a chamber and uses the combustion gases directly to produce power through the engine's moving parts. This is in contrast to an external combustion engine—such as a steam engine—which burns fuel in one chamber and then transfers the heat to a second chamber, where gases drive the engine's moving parts.

The term "internal combustion engine" is most often associated with spark-ignition piston engines, but it refers to compression-ignition piston engines, gas turbine engines, and rotary engines as well. At the present time, spark-ignition and compression-ignition piston engines are the most common types of internal combustion engines used in our society.

Consequently, the major content of this book relates to piston engines and piston engine applications.

2.1. Spark-Ignition Piston Engines

Notable achievements relating to the development of piston-driven internal combustion engines date back to the seventeenth century. During the 1670s, Dutch scientist Christian Huygens showed that useful work could be accomplished by exploding gunpowder in a closed container with a movable top (1-3). His gunpowder-fueled engine applied some basic principles that were also evaluated by Frenchman Jean de Hautefeuille in the same era. The complexity of charging the engine's cylinder with gunpowder and the lack of control over the combustion process severely hampered engine operation. Consequently, the gunpowder-fueled engine served no practical purpose (3).

It was late in the eighteenth century before anything approaching a practical internal combustion engine was developed. In 1794, the Englishman Robert Street patented the first reciprocating internal combustion engine that burned a gaseous fuel and air mixture (2). Street, who was a varnish maker by trade, proposed to use spirits of tar or turpentine as engine fuel.

In Street's engine (Fig. 1), liquid fuel was poured into the cylinder and was vaporized by the heated portion of the cylinder. At the same time, a lever was used to start raising the piston in the cylinder. As the piston moved upward, external air was drawn into the cylinder and a

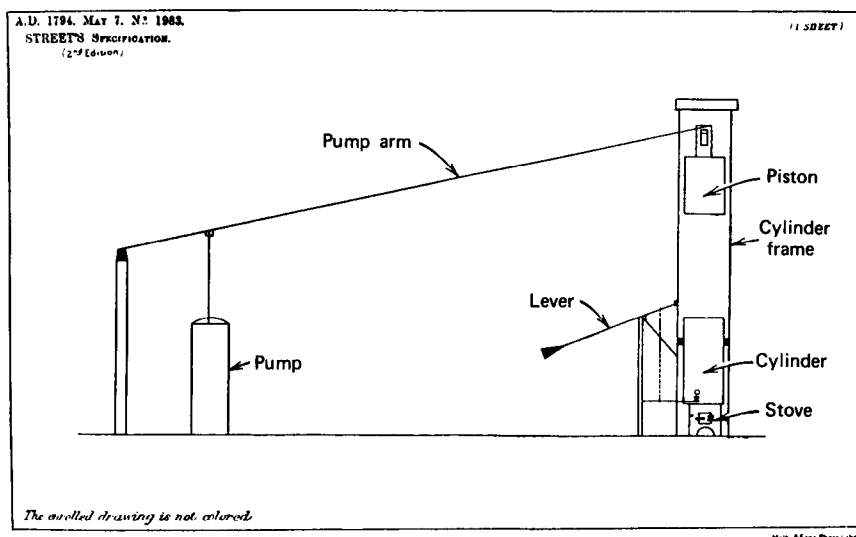


Figure 1. Robert Street's turpentine-fueled engine (redrawn from his 1794 English patent drawing.) [From *Internal Fire*, Lyle Cummins, 1976]

flame was raised to a touch hole in the cylinder wall. The cylinder's mixture of flammable vapor and rarified air ignited, driving the piston further upward in the cylinder frame. Gravity then forced the piston to return to its original position, completing the operating cycle. The manual operation and close attention required by Street's engine, as well as the engine's inherently low operating speed, kept this type of engine from gaining acceptance—so experimentation continued.

The remainder of the eighteenth century and the first half of the nineteenth century saw a wide variety of experimental engines developed by scientists and inventors around the world. It was 1860, though, before the first marketable internal combustion engine was developed. The Frenchman Jean J. Etienne Lenoir built and applied about 500 engines between 1860 and 1865. The Lenoir engine (Fig. 2) resembled a double-acting steam engine in appearance. It was a single-cylinder, horizontal, reciprocating engine with a crankshaft and flywheel. An electric spark ignited a gas and air mixture on each piston stroke, without compression.

By 1866, Nikolaus August Otto and Eugen Langen had developed a marketable vertical-cylinder engine in Germany. About 5000 Otto-Langen engines were subsequently produced.

