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Ground Impingement Noise of Supersonic Jets from Nozzles with Various Exit Geometries

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Acoustic measurements of single and twin free- and impinging-jets were made for circular convergent and convergent-divergent (CD) nozzles, rectangular CD nozzles, and D-shaped convergent nozzles. The measured free-jet screech tone frequencies agree with existing theory. Noise due to jet impingement correlates on the basis of the nozzle-to-ground distance relative to the free-jet shock structure, with the highest sound pressure levels generally due to jet impingement tones. All nozzle types experienced near-field overall sound pressure levels of 160 dB at some nozzle-to-ground distances, including the CD nozzles operating at their design pressure. The effect of the second jet was to sometimes increase levels due to twin jet resonance and at other times reduce levels resulting from either suppression of the screech/impingement feedback process, or more simply, by acoustic interference of the noise produced by the two jets.

Nomenclature

a = ambient sound speed
d = diameter of circular nozzles
f_s = screech tone frequency
h = distance from nozzle exit to ground surface
L = shock cell length
M_d = nozzle design Mach number
M_j = jet fully expanded Mach number
r = radius of semicircle of D-shaped nozzle
V_c = convection velocity
V_ℓ = loop velocity, $V_c/(1 + V_c/a)$
w = width of rectangular nozzle
α = ratio of convection velocity to fully expanded velocity
λ_s = screech tone wavelength

Introduction

THE interaction of supersonic jets with a surface is an important consideration for many aircraft applications, including hover and landing of advanced short takeoff and vertical landing aircraft as well as thrust vectoring for military configurations. The dynamic loads generated by direct contact of the exhaust plume with the aircraft structure, and those due to the acoustic near the field of the jet/surface interaction, may impose severe restrictions on weight and material.

Few studies of supersonic impinging jets have been reported in literature. Krothapalli[1] studied the tones emitted by two-dimensional underexpanded impinging-jets, and Ahuja et al.[2,3] performed extensive acoustic measurements of round impinging-jets at a Mach number of 1.4. Powell[4] reported on the oscillations produced by round supersonic jets impinging on surfaces of various sizes and presents a good list of references for impingement studies. A detailed experimental study of the loads generated by the ground impingement of a supersonic jet from a single convergent rectangular nozzle was reported by Norum.[5] It was found that the loading was dominated by jet impingement tones over wide ranges of jet Mach number and nozzle-to-ground distance. The current study expands these measurements to include both single and twin jets issuing from a variety of nozzle types.

Description of Experiments

The experiments were performed in the Quiet Flow Facility of the NASA Langley Noise Reduction Laboratory. This anechoic chamber has dimensions 20 × 24 × 30 ft and is lined with wedges to permit acoustic measurements down to 70 Hz. Details of the facility can be found in Ref. 6.

Three pairs of nozzles were constructed for these experiments. Each nozzle of the first pair is circular convergent with a straight-line internal contour and an exit diameter of 0.899 in. The second pair of nozzles are circular convergent-divergent (CD) with an area ratio corresponding to an exit Mach number of 1.5 and an internal contour consisting of converging and diverging straight-line segments. The third pair are rectangular CD nozzles with the same area ratio as the circular CD nozzles and an exit aspect ratio (ratio of breadth-to-width) equal to 2. The internal contour of these nozzles consists of a transition from circular to square cross section followed by convergent and divergent line segments in only one of the two dimensions (the breadth is unchanged). The lengths of the three sets of nozzles were different because all of the line segments of the internal contours converged at an angle of 4 deg and diverged at an angle of 3 deg. The converging and diverging portions of the CD nozzles were joined by a 0.25 in. radius at the throat, and all nozzles had an exit lip thickness of 0.01 in. The throat area of the CD nozzles was designed to match the exit area of the convergent nozzle to obtain equivalent mass flow at the same total pressure. A fourth pair of nozzles was obtained by installing a plug in each circular convergent nozzle. The face of the plug was mounted flush with the nozzle exit and blocked half of the exit area. Therefore, each of these D-shaped convergent nozzles, made to approximate the exit shape of a single expansion ramp nozzle, used half the mass flow of the others (a photograph of the nozzles and plugs is shown in Fig. 1).

