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HYBRID SYSTEMS FOR I.C. ENGINE BREATHING NOISE SYNTHESIS

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A summary is given of progress in the development of realistic models for predicting noise emission associated with a prescribed time varying source. The wave motion developed in I.C. engine intake and exhaust ducts provides the particular example described here. It is a result of non-linear wave propagation from the time varying source at the valves interacting with the remainder of the intake/exhaust system acting as an acoustic filter.

1. INTRODUCTION

Current and future intake and exhaust system design objectives include satisfying the increasingly severe legislative targets for noise and pollutant emissions on the one hand, with the optimisation of engine performance with increasing fuel economy accompanied by improvements in vehicle quality on the other, in response to the demands of the market. The design process includes a careful tuning of all the components of the intake/exhaust system with an optimised matching of these to the engine breathing characteristics that influence emissions, performance and economy. Such design objectives interact, since they involve several common factors which may conflict, implying that integrated design procedures are strongly desirable if not essential. Assessment of an integrated design begins with a comprehensive simultaneous evaluation of the wave action throughout the intake, valves, cylinder and exhaust corresponding to all likely conditions of engine operation, rather than such treatment for each of these components individually. The information thus provided can be processed to assess the current performance in terms of all the design objectives to provide a rational basis for optimisation.

Practical experience and acoustic theory suggest that the spectral content of the acoustic emissions of both intake and exhaust systems is strongly controlled by their acoustic behaviour, that is by their filter characteristics which may be readily described in the frequency domain. However, noise emissions are scaled in amplitude by the engine volume velocity output, which acts as the primary source. The associated engine breathing characteristics depend on gas dynamic processes which are non-linear and can only be reliably evaluated in the time domain. This suggests the adoption of a hybrid approach to system modelling, with elements with significantly non-linear behaviour analysed in the time domain, while elements with behaviour approaching that of an acoustic filter are analysed in the frequency domain. Provided the filter characteristics can be realistically represented by a systematic time sequence of stationary acoustic transfer spectra, an inverse Fourier transform of each member provides a record of its impulse response in the time domain, which can then be convolved with the associated time varying source to model the cyclic wave action throughout the combination.

2. TIME DOMAIN MODELS

Analytic procedures for modelling the gas dynamics associated with the cyclic wave action in intake and exhaust, whether as isolated or as integrated systems, are well documented in the literature, since they have been subject to development and refinement throughout most of this century. The calculations normally start with the unsteady discharge from the cylinders through the valves and progress towards the open termination. The gas dynamics is modelled by the partial differential equations representing conservation of mass, linear momentum and energy transport and the fluid's constitutive equations or the equation of state, taken together with the geometrical and surface properties of the boundaries. They are then solved numerically using a digital code representing the method of characteristics (MOC), the corresponding system of finite difference equations, or by some equivalent analytic procedure.

The successful and systematic application of such models to slow running heavy diesel engines of improved design [1] or to high performance racing two strokes [2] is well documented. But their corresponding lack of success to date in providing sufficiently realistic predictions of noise emission [3, 4] is also widely recognised. There are a number of well established reasons for this. A primary cause is the adoption of unrealistic boundary conditions for describing flow through the valves and wave transfer across and reflection from area and similar discontinuities with the other geometrically complex elements that together form essential features of practical intake or exhaust systems. Furthermore, though the models do set out to satisfy conservation of mass in the cylinder, they often fail to do so effectively throughout the intake the exhaust downpipe, or the rest of the system. Existing calculation procedures or codes often adopt ambient conditions for the initial values of pressure and temperature, with the fluid at rest, for starting the calculations, which can take of the order of hundreds of engine cycles to converge satisfactorily. Arbitrary increase of wave damping to hasten such convergence [1] may yield time histories of the unsteady breathing characteristics that are satisfactory for some engine performance estimates, but remain unrealistic for the prediction of noise emission. It is also widely recognised that flow noise generated at various points along the intake or exhaust system by shear layers and unsteady vortex shedding may make significant contributions to the emitted sound. As far as the authors are aware, existing codes make no provision for the existence of such sources.

An alternative approach to the development of more realistic models is described in what follows. It depends on the successful formulation of a hybrid time/frequency domain simulation for the prediction of the acoustic performance of piston engine intake/exhaust systems. This adopts a time domain cycle to predict the instantaneous mass flow through the intake/exhaust valves, the method of characteristics, or its equivalent, to predict instantaneous pressure and particle velocities to the end of the intake runner/exhaust downpipe and frequency domain acoustics to propagate the pressure waves through the remainder of the system. The correct handling of the MOC/frequency domain boundary proved crucial for successful modelling.

