Investigation of Acoustic Effects of Leading-Edge Serrations on Airfoils

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This paper presents and interprets a series of extensive studies of the application of leading-edge serrations as a device for reducing the vortex noise radiated from stationary and rotating airfoils in low Reynolds number flow. In these studies, a variety of serrations were attached at selected locations near the leading edge of stationary and rotating airfoils. The noise levels of the airfoils were reduced considerably with the serrations attached. An explanation of the aeroacoustic flow mechanisms involved is given.

Introduction

AERODYNAMIC sound generation from surfaces that rotate as propulsive devices (e.g., rotor and fan blades) has long been recognized as one of the dominant noise sources for a variety of subsonic aircraft. This paper describes a study of the application of leading-edge serrations as a device for reducing the noise radiated from stationary and rotating lifting surfaces. The effects of the serrations on the acoustic radiation are discussed and an interpretation of the results given.

The motivation for this rather novel use of serrations came from H. J. Allen, then Director of the NASA Ames Research Center. Allen was aware that owls fly very quietly while pursuing their prey. In 1934, R. R. Graham published a paper[1] describing the unique features of the owl's wing, observing that it has a comblike feather structure at its leading-edge, fringe feathers at its trailing-edge, and a special downy upper surface on the wings. A photograph of the owl wing is shown in Fig. 1. Allen suggested that an investigation of the owl wing might lead to techniques to reduce the noise radiated by airfoils.

The acoustic investigations were initiated by examining an owl wing. Of the features described by Graham, the comblike feather structure at the leading-edge of the wing seemed one of the most likely to have an effect on noise. Therefore, a series of experiments were devised to study the effect of this comb on noise generation. Studies of the trailing-edge feather structure might also be fruitful in light of Hayden's recent work[2] with airfoil trailing edges, but such studies have not been done. Brass strips were made which modeled the comb and the acoustical significance of each was evaluated on a 5-ft diam, two-bladed rotor, a two-dimensional 6-in. chord airfoil, and a 14-in. diam, two-bladed variable-pitch propeller. Unsteady forces and wake velocities of the two-dimensional airfoil were measured to relate the acoustic characteristics to aerodynamic characteristics. Aeroacoustic studies of an owl are reported in Ref. 3.

Results and Discussion

Exploratory Investigation

Initial studies by Soderman[4] consisted of placing different sized serrations at selected locations near the leading-edge of a 5-ft diam, two-bladed rotor. A sketch showing the geometry and locations of the serrations investigated is shown in Fig. 2. The rotor blade had a NACA 0012 section with a constant 2¾ in. chord and a square tip. The rotor was tested statically with the thrust axis horizontal. Sound pressure measurements were made 5 ft above a concrete floor at selected locations around the rotor, 15 ft from the rotor center, with and without the serrated strips. Sound-power measurements were not made.

Results were encouraging. The serrations reduced the over-all sound pressure levels from about 4 to 8 db for rotational speeds between 840 and 1440 rpm corresponding to chord- and tip-speed-based Reynolds numbers of 3.36×10^5 and 5.75×10^5, respectively. Similar noise reductions from serrations on a 2-ft diam model rotor have since been observed by Arndt and Nagel.[5] The sound pressure level spectrum shown in Fig. 3 was measured 15-ft forward of the rotor along the axis of rotation and showed that the serrations substantially reduced the high-fre-

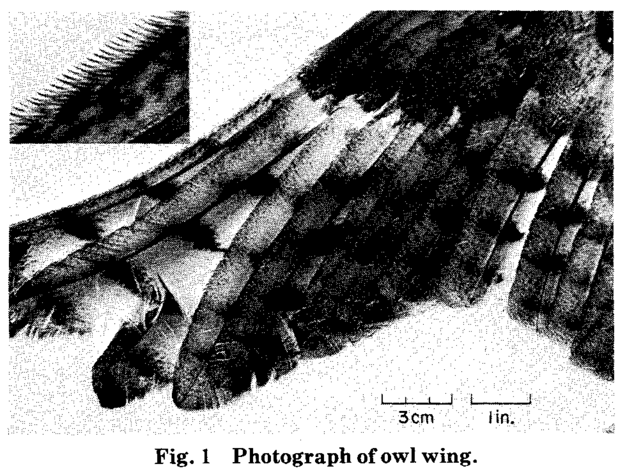

Fig. 1 Photograph of owl wing.