The geometry and designations of the configurations tested are given in Fig. 2. These five configurations consisted of the circular convergent nozzles (CCON), the circular CD nozzles (CCD), the D-shaped convergent nozzles (DCON), the rectangular CD nozzles with long edges parallel (RCDV), and these same nozzles with short edges parallel (RCDH). One nozzle of each pair was designated the primary nozzle, because it was used for both single and twin jet tests of its configuration. The other was designated the secondary noz-

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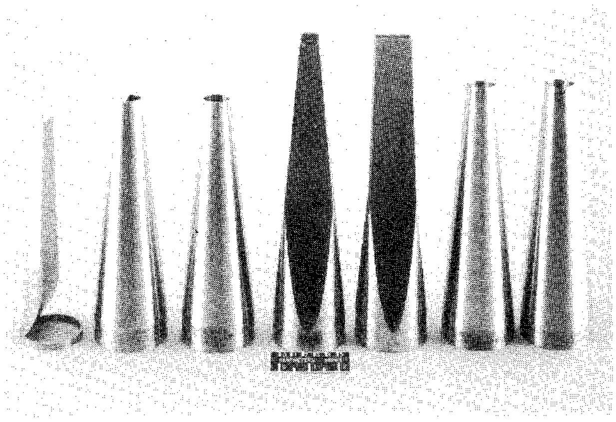

Fig. 1 Photograph of nozzles and plugs.

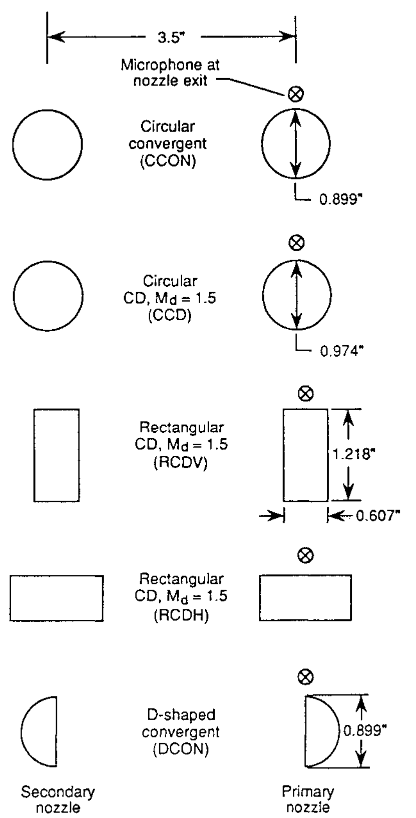

Fig. 2 Dimensions and designations of the five nozzle configurations.

zle. During the twin jet tests, the two nozzles had the same exit plane, and had a centerline separation distance of 3.5 in.

A microphone was located in the nozzle exit plane at a distance of about ¼ in. above the surface of the primary nozzle. A far-field microphone was also positioned in this plane on the line passing through the centers of the two nozzles, closer to the primary nozzle and at a distance of 56.5 in. from its center. Acoustic measurements of the free-jets were made with ¼-in. condenser microphones. The nozzle microphone was replaced by an ⅛-in. microphone during the jet impingement tests because of the generated higher sound pressure levels.

The impingement (ground) surface consisted of a ⅜-in.-thick, 42-in.-diam aluminum disc mounted on an axial traversing mechanism. The nozzles were attached to individual 2 in. internal diameter flexible steel hoses that were joined to a single 4 in. supply pipe. Single nozzle flow was obtained by removing the secondary nozzle and blocking its supply line. A photograph of the RCDV twin nozzle impingement setup is given in Fig. 3.

