Chapter 1

Introduction

One of the results of the continuing search for higher performance propulsion systems is the development of ultra high bypass turbofan engines. These large engines have bypass ratios in the range of 10:1 to 15:1, compared to 4:1 to 6:1 for the conventional turbofan engine (Thomas et al. 1995). At this high level of bypass ratios, the jet noise which usually dominates the engine noise signature, is significantly reduced thus leaving the fan as the primary engine noise source (Ribner 1975) and hence as the primary target for noise control (Groeneweg 1996). The typical noise signature of a high bypass turbofan engine indicates that at subsonic tip speeds, the discrete frequency tones generated by the fan or by fan/stator interaction are typically 10 dB to 15 dB above the broadband noise level (Groeneweg 1991; Hanson 1975). Attenuation of these fan tones would therefore significantly reduce the total sound power radiated by the fan.

One way of reducing fan noise is to use "quieter" fans (wide-chord, low aspect ratio fans) (Gliebe 1992; Dittmar and Woodward 1992). This type of fan demonstrates significant noise reduction at subsonic and transonic tip speeds, thus providing a first step toward meeting the Federal Aviation Administration community noise level regulations. However, for a large engine such as the ultra high bypass turbofan engine, these quieter fans produce significantly lower blade-passing frequencies than conventional fans since they tend to operate at lower RPM and have lower blade numbers (Montegani 1972;

Gliebe 1992). Therefore, if inlet and exhaust duct liners are to be used to obtain additional fan noise reduction, they will have to be thicker (in order to tune to the low frequencies) than what can possibly be accommodated in the available nacelle space without a significant weight and drag penalty. Moreover, the shorter and wider inlet duct inherent to the ultra high bypass turbofan engine makes passive attenuation of inlet fan noise even more difficult (Lowson 1975), since the pressure waves generated by the fan are refracted toward the engine axis as they propagate in the inlet against the boundary layer thus making the duct liners less effective.

Since duct liners do not appear to be a feasible method to completely reduce the radiated fan noise from ultra high bypass turbofan engines to acceptable levels, the door is left open to consider the potential that active noise control techniques may have toward achieving the same goal.

1.1 Overview: Active noise control - concepts and background

Several reviews such as Elliott and Nelson (1990), Nelson and Elliott (1992) and Fuller and Von Flotow (1995) discuss the concepts and historical background of active noise control.

The basis of active noise control rests on Young's principle (Hastings 1960) which states that the superposition of two acoustic waves 180 degrees out of phase results in silence (Figure 1.1(a) and 1.1(b)). This principle was first formally applied to active noise control by Lueg in 1934. He designed a system to actively control a sound wave propagating in a duct (Lueg 1934) as described in Figure 1.2. A microphone M detects a sinusoidal sound wave S_1 propagating in a duct. The microphone signal is fed through a controller V before driving a loudspeaker L, placed downstream from the microphone.

The controller is adjusted such that L produces a sound wave S_2 180 degrees out of phase with the disturbance wave S_1.

Lueg also introduced the concept of feedforward control, as his control approach required prior knowledge of the disturbance in order to generate the control field. The feedback control approach was introduced in 1953, by Olsen and May. In the control system that they designed (shown in Figure1.3), the loudspeaker generating the control field and the microphone detecting the sound disturbance were placed close to each other. The disturbance signal registered by the microphone is fed back to the loudspeaker after passing through a controller (high-gain inverting amplifier). The arrangement of the loudspeaker and the microphone is characteristic of the feedback control approach.

In 1956, Conover introduced two other important concepts of active noise control: (i) The use of a reference signal that is related to the sound generated by the noise source, and that is used in the feedforward control approach as input to the controller; (ii) the use of error sensors to monitor the controlled field and to adjust the controller such that the radiated noise be minimized. Conover applied these concepts in his study of active control of electrical transformer noise (Conover 1956).