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Index categories: Aircraft Noise, Powerplant; Nonsteady Aerodynamics; Aircraft Noise, Aerodynamics (Including Sonic Boom).

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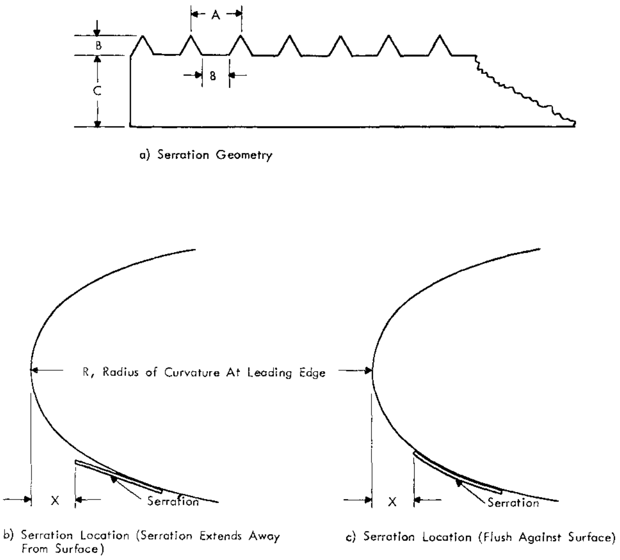


Fig. 2 Schematic and location of serrations.

quency sound by eliminating a high-frequency tone generated by the unmodified rotor. The tone occurred in the 8000 Hz octave band and was characteristic of vortex shedding noise rather than rotational noise. Because the serrations were successful in reducing noise not associated with blade rotation, a further in-depth investigation of an isolated airfoil was conducted.

Study with an Isolated Airfoil in Smooth Flow

To better understand how serrations reduce noise, a series of diagnostic tests were conducted in the BBN acoustic wind tunnel on a stationary two-dimensional 6-in. chord and 30-in. span NACA 0012 airfoil.

The BBN acoustic test facility is a low turbulence, low noise, freejet wind tunnel designed specifically to study low-speed aerodynamic noise phenomena. The speed of the low turbulence core of the jet is variable between 20 and 150 fps in a 16-in. by 16-in. square cross section or an 18-in. diam circular cross section.

Surrounding the free-jet facility is a semireverberant room of approximately 3000 ft^3 with ceiling and one wall skewed to improve the uniformity of the reverberant sound field. The cutoff frequency of the room was 180 Hz (in one-third octave bands). Below this frequency, absolute sound measurements were not highly accurate but meaningful relative measurements were acquired. Space-averaged sound measurements were made with a microphone mounted on a pendulum which had a period of approximately 2 sec. The sound data, recorded with a one-third octave band Real Time Analyzer, have been found to be very repeatable.

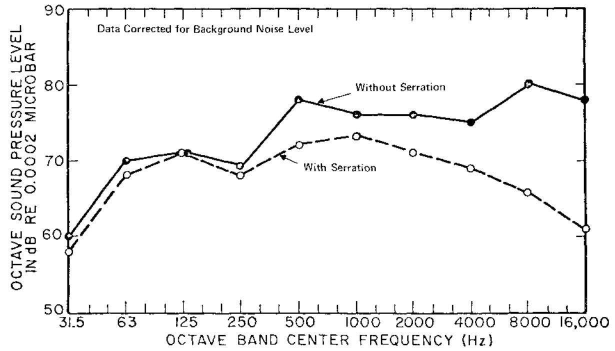


Fig. 3 NASA Ames test tail rotor, no superimposed forward speed β = 10°, 1440 rpm, tip speed 377 fps.

Table 1 Summary of serration size and location (shown on Fig. 2)

Serration	Location	A/R	B/R	C/R	x/R
Airfoil serrations (R = 0.095 in.)					
1	1	0.35	0.17	0.53	0
	2				−0.53
	3				0.26
	4				0.53
2	1	0.67	0.34	0.67	0.53
	2				0.79
	3				1.05
	3′				1.05
3	1′	1.05	0.53	1.05	0.53
	2′				0.79
	3′				1.05
4	1	1.40	0.70	1.40	0.79
	2				1.05
	3				0.53
	3′				0.53
Propeller serrations (R = 0.0317 in.)					
5	1′	0.98	0.47	0.98	0.51
	2′				0.76
	3′				1.01
6	1′	2.11	1.07	2.11	1.01
	2′				0.76
	3′				1.42

Noise measurements were made for angles of attack α, varying between 0° and 16° and for flow speeds V, of 25, 60, and 100 fps. These speeds correspond to chord-based Reynolds numbers (R_c) of 0.83 × 10^5, 2.00 × 10^5, and 3.3310^5, respectively. The airfoil angles of attack were not corrected for open jet wind tunnel effects; the angles were measured with a simple protractor arrangement.