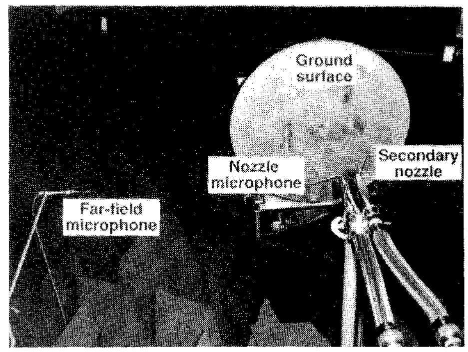

Fig. 3 Photograph of experimental setup for the RCDV twin nozzle impinging-jet configuration.

The experiments were performed in four phases 1) a probe attached to a three-direction traverse was positioned to make plume pressure measurements in the free-jets; 2) the traverse was removed from the chamber for acoustic measurements of the free-jets; 3) the impingement surface was installed for acoustic measurements of impinging-jets; and 4) optical equipment was installed for shadowgraph and schlieren visualization of the impinging-jet flow and acoustic fields.

The plume-pressure measurements yielded shock-cell lengths that compared favorably with predictions[7] and will be used in the next section to correlate free-jet screech frequencies. This article details results from the acoustic measurements only.

Free-Jet Acoustic Measurements

The acoustic properties of the free-jets were investigated over the Mach number range from 1 to 2. The overall sound pressure levels (OASPL) from the far-field microphone are given in Fig. 4 for both the single and twin circular convergent nozzles (configuration CCON). Higher levels occur for the twin jets throughout the Mach number range. Surveying the narrow-band spectra for these many conditions show a different behavior for the broadband and discrete shock-associated noise. The broadband shock noise levels for the twin nozzles are found to be consistently 3–6 dB higher throughout the spectrum at virtually all Mach numbers. The behavior of the discrete shock noise can be derived from the peak spectrum level comparison given in Fig. 5. In most cases, these peak levels represent the amplitudes of the second harmonic of screech, that is known to be the dominant noise propagated at 90 deg from the centerline of underexpanded circular jets.[8] Differences between single and twin jet peak levels are seen to vary considerably, with a definite twin jet resonance occurring near Mach number 1.75.

The dominance of the screech process over much of the Mach number range leads to some apparent anomalies in the near-field microphone results. The same OASPL comparison given in Fig. 4 for the far-field microphone is given in Fig. 6 for the near-field nozzle microphone. As expected, the near-field levels are higher than the far-field levels, and the twin jet resonance near Mach 1.75 is apparent. However, the single jet noise levels are higher than the twin jet levels in the Mach number range near 1.3. Narrow band spectra show that the near-field broadband shock noise behaves in a fashion similar to that in the far-field; however, the near-field microphone screech tone levels of the twin jets fall below those of the single jet in this Mach number range. Since it is evident from Fig. 5 that this does not occur at the far-field microphone, the screech process does not appear to be suppressed. Instead, destructive interference of the screech tones generated by the two jets must be occurring at the near-field microphone, resulting in a decrease in OASPL from the levels measured for the single jet. Therefore, large variations in sound pressure level with near-field position can be expected for twin jets rich in screech or impingement tones.

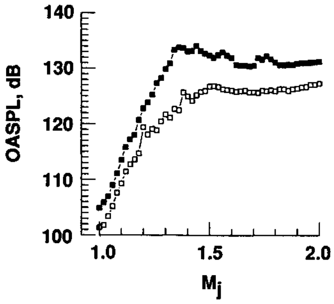

Fig. 4 Overall sound pressure levels for CCON free-jet configuration at the far-field microphone. Solid symbols—twin jets; open symbols—single jet.

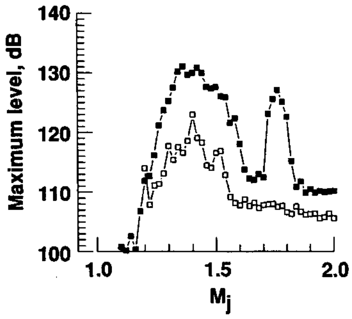

Fig. 5 Peak spectrum levels for CCON free jet configuration at the far-field microphone. Bandwidth 50 Hz; solid symbols—twin jets; open symbols—single jet.