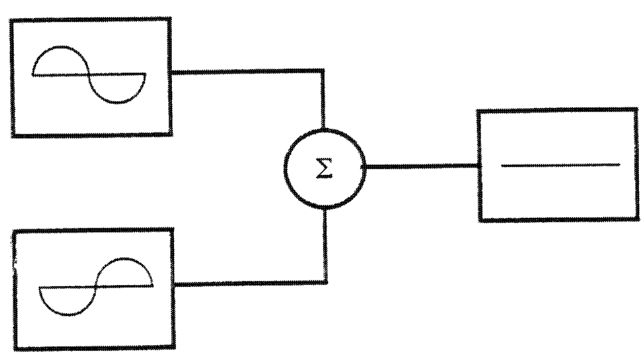

Figure 1.1 (a): Young's principle of superposition for a sine wave

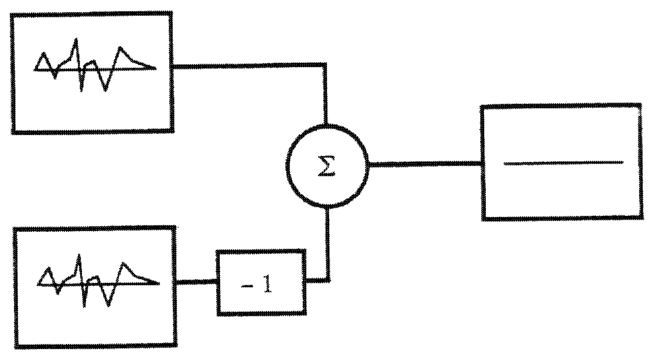

Figure 1.1 (b): Young's principle of superposition for a complex wave form

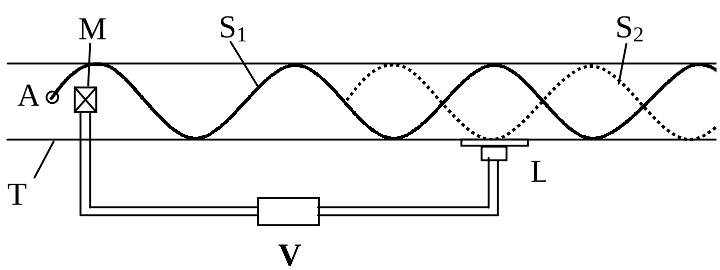

Figure 1.2: Diagram from Paul Leug's 1934 patent (feedforward control)

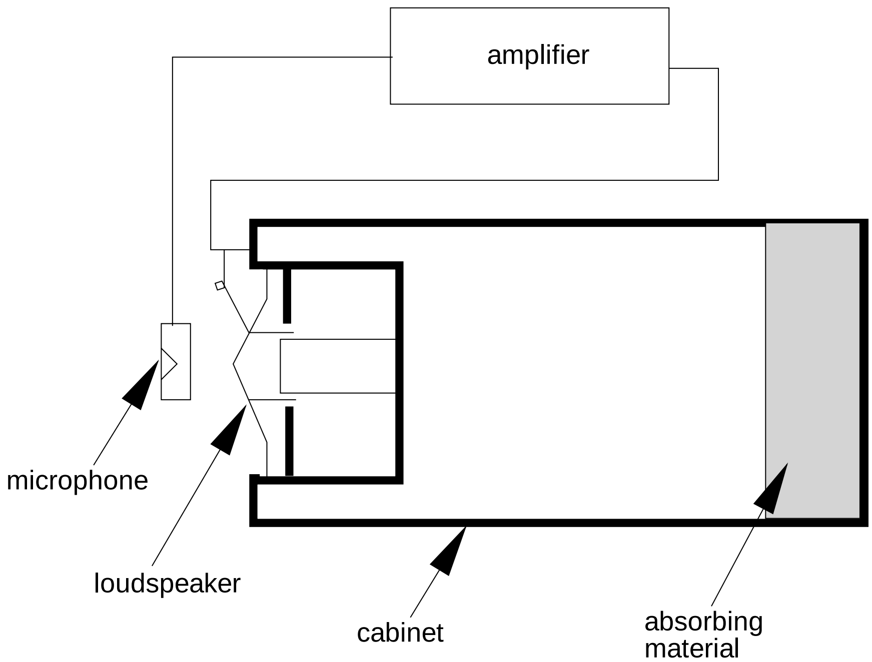

Figure 1.3: Illustration from the work of Olson and May (feedback control)

In this early stage of active noise control, the controllers were analog and adjusted manually in order to achieve optimum results. The application of active noise control was therefore limited to simple physical systems where the offending sound field was not subject to significant amplitude, phase or frequency changes. With a better understanding of the physics of acoustical systems, the development of adaptive algorithms and the appearance of inexpensive, powerful digital signal processing components, the field of active noise control has boomed over the last two decades (Jessel 1988). Several extensive reviews of active noise control discuss the state of the art (Warnaka 1982; Ffowcs-Williams 1984; Stevens and Ahuja 1990).