Four different serrations were tested. The serrations were placed on the airfoil lower surface slightly behind the leading edge. The details of their location and size are tabulated in Table 1. In the column entitled, "Location no," the unprimed numbers mean that the serrations were attached flush against the airfoil surface; the primed numbers mean that they extended out somewhat from the airfoil surface as shown in the lower half of Fig. 2. The serrations were located with a depth gauge and attached using thin double-backed masking tape.

Figure 4 shows a comparison of the sound radiation at α = 14° and V = 100 fps between the unmodified airfoil and the airfoil with serration 4 attached at Location 3′, the most effective serration studied. It was observed that the noise reductions attained with the serrations were extremely sensitive to serration size and location on the airfoil. The high amplitude, narrow band peak in the spectrum, generated by the unmodified airfoil at the one-third octave band center frequency of 1600 Hz, was found to be a result of discrete frequency vortex shedding from the airfoil similar to Aeolian tones generated by cylinders in low Reynolds number flow. Similar airfoil tones are reported in Refs. 6 and 7. Vortex streets behind airfoils were observed by Krzywoblocki[8] and Tyler.[9] Figure 5 shows the noise reduction achieved with the most effective serration for the broadband sound generated at α = 12°, which is above the stall angle of attack. This indicates that serrations reduced the random wake oscillations. In some cases, certain bands of the sound spectra of the serrated airfoils approached the background noise in the wind tunnel.

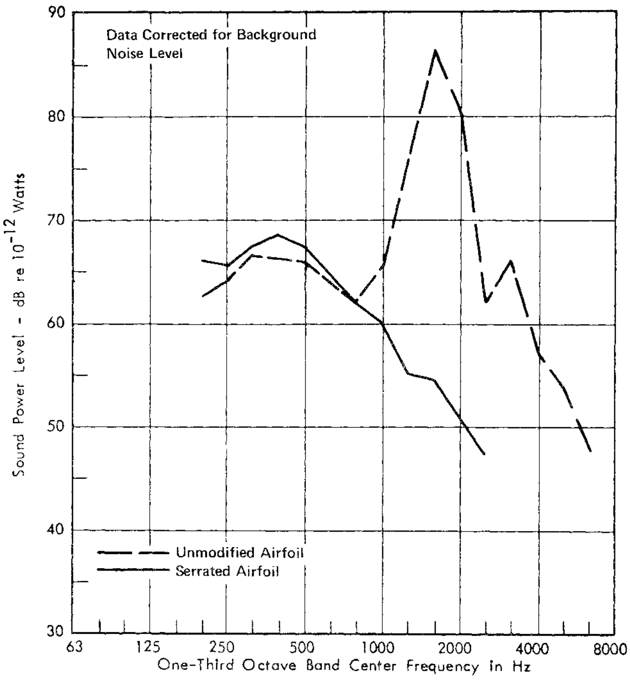


Fig. 4 Effect of serration 4, loc 3′ on airfoil sound radiation for $\alpha = 4°$, $V = 100$ fps.

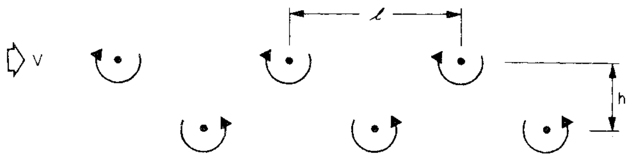
The one-third octave band peaks associated with the unmodified airfoil represent tones which were often unstable between neighboring one-third octave band center frequencies. The tones would occasionally change frequency abruptly with no apparent disturbance to the airfoil or inflow. It is evident that the serrations remove virtually all the tones. Without serrations, however, the tones disappear at angles of attack above 10°.