Throughout the early 1800s, scientists became increasingly aware of the low thermal efficiency and poor fuel economy of early internal combustion engines. Many recommendations for improving engine

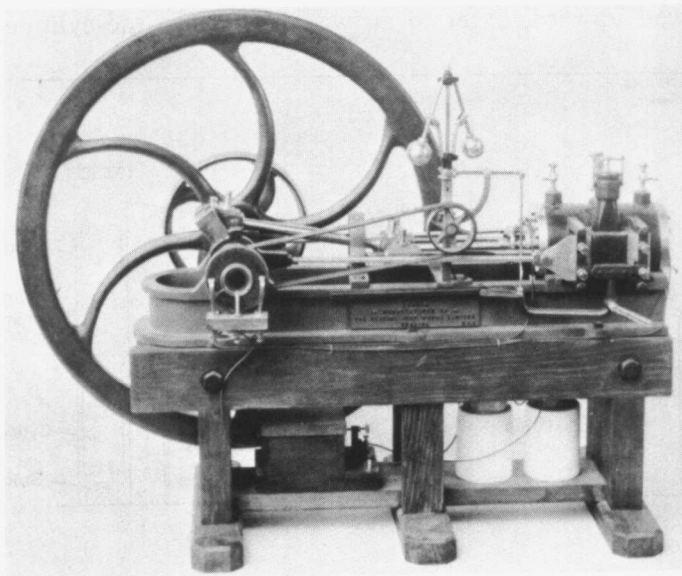


Figure 2. Lenoir noncompressing gas engine, 1861. [The Science Museum, London. From *Internal Fire*, Lyle Cummins 1976]

efficiency were made, but the suggestions were spelled out most completely in a little-publicized manuscript by the Frenchman Alphonse Beau de Rochas in 1862. To achieve the higher efficiency he desired, Beau de Rochas proposed to use a single-cylinder engine with the following four piston strokes:

1. Admission of gas and air charge.
2. Compression of gas and air charge.
3. Ignition of fuel charge at dead center point with subsequent explosion and expansion of gases.
4. Discharge of products of combustion from the cylinder.

Although Beau de Rochas had formulated the four-stroke cycle concept, he never built an engine based on his theory. The concept was first implemented by Nikolaus Otto, who, in 1876, built an engine (Fig. 3) designed with the same basic principles Beau de Rochas had outlined earlier. In 1878, Otto's engine was formally introduced to the world; and by 1890 nearly 50,000 four-stroke cycle engines had been produced (4). Because Otto was the first to implement the four-stroke cycle concept, engines operating in this manner are now commonly referred to as Otto-cycle engines.

The basic operation of four-stroke cycle spark-ignition piston engines (Fig. 4) remains the same today as when Otto's four-stroke engine was

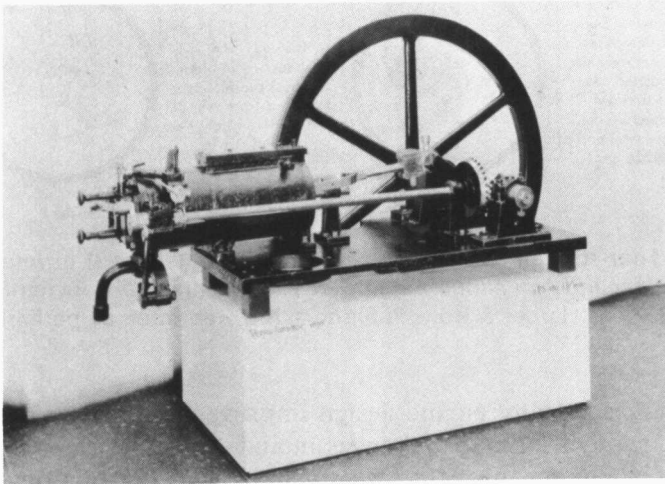


Figure 3. Nikolaus A. Otto's first four-stroke cycle engine, 1876; the engine developed 3 hp at 180 rpm. [Werkphoto Deutz. From *Internal Fire*, Lyle Cummins, 1976]