Examples of applications of active noise control are interior noise reduction in aircraft cabins (Elliott et al. 1989; Elliott et al. 1990; Dorling et al. 1989; Fuller et al. 1990), control of power train or road noise inside cars (Elliott et al. 1987; Elliott et al. 1988; Hasegawa et al. 1992; Sutton et al. 1994), propeller noise control (Slikuddin et al. 1984; Bullmore et al. 1987; Salikuddin et al. 1988), feeddback-silenced headsets (Van Laere and Sas 1988; Veit 1988), and control of turbofan engine tone noise which is the subject of this research.

1.2 Overview: Active control of turbofan engine tone noise - Experiments

The potential of active control techniques in reducing fan tone noise radiating from the duct of a turbofan engine has been demonstrated experimentally.

In the early nineties, a set of experiments was conducted at Virginia Tech on a Pratt and Whitney JT15D turbofan engine (Burdisso et al. 1992; Thomas et al. 1993; Thomas et al. 1993b; Burdisso et al. 1994). In these experiments, the fan blade passage frequency tone, the first harmonic, and the high pressure compressor tone radiating from the inlet of the engine were targeted for control. The engine was configured so that either axisymmetric modes (i.e., plane wave and radial modes) or first order circumferential modes were propagating in the engine inlet. These modes were controlled using an adaptive feedforward control algorithm. Two reference sensors, one placed at the fan stage location and another on the tachometer shaft from the high pressure spool, were used to provide time histories of the fan blade passage frequency and of the high pressure compressor fan blade passage frequency to an electronic controller. The control sources, driven by the electronic controller, were electromagnetic loudspeakers attached to exponential horns, and were mounted, evenly spaced, to the circumference of the engine inlet. The input to the control sources were aimed at minimizing the pressure at the error sensors (large area transducers of 7.6 cm diameter) placed in the far field of the inlet. First, a single-input, single-output controller was used in an attempt to control the axisymmetric modes propagating in the inlet at the fan blade passage frequency. A single error transducer was used and all the control sources were driven with the same control signal. A zone of noise attenuation was obtained over a thirty degrees sector around the error transducer location, with a maximum reduction of 20 dB on the engine axis. However, the sound power levels increased above the level of the uncontrolled fan noise at other angles. Better results were achieved using a three channel multi-input, multi-output controller. Three error transducers were used and the control sources were arranged into three groups, each group being driven by one of the three control channels. With this configuration of the control system, a zone of sound attenuation could be obtained over a sixty degrees sector around the engine centerline with attenuation levels of up to 16 dB. The sideline spillover was also reduced significantly. The Virginia Tech researchers therefore demonstrated that global sound reduction could be improved by increasing the dimensionality, and implicitly the flexibility, of the control system. This work was significant as it was the first time that active noise control was applied to an operational turbofan engine.

Thomas et al. also demonstrated simultaneous control of the axisymmetric modes propagating at the blade passage frequency and at its first harmonic (Thomas et al. 1994). It was achieved by using either two single-input, single-output controllers or two three channels multi-input, multi-output controllers both arranged in a parallel configuration. This approach yielded 8.4 dBA reduction in the overall sound pressure level with the single-input, single-output controllers, and 12 dBA and 5 dBA reduction of the fan blade passage frequency tone and its first harmonic, respectively, with the two multi-input, multi-output controllers. Likewise, significant levels of attenuation were achieved using the parallel controllers approach to simultaneously control the fan blade passage frequency and the high pressure compressor fan blade passage frequency.

The Virginia Tech researchers repeated these experiments in order to control the first order spinning modes that propagated in the engine inlet at the fan blade passage frequency (Burdisso et al. 1994). Control of these modes was achieved using, as earlier, a three channel multi-input, multi-output controller, as well as a six channel multi-input, multi-output controller. With the six channel multi-input, multi-output control system, the twelve control sources were grouped in six pairs of diagonally opposite control sources driven out of phase by the same control signal. With this configuration, the control sources were able to excite only the spinning duct modes (unlike with the three channel control system configuration). The best results were obtained using the six channel multi-input, multi-output controller. An average reduction of 15.5 dB in sound pressure level were achieved over a fifty degree sector around the engine axis with reduced noise increase toward the sideline.

Error sensors placed in the far field allow a direct measurement of the quantity to be minimized, i.e., the far field pressure. However, the use of far field error sensors is not feasible in actual flight. For this reason, configurations of the control system where the error sensors are placed at other locations, such as on the aircraft fuselage, or in the inlet or outlet of the duct, have been studied.