A periodic wake structure would produce fluctuating lift and drag forces which, according to the sound radiation theory of Curle,[10] generate an acoustic tone such as the measurements in Figs. 4 and 5 exhibit. Such a flow structure would be caused by periodic shedding of vortices. The disappearance of the tones above 10° is consistent with this explanation since the wake behind a stalled airfoil is random, not periodic. Reference 11 shows that for Reynolds numbers below 3.3×10^5 the NACA 0012 airfoils stalls at 10° (the Reynolds numbers for our tests were 2.0×10^5 and 3.3×10^5). The elimination of the tones by the serrations was caused by the generation of chordwise trailing vortices on the suction surface and generation of a turbulent boundary layer on the lower surface which changed the wake vortex shedding from periodic to random. Hilton[6] removed tones from airfoils by roughening the surface and changing the boundary layer from laminar to turbulent. However, there were aerodynamic losses inherent in this system compounded by the need to roughen large portions of the surface to eliminate the tones at all angles of attack. Soderman[12] found that properly designed serrations did not degrade the performance of a two-dimensional airfoil in a wind tunnel.

Measurements showed that at low angles of attack, the fundamental frequency of the tones occurred in the 250 Hz, 800 Hz, and 1600 Hz one-third octave bands for flow speeds of 25 fps, 60 fps, and 100 fps, respectively. The relationship between the frequency of the tones f, and the flow speed V, is most conveniently expressed in terms of the Strouhal number S, defined as

$$S = (fd/V) \tag{1}$$

The effective airfoil dimension d, is related to the width h, of the Karman vortex street shed by the airfoil. If S and d are calculated, the vortex shedding *frequency* can be predicted as long as the Reynolds number is in the range where vortex streets exist.§ Results of Ref. 7 indicate that vortex streets can exist behind a NACA 0012 airfoil for Reynolds numbers up to 2.2×10^6.



According to Karman,[13] the above vortex configuration is stable only if $h/l = 0.281$. Assuming that the vortices leave the airfoil with speed V, the shedding frequency is given by

$$f = \frac{V}{l} = 0.281\frac{V}{h}$$

Therefore

$$S' = \frac{fh}{V} = 0.281$$

And if the body dimension d is chosen such that $h = d$, then $S = S' = 0.281$.

R. Paterson et al.[7] propose that the proper dimension, d, is twice the thickness of the laminar boundary layer at the airfoil trailing edge. This is based on the concept that the vortices are shed near the outer edge of the boundary layers on the upper and lower surface near the airfoil trailing edge. However, calculations based on methods from Ref. 14 indicated that for the conditions of this study the boundary layer was turbulent over 80% of the airfoil upper surface and turbulent on the lower surface near the trailing edge. If so, the turbulence was not strong enough to destroy the von Karman vortex street.

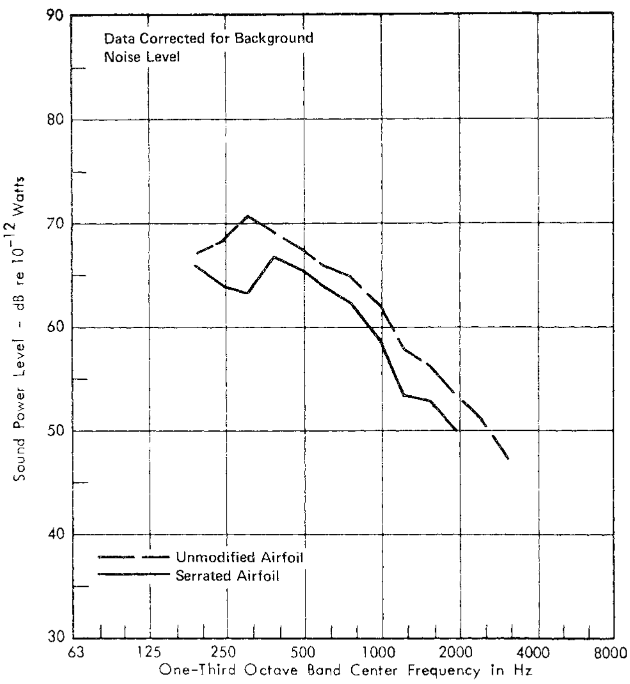


Fig. 5 Effect of serration 4, loc 3′ on airfoil sound radiation for $\alpha = 12°$, $V = 100$ fps.

§Prediction of fluctuating force amplitudes resulting from the vortex shedding is more difficult since small changes in surface roughness, edge configuration or freestream turbulence can substantially affect the shed vortex strength and the coherent length of the resultant pressure disturbance.