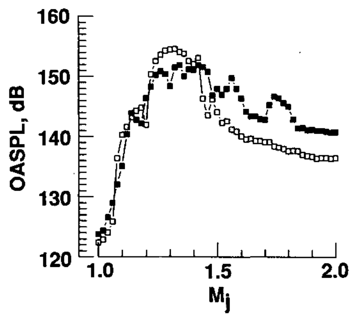

Fig. 6 Overall sound pressure levels for CCON free jet configuration at the near-field nozzle microphone. Solid symbols—twin jets; open symbols—single jet.

Although screech amplitudes are known to be very directional for single jets, and as seen above, can suffer additional interference effects for twin jets, their frequencies remain invariant at given nozzle operating conditions. Methods for predicting the screech frequency date back to Powell,[9] and though subsequent theories may differ in detail, the results agree. The simplest physical explanation for the observed fundamental screech tone frequency is that its period must equal the sum of time it takes for flow disturbances to travel one shock-cell length downstream within the jet and the time for sound waves to travel the same axial distance in the ambient medium. This leads to the feedback loop condition $f_s = V_\ell/L$, where f_s is the screech frequency, L is the shock cell length, and V_ℓ is the "loop velocity" given by $V_\ell = V_c/(1 + V_c/a)$. Here a is the ambient sound speed and V_c is the average convection velocity in the jet, that is usually expressed as a fraction, α, of the jet fully expanded velocity.

The wavelengths corresponding to the measured fundamental frequency of the dominant screech mode are given in Fig. 7 for the four different nozzle types. Single and twin jet results are superimposed. The solid lines are the wavelengths of the screech tones obtained from the feedback loop condition and shock-cell length predictions.[7] The experimental results in Fig. 7a show the staging behavior of screech that results from discrete jumps in frequency as the Mach number is increased. One can recognize the presence of the various modes typical of the screech from a circular convergent nozzle. Results from the circular CD nozzle in Fig. 7b show a staging behavior very similar to that of the convergent nozzle. In Ref. 5 it was shown that a rectangular convergent nozzle of aspect ratio 4 behaved similarly to a two-dimensional nozzle, with a single dominant screech mode existing above Mach 1.1. In contrast, Fig. 7c shows that the 2 to 1 aspect ratio rectangular CD nozzle exhibits at least one additional screech stage at the higher Mach numbers. Two screech stages are also evident for the D-shaped nozzle in Fig. 7d.

The screech wavelength predictions require values to be assumed for the convection velocity. Various experimental

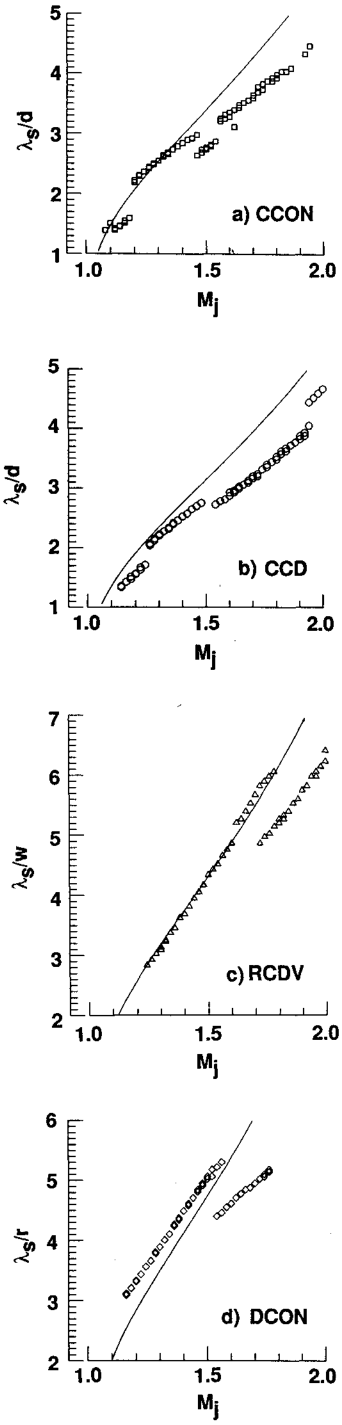

Fig. 7 Variation of screech wavelength with Mach number. Solid line—prediction; symbols—experiment.