Gerhold demonstrated the use of inlet error sensors for the active control of a plane wave and of first order circumferential modes radiating from the inlet of a ducted fan (Gerhold 1995). He considered a duct of 30 cm diameter; the outlet termination of the fan duct was assumed to be anechoic and the inlet was placed in an anechoic chamber where the far field sound measurements were made. The fan tone noise was generated by the impingement of the vortices shed from the rotor on downstream fan exit guide vanes. The number of fan exit guide vanes was adjusted in order to excite either the plane wave or the first order circumferential mode (of the lowest radial order) to dominance. The control system was composed of a single-input, single-output controller with a feedforward algorithm, a circumferential array of twelve control sources mounted in the inlet, upstream of the fan, and two error sensors placed in the duct inlet upstream of the control source array on opposite circumferential locations. In a first test, the ducted fan was configured with the same number of rotor blades and stator vanes in order to excite the plane wave to dominance. The control sources were driven in phase by the same control input in order to generate a plane wave. The control input was computed such that the sum of the signals from the inlet error sensors was minimized. When the plane wave was the only mode propagating in the duct, a uniform sound level reduction of approximately 14 dB was achieved in the far field at locations from the fan axis (0 degree) to 90 degrees. In a second test, the first order circumferential mode was excited to dominance. The control sources were, this time, driven with a thirty degree phase shift in order to generate a spinning first order circumferential mode, and the control input to the control sources was computed such that the sum of the signals (added out-of-phase) from the inlet error sensors was minimized. Gerhold observed a virtual elimination of the far field radiation due to the spinning mode. Along the course of his experiment, Gerhold noted that the noise reduction measured by the inlet error sensors was generally greater than the noise reduction achieved in the far field, and that for some fan operating conditions, the inlet error sensors indicated noise reduction but noise increase was measured in the far field. Analytical studies (Risi 1994, Burdisso et al. 1995) have led to similar observations, and concluded that it was very difficult to achieve reduction of the far field radiation by minimizing the acoustic pressure at the inlet sensor locations.

Burdisso et al. used another control approach in order to demonstrate the active control of inlet tone noise, using inlet actuators and error sensors. Their experiment was conducted on a Pratt and Whitney JT15D engine (Burdisso et al.1995). The engine was configured so that only first order circumferential modes were propagating in the engine inlet at the fan blade passage frequency. A three channel multi-input, multi output controller with a feedforward control algorithm was used to control these modes. A circumferential array of twelve, evenly spaced, control sources was mounted in the engine inlet, upstream of the fan. The control sources were configured in three groups of four control sources each. In each group, the sources were wired such that they would generate first order circumferential spinning modes. Three error sensors were placed along the circumference of the engine inlet inner wall at a single axial location. The error sensors were rectangular large area transducers of dimensions 5 cm by 12.7 cm. Aware of the difficulty to achieve reduction of the far field radiation by directly minimizing the pressure at the inlet sensor locations, Burdisso et al. used a control approach where the control system was adjusted such that the response of the inlet error sensors matched that of a reference model response (Clark 1993). The reference model response of the inlet error sensors was determined such that it would result in sound reduction in desired regions of the far field of the inlet. The error signal to be minimized by the control system was therefore the difference between the actual and the desired (set by the reference model) inlet sensor outputs. With this control approach, Burdisso et al. were able to achieve reduction in sound pressure level of as much as 10 dB toward the sidelines and in the sectors of the far field with the highest levels of noise. An overall reduction of 1.3 dB of the radiated sound power level could be achieved.

Pla et al. developed yet another approach for the active control of fan noise using error sensors mounted in the engine duct (Pla et al. 1996). They refer to it as a modal control approach. As explained by Pla et al., the principle of their control approach was as follows: The sound field generated by the fan and a circumferential array of control sources was sensed by a circumferential array of error sensors located in the engine duct. A modal decomposition of the signals registered by the error sensors was then performed using a spatial Fourier transform to extract the amplitude and phase of each of the modes to be cancelled. Next, this information was used to adjust the amplitude and phase of each of the control modes. Finally, an inverse spatial Fourier transform was performed on the control mode signal to generate the control inputs for each control source. The controller was composed of a set of independent single-input, single-output controllers, one per mode to be controlled. This allowed the individual control of each of the modes propagating in the fan duct. This control approach was tested in the NASA Lewis

Research Center's 48 inch ANCF facility (Heidelberg et al. 1996). One circumferential array of control sources and one circumferential array of error sensors were placed in the exhaust of the fan duct where a single mode, the sixth order circumferential mode, was propagating. Pla et al. were able to achieve complete cancellation of the disturbance mode at the design frequency of the control system, thus reducing the radiated sound power level by as much as 30 dB. A reduction of at least 15 dB occurred over the rest of the tested frequency range (fan RPM). Pla et al. repeated this experiment for the case where two fourth order circumferential modes were propagating in the exhaust. In this case, the two modes were reduced simultaneously, yielding a radiated sound power level reduction of 15 dB. However, the level of noise reduction achieved in the far field depended greatly on an accurate control mode generation process. In operating conditions other than design modal spillover occurred, reducing the levels of sound attenuation that could be achieved in the far field.