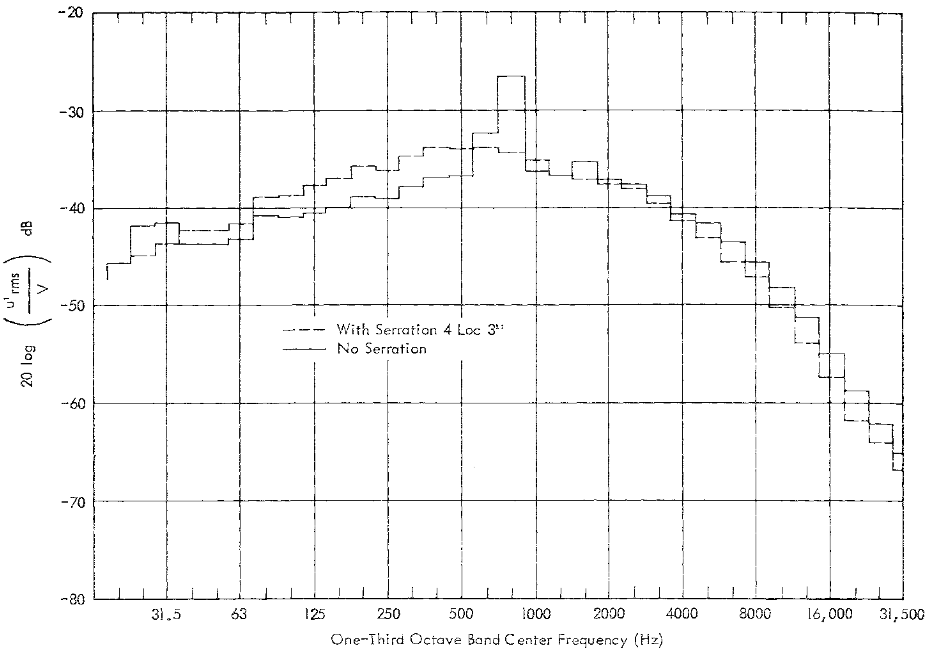


Fig. 6 Wake turbulence 1 in. from trailing edge $\alpha = +4°$, $V = 60$ fps.

Table 2. Boundary-layer thicknesses and vortex shedding frequencies

V, fps	δ_u, ft	δ_l, ft	f calculated, Hz	f measured tones, Hz (1/3 octave band limits)
25	0.027	0.017	266	224–282
60	0.022	0.012	825	708–891
100	0.019	0.010	1610	1413–1778

The turbulent boundary-layer thicknesses at the trailing edge, δ_u (upper surface) and δ_l (lower surface), shown in Table 2, were computed.¶ It was found that $d = 0.6\ (\delta_u + \delta_l)$ in Eq. (1) gave calculated vortex shedding frequencies which agree closely with the measured tones.

Diagnostic Studies

Two diagnostic studies were undertaken to verify our understanding that the tones are generated by boundary layer vortex shedding. These studies indicated that serrations remove the tones by generating vortices which changed the wake from periodic to random.

The first study, which consisted of recording spectral measurements of the fluctuating forces and moments imparted to the airfoil by the flow, was undertaken to locate the aerodynamic source of the acoustic tone on the airfoil surface and to relate the spectra of the unsteady forces to the acoustic spectra via Curlés theory. The measurements were made by attaching a lightweight isocyanate foam version of the NACA 0012 airfoil to a six-degree-of-freedom, eight-component force balance designed and built by BBN. The force balance is very accurate with mechanical crosstalk between force-sensing elements less than 1%. Only low-speed measurements were made because it is difficult to interpret the data at the higher speeds where the frequency of the tone related forces are near the resonance of the airfoil/force-balance combination. The spectral measurements show that the tones are generated by periodic or near-periodic unsteady aerodynamic forces located in the immediate vicinity of the trailing edge. The effect of the serration is to reduce considerably the level of the fluctuating forces, thereby reducing considerably the level of the tone. These data are not presented.

The second study, a recording of the spectral measurements of the fluctuating horizontal and vertical velocity components near the airfoil trailing-edge, was conducted to determine if periodic or near periodic vortex shedding occurs in the airfoil wake and if the serrations change the character of the vortex shedding from periodic to broadband.

Velocity fluctuations, in the one-third octave band center frequency of 800 Hz corresponding to the acoustic tone for $V = 60$ fps, were measured at various locations near the airfoil surface using a single 0.00025-in. diam hot-wire probe attached to a traversing mechanism. Only near the trailing edge and in the wake were strong velocity fluctuations observed although oscillations at the frequency of the acoustic tone were measurable upstream of the edge.

