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Discrete tones in subsonic jet engine test cells

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ABSTRACT

Jet Engine Test Cells used in testing large engines are often plagued by the generation of discrete frequency tones of up to 170 decibels necessitating emergency stoppage of tests to prevent infrastructure damage. The mechanism(s) behind these tones is not well understood and they present a significant issue to airlines, engine manufacturers' and test cell operators. This work provides an overview of typical u-shaped jet engine test cells before briefly presenting the mechanisms of jet impingement, edge tones, diffuser noise and room acoustics as well as the possibility of each of these mechanisms being a source of discrete tone noise in jet engine test cells. The limitations of noise prediction models applied to jet engine test cells is discussed for each aforementioned mechanism and where possible noise predictions are made. Select literature relating to test cell tone generation and super resonance is presented before examining duct resonance and finding it to be a likely source.

1. Introduction

With the commercial aviation industry growing, the need for larger and larger airplanes - thus larger and larger engines - is on the rise. Larger engines output greater thrust and mass flow rates than those of the past and are routinely tested in ground facilities, named jet engine test cells (JETC), to assess their performance and reliability. Fig. 1 adapted from Ref. [1] shows a typical u-shaped JETC which is commonly used for commercial aircraft engine tests.

Airflow enters through the inlet silencer before being turned 90° by turning vanes. In addition to these turning vanes, it is typical for test cells to have flow conditioning devices at the inlet. A portion of the inlet air is ingested by the engine and the remainder bypasses the engine. The high velocity engine exhaust entrains the bypassed air into the circular augmentor tube. This entrainment is responsible for the net airflow through the test cell as there are no pumps or fans. The exhaust-air mixture travels down the augmentor tube (often referred to as the de-tuner in the UK, the ejector or simply as the duct in certain literature) where it mixes before reaching the diffuser and blast basket. The blast basket is a round perforated duct allowing the exhaust gases to escape while attenuating some noise. Located at the rear inside the blast basket is a forward facing cone. This cone serves to direct the exhaust gasses out through the porous blast basket. Finally, the air-exhaust mixture passes through the exhaust silencer and out to atmosphere.

Although the blast basket and exhaust silencers provide some attenuation, engine tests are often done at airports near residential areas where the test noise can be of large concern [2,3]. In addition, testing larger sized engines has created an environment in which acoustic phenomena (which are non-existent in small engine tests) have emerged. Under certain conditions, a test facility generates high amounts of infrasound (< 20 Hz) as well as a low frequency (20–100 Hz range) broadband and tonal noise of great intensity. There have been reports of tonal noise generation of up to 168 dB inside the Arnold Engineering Development Complex's test facilities [4] leading to large physical loads and emergency stops of testing in order to prevent or minimize damage to the facility. Although this phenomenon can be traced back to the 1980's [5] even today the mechanism of tone generation is seemingly not well understood [1,6,7]. This lack of understanding has led to very little progress in eliminating these tones despite a fair amount of research. It is worth mentioning that the noise source is hydrodynamic in nature and does not originate from structural vibrations. This report theoretically investigates potential sources of discrete tone noise generation in the 20–100 Hz range inside JETC's operating at subsonic conditions (the case for most commercial engines). More specifically, the aft portion of the test cell (the augmentor tube, blast basket, cone and exhaust) is examined. This report also amalgamates recent literature and studies of JETC noise, which is fairly disseminated.

2. Potential noise sources and mechanisms of discrete tone generation

2.1. Jet impingement noise

Although a JETC is a complex environment with many potential

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Nomenclature

A	Cross sectional area of the Helmholtz Resonator neck
C	Constant used in the edge tone
c	Speed of sound
C_a	Phase velocity of the impingement feedback acoustic wave
C_i	Phase velocity of the impingement downstream propagating instability wave
d	Diffuser inlet diameter
D	Diameter of the small whistler nozzle pipe
D_j	Impingement nozzle diameter
f	Edgetone frequency
f_d	Diffuser natural frequency
f_D	Diffuser frequency of oscillation
f_H	Helmholtz frequency
f_n	Impingement frequency
$f_{R,C}$	Room acoustics frequency, rectangular and close ended room
$f_{R,O}$	Room acoustics frequency, rectangular and open ended room
h	Edgetone nozzle to wedge distance
h_1	Step height of the whistler nozzle
i	Longitudinal duct mode
j	Azimuthal duct mode
k	Transverse, or radial, duct mode
L	Impingement nozzle to wall distance
l	Room resonant mode in the x direction
L_c	Length of the whistler nozzle step segment
L_p	Length of the small whistler nozzle pipe
L_x	Room dimension in the x direction
L_y	Room dimension in the y direction
L_z	Room dimension in the z direction
Le	Length of the Helmholtz Resonator neck
M	Mach number
m	Room resonant mode in the y direction
n	Room resonant mode in the z direction
n_1	Constant used in the edge tone
n_2	Jet impingement mode of oscillation
n_3	Diffuser mode of oscillation
St	Strouhal Number
u	Flow velocity at the diffuser inlet
v	Jet velocity
Vol	Volume of the Helmholtz Resonator cavity
β	Length of the wall of the diffuser