The error wavenumber technique is another approach that has been used for active control of fan tone noise. With this technique, an axial array of error sensors is placed along the duct wall in order to observe the duct wavenumber components. Certain wavenumber components are then minimized in order to reduce the acoustic radiation towards specific directions in the far field. This active noise control approach was tested by Burdisso et al. on a JT15D turbofan engine at Virginia Tech (Smith et al.1997a) and on the ducted fan facility at NASA Lewis (Smith et al. 1997b). In these experiments, inlet radiation from spinning first order circumferential modes was targeted for control. A single circumferential array of control sources (phased to generate spinning modes of circumferential order one) and a single axial array of wavenumber sensors were mounted along the inlet wall. Because of the limited number of sensors that could be realistically placed along the duct, the resolution of the calculated estimates of the wavenumber components was limited. Nevertheless, Burdisso et al. found that this wavenumber sensing approach could be an effective way for reducing radiation towards particular directions in the far field, and that it could effectively reduce the fan tone noise.

All of the control approaches described so far involved the cancellation of the modes propagating in the engine duct via anti-sound. Another approach of active noise control that has been more recently tested involves the reduction of rotor wake/stator interaction noise via active aerodynamic control. This approach was demonstrated by Simonich et al. on an isolated airfoil (Simonich et al. 1992). The airfoil had a moveable trailing edge flap whose motion could be controlled to reduce the unsteady lift generated by an incoming periodic disturbance. The interaction noise caused by the fluctuating lift could be reduced by as much as 10 dB for certain harmonics. This approach was later extended to combine the use of oscillating flaps (aerodynamic control) with that of oscillating pistons (anti-sound) mounted on the stator vane. This technique was demonstrated experimentally by Minter and Fleeter (Minter and Fleeter 1995) in the Purdue annular cascade facility with an isolated vane and with a three vane row. First order circumferential modes propagating upstream and downstream were targeted for control. Minter and Fleeter demonstrated that simultaneous cancellation or reduction of the upstream and downstream propagating modes required that the number of control surfaces be equal to the number of acoustic modes to be controlled.

Analytical and computational models have also been developed to further study this aerodynamic/ anti-sound active control approach of duct fan noise. Hugo and Jumper developed a model to simulate the control of unsteady lift over an airfoil using trailing edge flap motions (Hugo and Jumper 1992). Kousen, Verdon, Minter and Fleeter modeled and studied the use of anti-sound actuators and/or trailing edge flaps mounted on the stator vanes for controlling the noise generated by wake/blade-row interaction (Kousen and Verdon 1993; Kousen and Verdon 1994; Kousen 1996; Minter et al. 1994; Fleeter 1994).

The present research work deals with the modeling of active noise control of duct fan tone noise based on an anti-sound approach. The models that are currently available to simulate and study this approach are reviewed next.

1.3 Overview: Active noise control models

Kraft and Kontos were among the first to develop a model to allow performance assessment and system design of active noise control systems for aircraft engines (Kraft and Kontos 1993). They modeled the propagation and control of inlet fan noise. Their analytical model, based on duct modal analysis, considered a hard walled cylindrical duct. Reflections from the duct openings and from the engine source plane were ignored, and the effects of mean flow were neglected. In their analysis, Kraft et al. assumed that the source modal content was known and that a single disturbance mode was cut on. The secondary control sources were modeled as square wave velocity sources radiating from rectangular shaped ports flush to the wall. These control sources were located around the periphery of the duct, at a single axial location and equally spaced. Kraft et al. used this model to determine the optimum number of ports, velocity amplitude and phase of excitation of each of the speaker ports, that are required to generate a control spinning mode that will couple destructively with the one that is being produced by the fan. Their results indicated that, in transducer design and operation, weight reduction may be a more important factor than power requirement. Hence, they determined that a number greater than twice as many ports as the desired spinning mode order is required to guarantee that the desired control mode dominates.

