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FURTHER TIME DOMAIN ANALYSIS OF EXHAUST PRESSURE PULSES FROM A SMALL ROTARY ENGINE

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INTRODUCTION

Although the novelty of using rotary engines as power plants in automobiles has worn off, the engine cannot be written into history. There are a number of areas such as recreational vehicles or other applications where the smoother power output and smaller number of moving parts may be advantageous. It is also important to note that, in the interests of fuel economy, the specific fuel consumption of a rotary engine does not differ greatly from that of an equivalent four-stroke engine and it is better than that of an equivalent two-stroke engine. The problem area of light load performance has, in fact, largely been eliminated by design improvements.

It has been shown in previous work [1] that, nonlinear behaviour of the exhaust pressure wave does occur over a large portion of the operating range of a small (4.8 kW at 5500 R.P.M.) rotary engine. The observation that the blow-down pressure wave at the exhaust port is essentially a distorted positive half of a sine wave is important. This leads to an alternate way of analysing the pressure wave in an exhaust system. The most commonly implimented approach is the use of the method of characteristics in conjunction with a computer simulation of the exhaust system [2]. Essentially this method makes use of compressibility effects which contribute to changes in the speed of sound in the exhaust gas. The objective is usually the determination of the pressure as a function of time at a specific location in the exhaust system. The difficulty with this method is that it is an iterative technique in which the location of interest in the exhaust system must be specified as well as the property to be determined. The entire process must be repeated if it is necessary to predict the behaviour of the same property at a different location. What is needed is an alternate approach in which the pressure wave propagation can be predicted from the knowledge of its properties at one point only.

It has been observed that the pressure wave is composed of a fundamental frequency component and a finite number of higher harmonics. The low number of harmonics, which contribute significantly to the wave form, make it possible to attempt to model the pressure wave by a truncated representation of the infinite series:

$$\frac{P}{P_o} = 2 \sum_{n=1}^{\infty} \frac{Jn(nx/l)}{(nx/l)} \operatorname{Sin} n(\omega t - kx) \qquad (1)$$

Where: P and P_o are the local wave pressure and local peak wave pressure respectively, n is the harmonic number, Jn is the Bessel function of the first kind of order n, x is the distance that the wave has travelled from its point of origin, l is the distance that the wave must travel before a shock wave starts to form (the discontinuity distance), ω is the angular velocity, t is time and k is the wave number. The truncation of the series is made at the twenty-first term because there are a limited number of harmonics in the exhaust pressure wave and because the values of the higher order Bessel function approach zero.

PROCEDURE

Equation 1 is nonlinear and it would be difficult to map experimentally derived data in a way such that normal correlational procedures could be used. The present method involves the use of an iterative procedure employing a Taylor Series expansion for minimizing the least square error between the data and the mathematical model [3]. The procedure does require that the experimental data be digitized. This was accomplished by feeding the analog pressure signal into an eight bit analog to digital converter, compatible with an Apple II+ personal computer. The computer was configured to sample the analog signal every 19.55 microseconds to measure either the calibrated peak pressure or the time varying pressure. Each sampling run consisted of 22,016 consecutive data points. The data was then processed to determine the average peak pressure in the sample or to save only that portion (from 2000 to 3500 samples) which was associated with the exhaust pressure wave. In addition, during the second processing procedure, the mean value of the data was determined. This was used to identify a reference point in the sampling time with which to couple the modelling equation.

Three parameters in the modelling equation were varied to fit the data. These were P_o, ω and x/l. P_o was varied to best fit the peak pressure value of the waves. The value 2π f was substituted for ω, where f designates the pseudo frequency of the wave; this was varied to obtain the general sinusoid that would best fit the pressure wave shape. Finally, to fit the sinusoidal model to the distorted pressure wave, the value of x/l (distortion coefficient) was varied. The results of this curve fitting yielded correlation coefficients of better than 0.98 for all waves where the number of consecutive waves sampled varied from 13 to 33.

RESULTS

Figure 1 is a plot of the ratio of peak wave pressure (also called the peak acoustic pressure) to the absolute static pressure versus engine speed. It can be seen that 75% of the engine operating conditions fall in the range above the limit of the linear acoustic theory range. The trend of the data appears to be linear except for the dip in the data at approximately 4800 R.P.M. This phenomena can be explained by using Figure 2 which is a graph of pseudo wave frequency versus engine speed. It can be seen that the pseudo wave frequency at 4800 R.P.M. is approximately 218 Hz. This information can be combined with measured average exhaust gas temperature of 555°C. This corresponds to an approximate speed of sound in the gas of 576 m/s. For a 1.52 m exhaust pipe treated as open at both ends, the resonance frequency is 189 Hz. This corresponds closely with the pseudo frequency of the wave. When the transit time for an exhaust wave to travel to the end of the exhaust pipe and have its expansion wave return is calculated, it indicates that the expansion wave arrives during the minimum volume condition of the exhausting chamber. Thus it is a tuning effect.

Figure 3, the graph of distortion coefficient versus engine speed, illustrates the fact that the wave is distorted at the lowest engine speeds. The scatter in the data makes it difficult to predict any trend, however; it indicates that the point in the exhaust pipe, at which the shock will develop, moves closer to the exhaust port. Therefore, for high engine speeds, the nonlinear effects will be greater and will occur sooner in the exhaust pipe.

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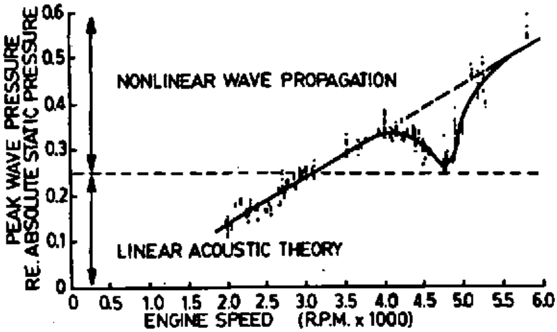

FIGURE 1. GRAPH OF PRESSURE RATIO VERSUS SPEED

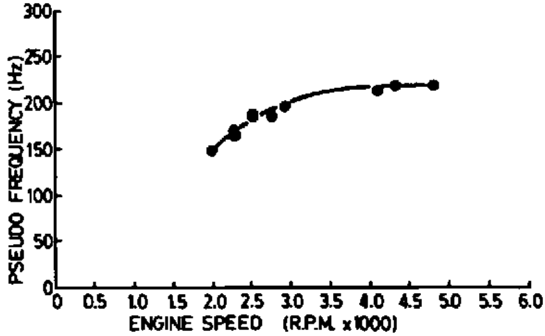

FIGURE 2. GRAPH OF FREQUENCY VERSUS SPEED

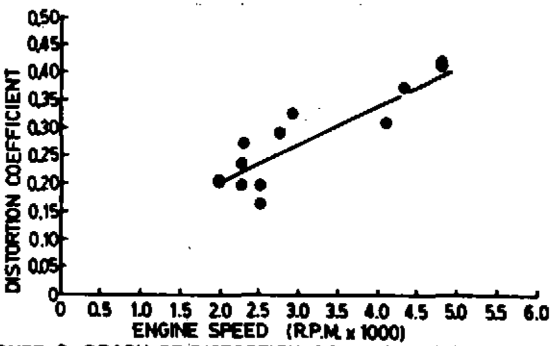

FIGURE 3. GRAPH OF DISTORTION COEFFICIENT VERSUS SPEED