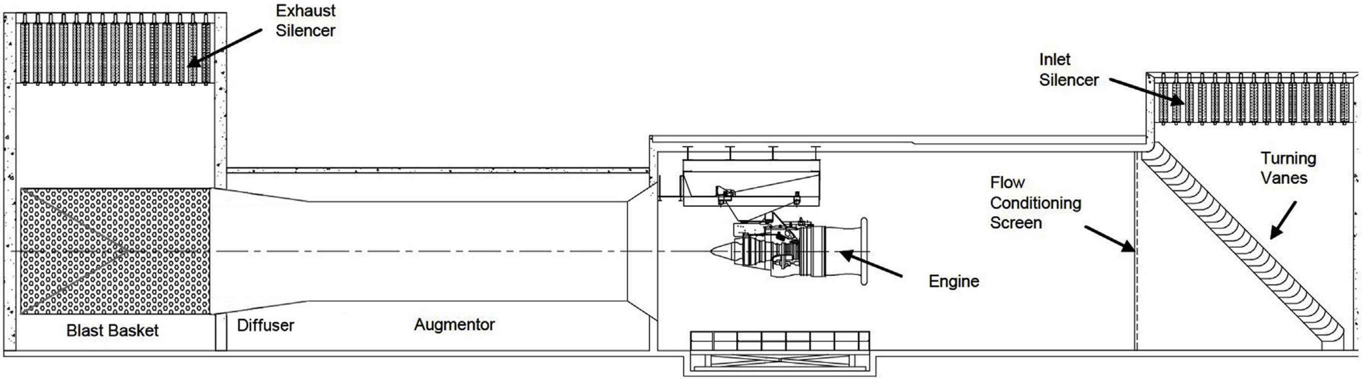

Fig. 1. A typical U-shaped Jet Engine Test Cell, Adapted from Ref. [1].

noise sources, jet impingement noise seems to be one of the most apparent sources. Jet impingement noise is the creation of both broadband and discrete tone noise resulting from a high velocity jet impacting a surface normal to the jet axis with the resulting noise potentially being greater than that of the free jet [8]. Jet impingement tones have been a subject of research for over half a century and the flow field generated by impingement is surprisingly complex. Even in recent times the details of the relationship between the flow field and noise field are still not well understood [9], [10]. In a JETC the high velocity jet impinges on the cone before passing through the blast basket and exiting the exhaust stack. Given that augmentor tubes tend to be of circular cross section, only axisymmetric impingement is relevant.

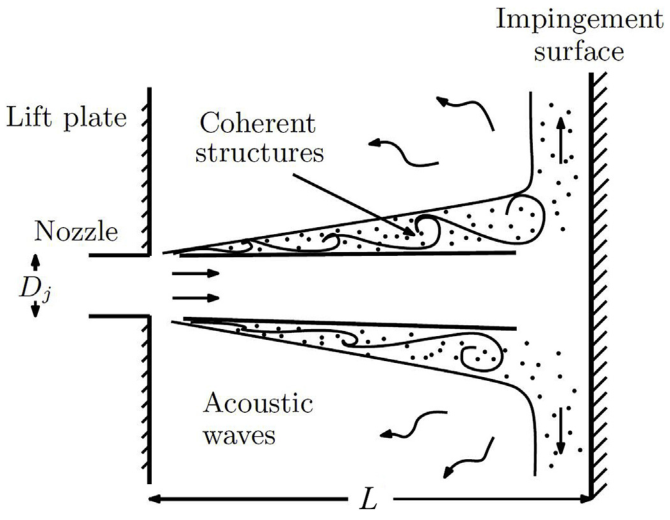

Fig. 2. Jet impingement feedback phenomenon, from Ref. [12].

Reference [11] reasons that a small scale instability, or coherent structure, at the nozzle exit grows as it moves downstream in the shear layer of the jet. When the instability makes contact with the impingement surface, a pressure wave is reflected upstream. This pressure wave moves upstream until reaching the nozzle exit (the most susceptible region of the jet to disturbances), where it causes the creation of another small scale instability thus locking the jet into a feedback loop. Upon impact with the wall the large coherent structures emit sound waves. The frequency of the tone in the subsonic case depends primarily on the jet Mach number and the nozzle diameter to plate distance ratio. Reference [12] presents a good schematic of the feedback situation, shown in Fig. 2.

The coherent structures generally take on one of two forms depending on the mode of oscillation; the axisymmetric or helical modes.