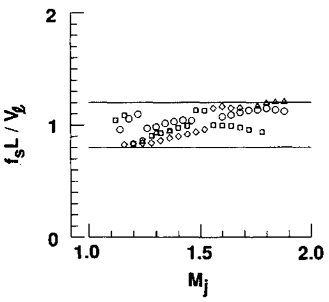

Fig. 8 Loop Strouhal number of screech tones from the four nozzle types. Symbol types as in Fig. 7.

attempts to determine the convection velocity reported in the literature give a value of a between 0.5–0.7. The value used for the computations in this paper is $\alpha = 0.7$, with no attempt made to modify this to obtain the best agreement between theory and experiment. It should be noted that the staging behavior of screech, found in past experiments to correspond to noticeable jumps in the lengths of the downstream shock cells,[8] is not predictable from models like those discussed here, that incorporate continuous variations with Mach number. The experimental screech wavelengths show reasonable agreement with the predictions.

Combining the independent measurements of screech frequencies and shock-cell lengths, and again using a value of $\alpha = 0.7$, yields experimental values of the "loop Strouhal number" f_sL/V_ℓ shown in Fig. 8. Because of data density, only every other data point of the single-nozzle data given in Fig. 7 is shown. The experimental results from all four nozzles are within 20% of the predicted value of unity.

Impinging-Jet Acoustic Measurements

The influence of the ground surface on the noise received by the nozzle microphone was found to be qualitatively similar for all nozzle configurations. It can best be described by dividing the nozzle to ground distance h into four regions, designated as the far, intermediate, near, and very near regions. Spectra typical of each region are shown in Fig. 9 for the circular CD nozzle operating at the overexpanded condition $M_j = 1.2$. The top spectrum in Fig. 9 is that from the free-jet. The discrete peaks correspond to three modes, a dominant screech tone at about 9 kHz and two secondary tones of much lower amplitude and lower frequency. The discrete peaks at higher frequency correspond to sums of frequencies of the dominant and secondary modes.

The changes that occur when the ground surface is introduced and brought closer to the nozzle are seen in the remaining spectra of Fig. 9. The far-region, defined as ground positions beyond the end of the shock-cell development of the free jet, is illustrated by the spectra at $h = 30$ and 11 in. In this region, there is little change with h in the dominant screech tone amplitude, and no change in its frequency. There is, however, low frequency broadband noise that appears in the spectrum and increases in amplitude as h is decreased.

The intermediate region occurs at ground positions near the end of the free-jet shock structure and is illustrated by the spectrum at $h = 6.5$ in. In this region, changes in h may cause variations in the amplitude of the screech tone and a staging of its frequency. This staging behavior is different from that found for the screech of free-jets, which corresponds to mode changes with the Mach number. In contrast, the staging in the intermediate region of ground-to-surface distance is characteristic of edge tones and impingement tones, and is caused by an adjustment in the number of acoustic wavelengths between the nozzle and surface to maintain a relatively constant frequency and therefore a continuation of the excitation of this mode.[5] Other modes may also be excited in the intermediate region, as illustrated by the tone near 4 kHz. The low-frequency broadband noise levels off in amplitude, and the broadband spectrum at higher frequency begins to rise significantly.

The near region, shown by the spectrum at $h = 3.5$ in., corresponds to ground positions near the middle of the shock-cell development of the free-jet. Here, jet impingement tones at frequencies other than that of screech, may dominate the spectrum. As in the intermediate region, the amplitudes of all the tones may have large variations with small changes in h. The wide-spectrum broadband noise continues to increase with decreasing h.

Finally, as the very near region is approached (ground positions within the first one or two shock cells), most tones disappear; if any are present they occur at much higher frequency, corresponding to the smaller nozzle-to-ground distance. The high-frequency broadband noise continues to rise, resulting in an almost flat broadband spectrum across the measured frequency range (this is shown in the bottom spectrum of Fig. 9).