A few years later, Kraft extended his analysis to annular ducts in order to provide a first approximation to simulating active noise control in a fan exhaust system (Kraft 1996). In this later model, Kraft also included the effect of mean flow. He considered an axisymmetrical annular duct with constant inner and outer radii. The walls of the duct were assumed to be rigid, and reflections from the duct openings were neglected. A circumferential array of control sources was placed on both inner and outer walls of the annular duct in a single plane. The control sources were again modeled as rectangular shaped piston-like actuators. As explained by Kraft in his report, the approach he used to derive the analytical model for the annular duct case was very similar to the approach he used to derive his previous model - a classical modal solution to the wave equation in an annular duct with non-homogeneous boundary conditions was used. First, a transformation of variables method was applied in order to transform the homogeneous differential equation (the wave equation) with non-homogeneous boundary conditions to a non-homogeneous differential equation with homogeneous boundary conditions, which is simpler to solve (Friedman 1956, Boyce 1969). The solution of the non-homogeneous differential equation was then written as an expansion series of eigenfunctions of the radial modes and was inserted back into the non-homogeneous differential equation, yielding a new differential equation in terms of the expansion coefficients. This new equation was then solved using the method of infinite Fourier transform, and the complete expression for the pressure field was finally obtained by adding to the series of eigenfunctions a particular solution that satisfied the boundary conditions. Kraft demonstrated with this model that efficient matching between the primary and the control fields could be achieved when only a single radial mode was cut-on in the annular duct. He also observed that two coplanar arrays of control sources had a difficult time simultaneously controlling two radial modes.

Risi and Burdisso also developed an analytical model to predict the radiated sound field of a turbofan engine inlet and of an active control system (Risi and Burdisso 1994). They considered a duct of finite length with rigid walls. The inlet opening was assumed to be embedded in an infinite baffle, no mean flow was present, and reflections from the duct opening were deemed negligible. A feedforward algorithm was simulated. The control sources were modeled as circumferential arrays of point sources placed along the inner wall of the inlet, and the error sensors were modeled as point microphones placed in the far field. The control inputs to the secondary sources were computed by minimizing the sum of the error signal mean-square-values. The resulting controlled field was studied. The fan disturbance in the duct inlet was modeled as a sum of spinning modes (Tyler 1962), while the sound field generated by the control sources was based on Green's function in a hard walled infinite duct (Morse 1986). The radiated sound field was obtained by using the Rayleigh integral (Fahy 1989). In their study, Risi and Burdisso simulated the generation of first order circumferential modes for a small turbofan engine. An inlet diameter of 0.53 m and an inlet length of 1 m were considered. The first three radial modes were assumed to be cut on and to be propagating with the same magnitude. Different configurations of the control system were studied, the primary objective being to attenuate the radiated noise in all directions of the far field of the inlet. They found that the locations of the error sensors and the configuration of the control sources were equally critical to the operation of the active noise control system, and they also demonstrated that multiple arrays of control sources were required to reduce higher order radial modes. In a subsequent study (Risi 1994), Risi and Burdisso extended their model to include the effect of mean flow and to model the use of inlet mounted error sensors.

In 1995, Burdisso, Fuller and Glegg (Burdisso et al. 1995) developed a model for active control of tonal inlet fan noise with a more realistic representation of fan noise than that used in the previous models. In this model, the fan noise was assumed to be generated by the movement of the fan blades through the wakes of upstream obstructions, thus simulating previous experiments (Thomas et al. 1993 and Burdisso et al. 1994) in which the inlet fan noise was enhanced and made more deterministic by placing fixed cylindrical thin rods upstream of the fan. The engine inlet was modeled as a semi-infinite circular duct with rigid walls. The control sources were modeled as circumferential arrays of point sources placed at different axial locations of the duct inlet. In order to simplify the development of the analytical expression for the radiated sound field, the inlet opening was assumed to be embedded in a baffle (Goldstein, 1976). To derive the fan noise model, Burdisso et al. considered the problem of sound radiation from a time varying rotating force distribution in an open ended duct (Goldstein, 1976). A force distribution representing the time varying load per unit area applied by the fan blades to the fluid was defined at the section of the duct where the fan is assumed to be located. An expression for the pressure field generated in the duct by the fan was obtained in terms of Fourier series expansions of the fluctuating loading force and of the Green's function for a hard walled circular duct of infinite extent with a uniform flow. The Fourier coefficients of the loading force were obtained using the Wiener Hopf technique (Mani and Hovray 1970, Koch 1971 and Peake 1992). The acoustic field produced in the duct inlet by the control sources was obtained using Green's function for a hard walled infinite duct and ignoring the reflections from the fan. Finally, since the inlet opening was assumed to be embedded in an infinite baffle, the Rayleigh integral was used to compute the resulting radiated pressure in the far field of the inlet for the case of no mean flow. Burdisso et al. used this model to study the mechanisms of active noise control in attenuating inlet fan noise when using error sensors placed in the far field or along the inner wall of the duct inlet. Their results showed that when far field sensors were used, the control mechanism corresponded to a re-structuring of the duct modes which yielded a weak radiating source at the inlet opening. When inlet error sensors were used, they observed that the attenuation in radiated sound power was achieved by suppression of the significant radiating modes. Burdisso et al. also used this model to study the influence of the evanescent modes generated by the control sources on the performance of the control system. They concluded that the non-propagating modes had an important effect on control system performance since they generated control spillover towards the sidelines of the inlet opening.