3. BOUNDARY CONDITIONS

Since the gas dynamics of unsteady flow through constrictions and expansions is well established, realistic boundary conditions in relation to the flows through the valves might seem to present little difficulty in principle. For any practical case of current interest however, the situation is somewhat more complex, since the relevant position of the rigid bounding surfaces at the valve change with time, as does the pressure ratio across the valve, which is normally critical during the initial part of the exhaust process. The problem is further complicated by flow separation with the time dependent changes in flow direction that exist during valve opening.

Realistic models describing finite amplitude wave reflection, and thus the boundary conditions at an open termination, do already exist [5, 6, 7]. Rudinger [5] developed an analytic time domain model restricted to subsonic flows derived by performing an inverse Fourier transform of the corresponding acoustic reflection coefficient spectrum. This gave good agreement with observation for single pressure pulses with arbitrary time histories. Davies *et al* [6, 7] developed an alternative time domain model for continuous cyclic finite amplitude wave reflection derived from an empirical fit to many observations [6] which was in close correspondence with a subsequent analytically derived expression [7]. Also of interest here is the observation [5, 6] that the reflected wave was delayed by about the time in which a sound wave travels one or two duct diameters. This corresponds to the well documented end correction found with acoustic excitation of an open ended pipe, which is expressed either as an equivalent length of pipe or by the imaginary part of the corresponding complex pressure reflection coefficients spectrum.

Corresponding realistic and experimentally validated models appropriate for the other geometric features normally found with practical inlet and exhaust systems do not, to the authors knowledge, exist yet. Wave transmission and reflection with cyclically fluctuating finite incident waves was found to differ significantly [8] from that observed with single steep fronted waves although these have been adequately modelled [9] for some time.

However, acoustic characteristics such as impedance spectra, wave reflection and wave transmission spectra are readily derived with well established and experimentally verified methods [10] for almost any complex geometry. An inverse Fourier transform of such frequency dependent wave reflection spectra describing the corresponding wave reflection impulse function in the time domain represents the boundary condition describing their influence on the remainder of the system. This provides a first approximation in general terms, but is more realistic for those system elements that behave as an acoustic filter. The validity of such procedures has been already demonstrated [5], for one group of relevant specific examples. One notes that acoustic characteristics are a function of gas temperature and composition and of mass flow as well as of geometry, so may need updating accordingly as any calculation proceeds.

The mean gas axial temperature distribution along exhaust ducts (and across expansion chambers) provides an additional boundary condition which represents an essential factor in realistic acoustic modelling. Similarly it represents the local base line reference conditions along the downpipe, thus is also an essential factor for realistic calculations of the wave motion by MOC or equivalent methods. The gas temperature distribution is a function of heat loss from the exhaust system surfaces to the surroundings and of any reactions occurring in the catalyst., therefore it will depend on ambient conditions, engine speed and load, fuelling characteristics and so on. Thus it will be necessary to calculate boundary conditions relevant for each of an appropriate range of representative vehicle operating conditions.

3.1 Initial Data Set

The calculations of the wave action performed with a hybrid integrated system model divide naturally into those carried out in the frequency domain on system elements represented by linear acoustic models and those on elements represented by non-linear models and performed in time.

Once the relevant mean axial and radial temperature distributions have been established, along with the time averaged mass flow, well documented analytical procedures [10] are known to deliver reliable predictions of the related spectral characteristics. The flow temperature has a direct influence on the speed of sound and hence only on the frequency scaling while temperature gradients and mean mass flow have a significant influence on the shape of the spectral distribution. Thus along with the geometry these three flow related factors provide the data set, necessary for the acoustic calculations. This reduces to geometry, mass flow and ambient temperature for the intake system. The mass flow is directly related to engine breathing and is thus directly influenced by the non-linear wave action, which is not finally established until the calculations have been completed. Alternative methods are therefore required to establish appropriate initial estimates of the mean temperature and its gradients as well as the mean mass flow. These can be obtained by applying the scaling rules [11] that relate cyclic exhaust temperature and flow to cyclic cylinder geometry with the associated cycle thermodynamics. The cycle averaged values can then be processed along with the system geometry to estimate the corresponding mean temperature distributions and mean mass flow, yielding a first estimate for an initial data set for the acoustic calculations that can be appropriately updated as the calculations proceed. Estimated initial base line temperature conditions along the downpipe required for the time domain solution can be calculated in the same way.