Therefore, the changes in the measured spectrum of the noise propagated upstream to the nozzle microphone, result from the change in noise generation from that of a free-jet to that of an impinging-jet. The shift in these generation mechanisms generally results in higher noise levels as h is decreased, modified by large amplitude variations in the impingement tones.

Results of OASPL vs h from the nozzle microphone are given in Figs. 10–12, corresponding to fully expanded Mach

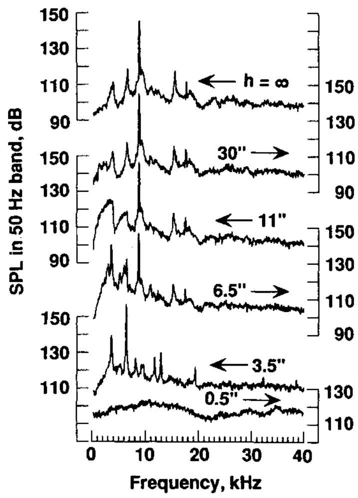

Fig. 9 Sound pressure level spectra of impinging-jets at the near-field nozzle microphone for the CCD single jet configuration at Mach number 1.2.

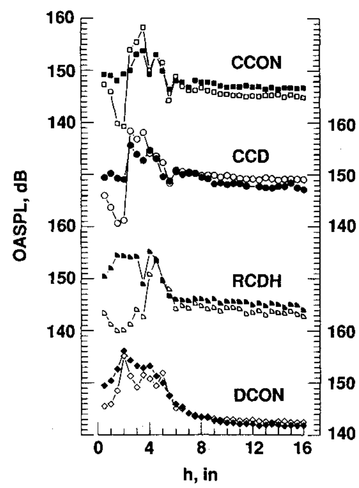

Fig. 10 Variation in overall sound pressure level of impinging-jets with nozzle-to-ground distance at Mach number 1.2. Solid symbols—twin jets; open symbols—single jet.

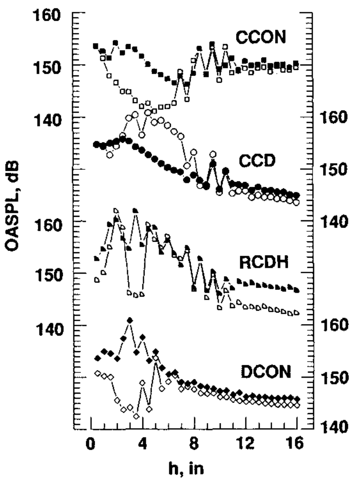

Fig. 11 Variation in overall sound pressure level of impinging-jets with nozzle-to-ground distance at Mach number 1.5. Solid symbols—twin jets; open symbols—single jet.

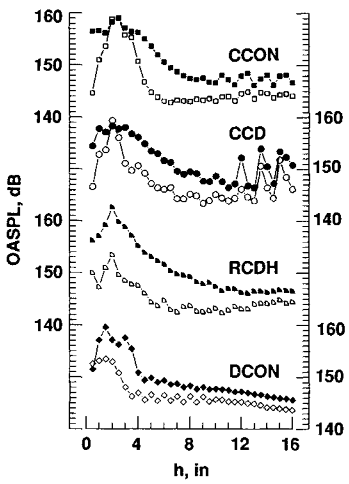

Fig. 12 Variation in overall sound pressure level of impinging-jets with nozzle-to-ground distance at Mach number 1.8. Solid symbols—twin jets; open symbols—single jet.

numbers of 1.2, 1.5, and 1.8, respectively. Both single jet (open symbols) and twin jet (solid symbols) results are given for each of the four nozzle types. The nozzle-to-ground far region at $M_j = 1.2$ can be seen in Fig. 10 as relatively constant levels at large h, where screech tones dominate the spectra. The rise in level in the intermediate and near regions as h decreases below 6 in., corresponds to the shift from screech-tone to impingement-tone dominance, and the larger amplitudes of the latter. As the very near region is approached (at about $h = 2$ in. for the circular configurations), large decreases in OASPL occur due a sudden large reduction in impingement tone amplitudes. The levels increase again as h further decreases (caused by increases in the now dominant broadband noise). The larger levels for the twin jet configurations over those of the single jet at small h (particularly noticeable in the rectangular configuration) are due to stronger impingement tones as well as to higher broadband noise.