All of the above models were based on infinite duct theory. Reflections from the duct opening were neglected and the computation of the pressure field was limited to regions upstream of the plane containing the duct inlet opening (or downstream of the plan containing the outlet opening, as in the case of the annular duct model developed by Kraft).

Berge, Bouty and Cailleau developed a model (Berge et al.1993) based on a boundary element method (Rego Silva 1994) which, as for boundary integral equation methods, allows a point wise computation of the pressure field anywhere inside or outside the duct, and implicitly accounts for reflections from the duct opening. However, Berge et al. did not include the effect of mean flow in their model, and only considered the upstream propagation and radiation of acoustic waves. A cylindrical duct of finite length with rigid walls and a bellmouth termination was modeled. This model also required prior knowledge of the pressure distribution in the section of the duct where the fan was assumed to be located. Hence, Berge et al. developed an expression for the pressure distribution in the fan section based on the expression for annular hardwall duct acoustical modes. The control field was generated by an array of eight piston-like control sources that were evenly distributed around the circumference of the duct. The pressure outputs of the control sources were modeled by considering a non-zero normal acoustical velocity at the assumed locations of the sources. Error sensors were placed in the far field of the radiation from the inlet and the output pressures generated by the control sources were computed in order to minimize the pressure at the error sensor locations. This model was used to reduce the noise radiating in specific regions of the far field of the inlet. Berge et al. observed that reduction in sound power level would occur only in the directions of the far field where error sensors were located.

Thus, the models that are currently available to conduct active noise control studies for turbofan engines, although very useful to help uncover the physical mechanisms of noise generation and control for a turbofan engine, are not very realistic nor versatile since they have most or all of the following limitations:

(i) The computation of the acoustic field is limited to regions upstream of the duct inlet opening.

(ii) They do not include simultaneous radiation from the duct inlet and outlet.

(iii) They do not include the effect of a mean flow.

(iv) They do not account for reflection from the duct openings.

(v) They do not account for the presence of evanescent modes.

(vi) They do not have liner (i.e., wall impedance boundary condition) capabilities.

(vii) They are limited to cylindrical duct geometry.

In order for a model to be a useful tool for designing active noise control systems for ultra high bypass turbofan engines, it has to be able to realistically predict the engine acoustic behavior. Thus, the model should include the effect of mean flow because it can significantly modify the duct modal content as well as the direction of peak radiation of the propagating modes. The model should also account for the presence of evanescent modes since they have been shown (Burdisso et al. 1995) to impact the control system performance. In addition, when a model only accounts for the upstream propagating modes and is restricted to provide information regarding the pressure field in regions located upstream of the inlet opening, any optimization effort will be limited to those regions only. Consequently, it is not known whether the configuration of the control system that would lead to the maximum attenuation of the inlet radiated sound power would also lead to a very large increase in sound power level of the outlet radiation, which would affect the EPNL.

Because of these shortcomings, a more advanced analytical model is obviously desirable. The algorithm used for computing the acoustic field should be fast, versatile, and reliable in order to efficiently conduct the parametric studies required during the design and optimization of an active noise control system.

Computational Aeroacoustics (CAA), Computational Fluid Dynamics (CFD) and finite element techniques have been used to compute ducted fan noise (Ozyoruk and Long 1995; Dong and Mankbadi 1995; Horowitz et al. 1986; Parrett and Eversman 1986;

Eversman 1997). These computational techniques have the advantages of being highly accurate and able to model the complex geometries of an actual engine nacelle. However, they require calculation of the entire region of interest and are therefore expensive and hence inappropriate to conduct parametric studies. Boundary elements methods (Berge et al. 1993) and boundary integral methods (Martinez 1990; Martinez 1993; Myers and Lan 1993; Dunn et al. 1996) are much less computationally expensive because they allow a pointwise computation of the pressure field and require detailed calculations only on the surface of the duct. However, their use is usually limited to the resolution of problems of simple geometries since the surface integrals that have to be solved in order to obtain the pressure field quickly become complicated when the method is used to model ducts of complex shape. Nevertheless, when it comes to conduct extensive parametric studies, the fact that the boundary elements and integral methods allow a point wise computation of the pressure field and require little computational time (compare to CAA, etc.), outweighs the fact that the use of these methods is (for now) limited to the modeling of ducts of simple geometry.