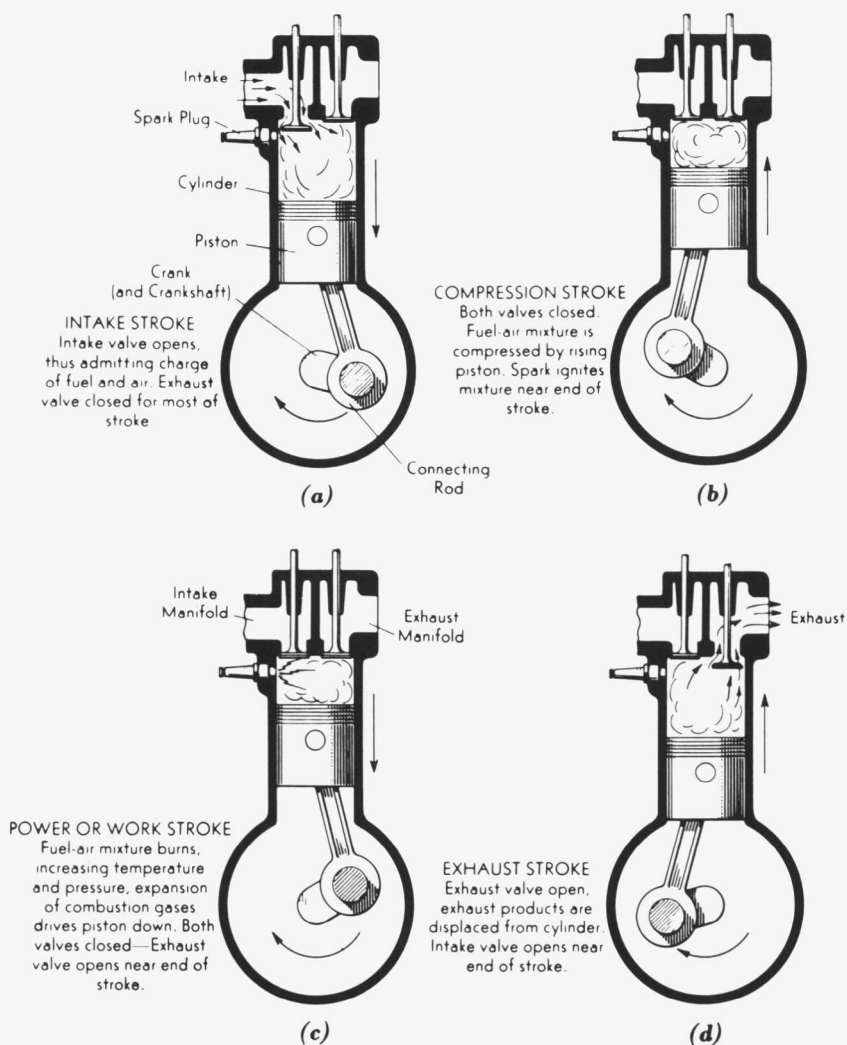


Figure 4. Four-stroke-cycle engine operation. [Fig. 1-1 (p. 3) in *Internal Combustion Engines and Air Pollution* by Edward F. Obert (In text). Copyright 1944, 1950, © 1968, © 1973 by Harper & Row, Publishers, Inc. Reprinted by permission of the publisher]

first introduced. Many engine design improvements have occurred over the years, though. Principal changes include increases in engine operating speeds, increases in operating efficiencies, and reductions in engine weight and bulk.

By 1880, several inventors had successfully applied the two-stroke cycle concept to internal combustion engines. A two-stroke cycle

engine combines exhaust and intake steps near the end of the engine's power stroke.

In most cases, two-stroke engines do not have valves. The fuel charge enters and exhaust gases leave through ports in the engine's cylinder walls. A cycle begins when a compressed fuel charge is ignited near piston top dead center. Expanding gases force the piston downward for the engine's power stroke. Near the bottom of its power stroke (Fig. 5), the engine's exhaust and intake ports are uncovered, expelling exhaust gases from the cylinder while transferring a fresh fuel charge from the engine's crankcase into its cylinder. The exhaust and intake ports are then covered again during the engine's compression stroke. Also, a new fuel charge is drawn into the engine's crankcase during the compression stroke.

Two-stroke cycle engines are generally simpler and less expensive to build than four-stroke engines. Furthermore, a two-stroke engine has a higher power/weight ratio than a four-stroke engine. The major disadvantage of most carbureted two-stroke engines relates to the engine's scavenging process—the method used to replace a cylinder's exhaust gases with a fresh fuel charge. During scavenging, on a ported engine, some fresh fuel will escape through the exhaust port with burned gases. This reduces fuel efficiency and results in high levels of some air pollutants.

At the present time, efforts are being made to produce two-stroke engines that lose no fresh fuel during scavenging. One technique that has been applied uses air to scavenge exhaust gases and then injects fuel directly into the cylinder after exhaust port closing. Alternative approaches use unique engine configurations that scavenge with pure air before fresh fuel is transferred from the engine's crankcase into its cylinder.

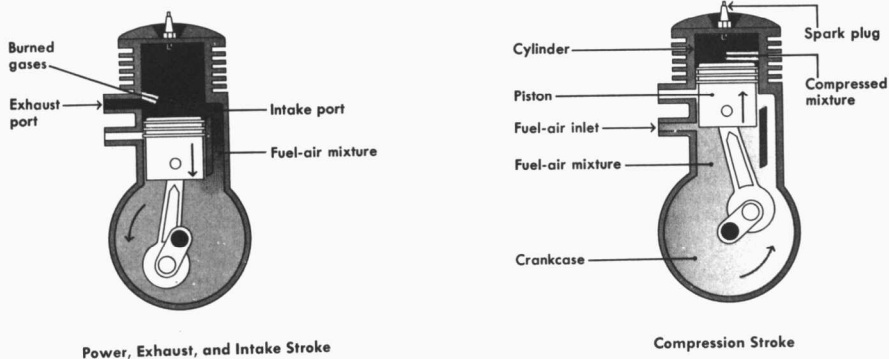


Figure 5. Two-stroke-cycle engine operation. [From *The World Book Encyclopedia*. © 1981 World Book-Childcraft International, Inc.]