The behavior of OASPL with nozzle-to-ground distance for the CCON configuration at $M_j = 1.5$ in Fig. 11 is very similar to its behavior at $M_j = 1.2$, except that corresponding regions occur at larger h due to the much longer shock cells. The large changes in tone amplitudes that occur in the intermediate region can be seen in the OASPL fluctuations near $h = 9$ in. When h is between 6 and 2 in., the spectra are devoid of tones, and the differences between single and twin jet OASPL are due to broadband noise differences.

In contrast to the CCON configuration, the CCD configuration exhibits a behavior at Mach 1.5 (its design Mach number) that is much different from the overexpanded condition of $M_j = 1.2$. Since the free-jet does not screech appreciably, the OASPL follows the increasing broadband levels as h is decreased in the far region. Strong impingement tones are generated near $h = 9$ in., where the variations of the intermediate region are again apparent. Tones of even higher amplitude exist for the single circular CD nozzle throughout the near region, resulting in levels that are 18 dB higher than the single circular convergent nozzle; a behavior completely opposite to that when the free-jets are compared. Therefore, any free-jet noise benefit obtained through the use of a CD nozzle cannot only be lost, but actually reversed, when jet impingement takes place. The CCD twin jets, however, behave very similar to the CCON twin jets, with only weak impingement tones present in the nozzle microphone spectra. Since the far-field microphone spectra show similar results, actual suppression of the single jet impingement tones is indicated when the secondary nozzle is present.

The rectangular CD free-jet produces stronger screech than the circular CD free-jet at their design Mach number of 1.5. This is even more evident for the twin jets, as seen in the higher twin jet levels for the RCDH configuration in the far region of Fig. 11. Both CD single jet configurations have impinging-jet OASPL levels that exceed 160 dB. In general, the jet impingement behavior of both the RCDH and DCON configurations resemble the CCON configuration more than they do the CCD configuration.

The intermediate region at Mach number 1.8 extends beyond the nozzle-to-ground distances shown in Fig. 12 for all but the DCON configuration. Impingement tones dominate the spectra only for the circular configurations at about $h = 14$ in. and all configurations below $h = 4$ in. Otherwise the broadband noise dominates, as reflected by the gradual changes in OASPL with h.

Variation in the OASPL with Mach number at various nozzle-to-ground distances are given in Fig. 13. Results for the single circular convergent nozzle and the single circular CD nozzle are superimposed. The highest amplitude levels of both free-jets ($h = \infty$) correspond to the strongest screech tones and occur at Mach numbers near 1.3. The CD nozzle free-jet has the expected minimum near its design point ($M_d = 1.5$), with the levels rising again as the jet becomes underexpanded.

At $h = 10$ in., some remnants of the free-jet results can still be noticed, such as the maximum levels near $M_j = 1.3$. The characteristics that differentiated the results of the CD nozzle free-jet from those of the convergent nozzle free-jet have almost disappeared, with level differences between the two nozzle types being small throughout the Mach number range. At low Mach number, this nozzle-to-ground distance corresponds to the far region, where the major spectral changes from the free-jet are in the low frequency broadband noise. Therefore, there is an increase in OASPL over that of the free-jet at very low Mach number, where no strong screech tones exist, but there is no change in level at the screech-dominated conditions such as at Mach 1.3. Since the extent of the shock structure lengthens as the Mach number increases, $h = 10$ in. corresponds to the intermediate region at Mach numbers near 1.5. Here one can see the large OASPL variations with Mach number that correspond to the large tone amplitude fluctuations of the intermediate region. The ground surface is in the near region at the highest Mach numbers. Here, the spectra for both nozzle configurations are void of strong tones and, therefore, very little variation in OASPL with Mach number takes place.