A model of active control of duct fan noise featuring the desired characteristics of reliability, versatility and rapidity could be developed by implementing active noise control to the ducted fan noise prediction code TBIEM3D (Dunn 1997). This code is based on a Boundary Integral Equation Method, the BIEM, which was developed by Dunn, Tweed and Farassat (Dunn et al. 1996, Dunn 1999). TBIEM3D predicts the acoustic pressure scattered by an infinitesimally thin, finite length cylindrical duct that has been irradiated by incident internal sound. The incident sound is generated by a collection of internal spinning point sources that are used to model the fan noise. The boundary conditions on the duct interior allow for an axially segmented, locally reactive liner with circumferential uniform impedance, which can be positioned anywhere inside the duct. This ducted fan noise prediction model includes the effect of a uniform mean flow, simultaneous radiation from the inlet and exhaust duct and the reflection at the duct openings (but not from the fan). It also accounts for the presence of evanescent modes and for edge diffraction, and permits noise predictions in the duct shadow region. Successful implementation of active noise control to this ducted fan noise prediction model would therefore lead to a model of active control of ducted fan engine noise that would be more accurate and much more versatile than the active noise control models that are currently available. Unlike the other active noise control models, this one would permit the computation of the pressure field at any location of interest inside or outside the duct, without being restricted to the regions upstream or downstream of the duct openings. This feature would allow, for example, the monitoring of the acoustic sound field downstream of the outlet and to the sides of the duct when active control of the inlet noise is being performed. Two other important features of this model are that it would include the effect of a mean flow and of the evanescent modes into its calculations. Hence, the influence that evanescent modes or a mean flow have on the performance of the active control of the fan noise could therefore be studied. Finally, the lining capabilities of this model would allow the user to study the performance that an active control system can achieved when used in combination with a liner.

1.4 Scope and objectives

The first objective of this work is to develop a model of active noise control for turbofan engines that overcomes many of the deficiencies of currently available models, thus resulting in a more realistic and useful model of active noise control for ultra high bypass turbofan engines. This is accomplished by implementing active noise control to the ducted fan noise prediction code TBIEM3D. This new model will simulate the propagation, radiation and control of the noise generated by an engine fan surrounded by a duct of finite length and cylindrical shape, placed in a uniform flow. The control sources are modeled by point monopoles placed along the periphery of the duct inlet and/or outlet inner wall. Feedforward control algorithms are simulated. Control of the sound radiation through the use of error sensors placed in the far field of the duct, or along the aircraft fuselage or the duct inner wall, is modeled. The spinning point sources originally used in the TBIEM3D code to model the fan noise are replaced by spinning line sources or by radial arrays of spinning point dipoles. The fan model based on spinning line sources is developed in order to model more accurately the forces that the fan blades apply to the medium, while the fan model based on radial arrays of spinning point dipoles is developed for the case where fan modes of specific phase and amplitude have to be reproduced.

The other main objectives of this work is to (1) use this advanced model to investigate the potential active noise control has in reducing fan noise for ultra high bypass turbofan engines. (2) study the physical mechanisms of active noise control in ultra high bypass engines. A case representative of a large turbofan engine in take off or landing conditions is considered. Pure active control techniques as well as hybrid control techniques (i.e., combination of active and passive noise control) are studied.

1.5 Organization

The remainder of this thesis is organized into six chapters. Chapter 2 describes the boundary integral equation method BIEM on which the ducted fan noise prediction code TBIEM3D is based. The development of two different fan models is presented in Chapter 3. Their purpose is also explained. Chapter 4 describes the approach use to implement active noise control to the TBIEM3D code. The model for the generation of the control field is derived, and the different algorithms of active noise control implemented into the code are described. The fan and control source models are validated in Chapter 5. Some demonstrative cases of active noise control are also presented in order to assess the feasibility of the model to perform active noise control studies and to investigate general mechanisms of control. In Chapter 6, the model is used to investigate the potential of active noise control to reduce fan noise on an ultra high bypass turbofan engine. Finally, conclusions drawn from this study, along with recommendations for further research, are presented in Chapter 7.