3.2 Time Domain Convergence

Time domain solutions of the unsteady gas flows from the intake runner through the cylinder to the downpipe termination are necessarily iterative, with an essential requirement that they converge to a stable result. It turns out that the rate of convergence in terms of number of engine cycles required increases with the temporal and spatial resolution adopted for the calculations. Thus satisfactory convergence may require fewer engine cycles at the expense of many more calculations per cycle. The improved temporal resolution of the solutions that results is also beneficial since it increases the frequency resolution of the corresponding noise estimates. Such improvements carry the penalty of increasing the computational time to such an extent that on balance it becomes impractically long compared with the benefits achieved.

An alternative approach adopted by Benson [1] and his successors is to hasten convergence by the use of artificial friction factors for which there is no physical justification. Indeed experience demonstrates that the resulting time histories lack sufficient temporal resolution to provide realistic sound emission predictions. Clearly the more closely the starting values can approach the final stable solution, the more rapidly the calculations will converge. The scaling rules [11] mentioned above provide a rational estimate of the volume flows through the inlet and exhaust valves averaged over one cycle, which can be converted to a volume velocity impulse by dividing it by the proportion of the cycle time that the relevant valve is open. Convolution of this with the impedance impulse response of the corresponding linear element provides an initial pressure distribution in the corresponding intake runner/exhaust downpipe. The required impulse response is the inverse Fourier transform of the corresponding impedance spectrum already established by the acoustic calculations. Not surprisingly this results in a rapid increase of convergence. As already mentioned, the impedance spectra should be appropriately updated each cycle.

3.3 Conservation of Mass and Momentum

With stable engine operation at steady load and speed, conservation of mass implies that an appropriate cyclically averaged balance of working fluid mass must exist throughout the integrated system. This is reflected by constancy of cyclically averaged mass flux through every relevant cross-section along the integrated system and in particular throughout the length of the intake runner/exhaust downpipe. Similar considerations apply to the cyclically averaged momentum flux in the same two elements. The models adopted for the acoustic spectral calculations [10] always specifically conserve both mass and momentum flux, so the cyclic averages are only necessary for the iterative non-linear stepwise calculations in the time domain. Comparisons between observations and MOC calculations of the wave action in a cyclically excited pipe [12] indicated that a valid estimate of the time averaged mass flux was dependent on the temporal resolution of the calculated velocity records. When this was insufficient the value decreased monatonically, though slowly with distance along the pipe!, while the observed and predicted pressure records still remained in close agreement. In fact it turns out the calculation of realistic velocity time history records requires a much higher temporal resolution than that required for the corresponding pressure records, implying that pressure records alone may not provide a robust indication of the validity of solutions with MOC.

4. WAVE ACTION CALCULATIONS FOR INTEGRATED ASSESSMENT OF DESIGN OBJECTIVES

A comprehensive evaluation of the wave action appropriate for an integrated approach to design assessment requires the identification of all the factors that influence the results, together with quantitative descriptions of their individual and interacting behaviour. The hybrid model assumes that the acoustic behaviour of the system has a major influence on the spectral content of the noise emissions which are scaled in amplitude by the engine volume velocity output. Acoustic assessments require prior descriptions of the cyclically averaged temperature distributions and mass flow associated with the corresponding system elements. It is assumed here that these basic gas temperature and flow parameters can be defined initially by appropriate scaling of the corresponding thermodynamic cycle and then appropriately updated after each cycle.

As the calculation proceeds the engine volume velocity output is established from the time domain solution based on the method of characteristics. The MOC calculations are carried out over the lengths of the input runner/exhaust downpipe. They require descriptions of the cyclic conditions in the cylinder with those at the adjacent ends of the pipe to quantify the corresponding flows through the valves, together with appropriate descriptions of wave reflection at their junctions with the rest of the system. It is assumed that an inverse Fourier transform of the acoustic reflection coefficients spectra provides a realistic temporal description of wave reflection at the junctions. It is further assumed that cyclic conditions in the cylinder and the corresponding impulsive flow through the valves can be derived initially from the corresponding thermodynamic cycle. Finally, it is assumed that the inverse Fourier transform of spectral descriptions of the acoustic impedance at the junctions after it is convolved with the volume velocity can then be appropriately rescaled to define the initial pressure distribution in the respective pipes before the calculations start. To maintain the temporal resolution necessary for realistic noise estimates one must re-establish an appropriate pressure distribution after each cycle.

The last assumption considerably enhances the rate of convergence, while the values of all the relevant parameters are reassessed at the end of each cycle until the resulting wave action converges to an acceptable solution. As well as a cyclically repetitive pressure signal the criteria by which this is assessed include conservation of cycle averaged mass and momentum flux. Although many details require further refinement and the relative validity of all the assumptions has not been fully investigated, calculations already performed with preliminary computer code are already yielding realistic results.

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