The third set of data in Fig. 13 are for $h = 5$ in. The ground surface is in the near-region for the mid-Mach number range. The convergent nozzle spectra is devoid of tones above Mach 1.5, resulting in its OASPL showing a gradual rise with increasing speed, corresponding to increasing broadband noise. As previously seen in Fig. 11, very strong impingement tones

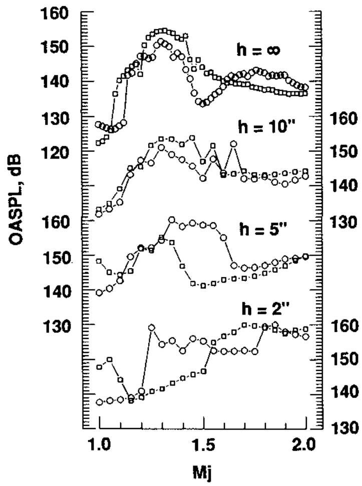

Fig. 13 Variation in overall sound pressure level of impinging-jets with Mach number. Square symbols—CCON; circular symbols—CCD.

occur with the CD nozzle around its design Mach number of 1.5, yielding OASPL levels 18 dB higher than those of the convergent nozzle impinging-jet, and 25 dB higher than those of the CD nozzle free-jet.

The very near region occurs over most of the Mach number range at $h = 2$ in. Here, certain Mach number regions have strong impingement tones, while others have no apparent tones. Therefore, the last set of OASPL data in Fig. 13 shows jumps at discrete Mach numbers that correspond to the sudden appearance of strong impingement tones as the jet pressure is increased.

Surveying Figs. 10–13 show that the highest sound pressure levels generally occur in the near-region. The maximum OASPL measured by the microphone near the nozzle exit is approximately 160 dB for all four nozzle types, although the conditions at which each configuration attains this level, differ. The maximum levels are generally due to strong impingement tones, although at high Mach number and small nozzle-to-ground distance, they can result from broadband impingement noise. Ironically, both CD nozzles reach these high levels for impinging-jets at their design Mach number of 1.5.

Conclusions

Acoustic measurements for four nozzle types were obtained for both single and twin free- and impinging-jets. Screech frequencies of the free-jets show good agreement with predictions for all the nozzles, that included circular convergent nozzles, circular and rectangular CD nozzles of design Mach number 1.5, and D-shaped convergent nozzles. Measured near-field twin jet sound pressure levels were much higher than those of the single jet at some conditions due to plume resonance, but were lower than those of the single jet at other conditions because of destructive interference of the tones generated by the two jets.

The impinging jet acoustic results can best be described by dividing the nozzle-to-ground distance into regions that correlate with the free-jet shock cell development. For distances beyond the end of the shocks, the main change from the free-jet acoustic spectrum is the creation of a low frequency broadband jet impingement noise. As the distance is decreased to near the end of the free-jet shock cell development, large changes in the amplitude of the tone near the free-jet screech frequency can occur along with a staging of the frequency. As the ground surface traverses the shock cells by further reducing the distance, jet impingement tones at other frequencies can dominate the spectrum, with large changes in their amplitudes occurring with distance. At very small distances, the only tones that can exist are at higher frequency; otherwise the spectrum is dominated by the broadband noise that now extends across the measured frequency range.

The different nozzle configurations all produced sound pressure levels of at least 160 dB near the nozzle. The highest levels are generally attributable to jet impingement tones, although broadband impingement noise can dominate at high Mach number and small nozzle-to-ground distance. The conditions at which the levels were maximum varied with nozzle configuration, with some of the highest OASPL being generated for impinging-jets from the CD nozzles operated at their design condition.

Some very large differences were found between single and twin jet OASPL at small nozzle-to-ground distance. These are the result of tone amplitude differences, that could either be caused by acoustic interference of the directivity patterns of the tones generated by each of the twin impinging-jets, or be caused by modification of the amplification of the feedback process due to the presence of the second jet.

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