2.2. Compression-Ignition Piston Engines

In 1892, the German scientist Rudolf Diesel proposed a four-stroke piston engine that could burn kerosene or coal dust without spark ignition. His first successful engine was completed in 1897.

The Diesel cycle is similar to the Otto cycle except that a much higher compression ratio is required, and air alone—instead of a combustible mixture—enters the cylinder on the engine's intake stroke. During the engine's compression stroke, the air in the cylinder is compressed to a high pressure. This rapid compression increases the temperature of the air enough to cause spontaneous ignition of fuel as it is injected into the cylinder near the beginning of the engine's expansion (power) stroke.

Rudolf Diesel is recognized as being primarily responsible for the development of compression-ignition piston engines. Consequently, the terms compression-ignition and Diesel are now used interchangeably.

2.3. Continuous-Combustion Gas Turbine Engines

A gas turbine engine is a continuous combustion device whose exhaust gas flow can either be used to provide thrust or to drive an output shaft. The fundamental principles on which gas turbine engines operate were established long before such an engine was successfully applied. In 1791, the Englishman John Barber outlined all the basic elements of a gas turbine engine—but he did not build one.

In 1872, the American inventor George Brayton developed an engine that allowed constant pressure combustion with the capability of expanding burned gases to atmospheric pressure. Brayton's engine used two pistons to achieve this purpose, but the basic thermodynamic cycle proposed by Brayton is the cycle that gas turbine engines operate on.

By the early 1900s, several gas turbine engines had been developed, but none of these early engines received significant usage. Then, several advances brought commonplace usage of gas turbine engines closer to reality. Major advances included improvements in the aerodynamics of engine components, improved cooling system designs, and the development of materials capable of withstanding the high temperatures inherent in gas turbine engines.

The first major application of a gas turbine engine took place in the 1940s when it was successfully implemented as a jet aircraft engine. Today, gas turbine engines are used to power most military and commercial aircraft. Other typical applications of gas turbine engines include ships, electric generating stations, pipeline pumping stations, and heavy industry. Also, gas turbine engines are receiving some consideration for use in trucks and automobiles.

2.4. Rotary Combustion Engines

Efforts to develop a rotary combustion engine reflect the desire of inventors to eliminate the complexities and material stresses inherent in reciprocating-piston engines. Attempts to develop a mobile rotary power source actually predate the internal combustion engine. In the eighteenth and nineteenth centuries, several rotary steam engines were developed, but none received large-scale application (7).

By the end of the nineteenth century, rotary engine design efforts shifted from steam engines to internal combustion engines. Although a wide variety of experimental rotary combustion engines have been proposed over the years, the first practical rotary engine was not produced until 1957. That engine, which evolved through many years of research and development, was based on the designs of the German inventor Felix Wankel.

The Wankel engine uses a triangular rotor in a specially shaped, ported chamber. The engine operates on the Otto cycle with the four operating steps (intake, compression, power, and exhaust) occurring in different sections of the engine's chamber (Fig. 6). The engine produces three power impulses per rotor rotation, but internal gearing causes the driveshaft to rotate once for each power impulse.

3. INTERNAL COMBUSTION ENGINE NOISE

Several alternative methods can be used to classify internal combustion engine noise. The two most typical classification techniques are discussed here.

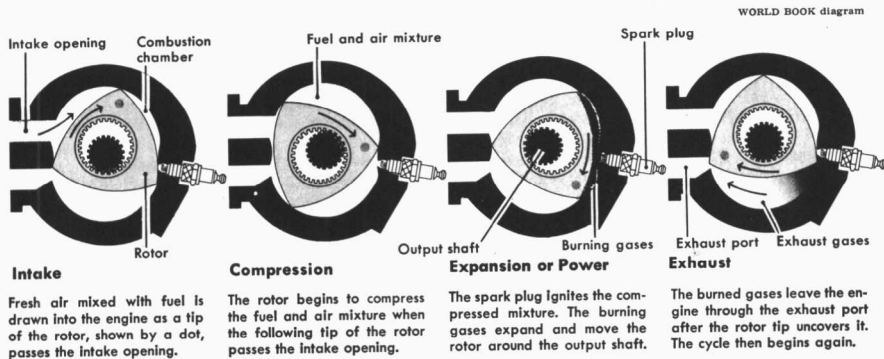


Figure 6. Wankel engine operation. [From *The World Book Encyclopedia*. © 1981 World Book-Childcraft International, Inc.]