Figure 6 shows a comparison of the velocity fluctuations in the wake of the unmodified airfoil with those of the airfoil modified by serration 4 attached at location 3′. The hot-wire probe was located 1 in. behind the airfoil trailing edge. In general, other measurements of the velocity fluctuations at various locations in the wake showed that most of the energy of the shed vortices were concentrated at the 800 Hz one-third octave band center frequency, the frequency of the tones at this freestream velocity. The effect of attaching serration 4 at location 3′ was to reduce the peak velocity fluctuations in this band. This reduction is consistent with the earlier observations which showed that the serrations either reduce or eliminate both the acoustic tones and the fluctuating lift. No measurements were made to assess the effect of the serration on the spanwise correlation of the velocity fluctuations in the various one-third octave bands.

Analysis of the data showed the velocity fluctuations in the immediate neighborhood of the trailing edge to be dominated by narrowband peaks superimposed on a weak turbulent background. (This was further substantiated by flow visualization studies using smoke which showed a well-defined, highly periodic wake behind the airfoil).

¶ We are indebted to L. Olson of NASA-Ames for the computer computations.

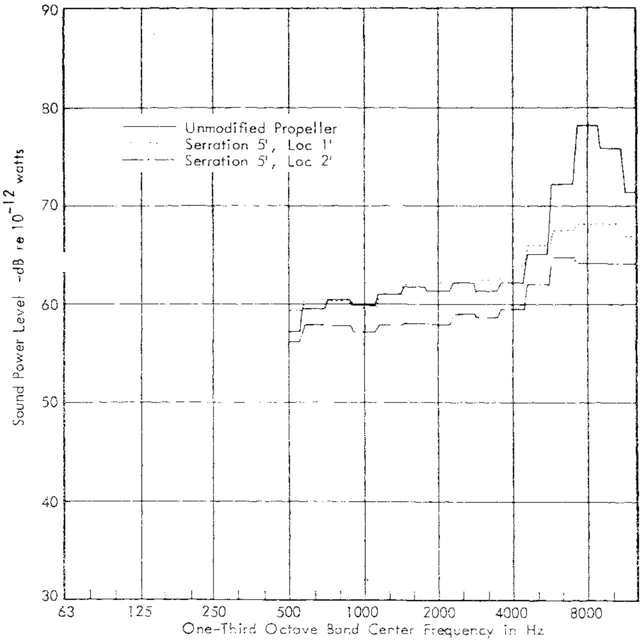


Fig. 7 Effect of serration 5, loc 1′ and 2′ on propeller sound radiation; 4000 rpm, $V = 40$ fps, $\beta = 17.5°$.

Propeller Studies

A series of investigations were conducted to study the effects of leading-edge serrations on vortex (broadband) sound radiation from a two-bladed, variable pitch NACA 0012 section propeller with a 2-in. chord and a 14-in. diam. Measurements were made of the sound power with the propeller in the laminar core of the BBN freejet. The propeller was spun at rotational speeds of 2000 and 4000 rpm in a low turbulence free stream of 40 fps. The Reynolds numbers based on chord length and flow speed at the three-quarter propeller radius were 1.16×10^5 for 2000 rpm and 2.18×10^5 for 4000 rpm—well within the previously discussed airfoil Reynolds number range.

The size and location of the serrations tested are shown in Table 1. Serration No. 5 attached at Location 2′ yielded the greatest reduction in sound power.

The unmodified propeller noise spectra produced the usual peaks at multiples of the rotational speed. When the propellers were in the lightly loaded configurations (i.e., small effective angles of attack), narrowband sound appeared in the spectra at frequencies far removed from the rotational rate peaks. These tones dominated the spectrum; their frequencies increased with tip speed for the two rotational speeds used.

Figure 7 shows raw data from a typical propeller test where the tone dominates the spectrum for the unmodified blade. It is evident that the serration reduces considerably the tone and the broadband noise. Arndt and Nagel[5] observed similar results which they attributed to, among other things, serration vortex generation which reduced wake-induced airfoil noise. They also found that serrations caused a faster dissipation of tip vortices than occurred behind an unmodified model rotor.

To isolate the dominant sound-producing region of the blade, the spanwise length of the serration was progressively reduced, the inboard portion being removed each time. As shown in Fig. 8, little or no effect upon the tone was found until less than one-quarter of the original serration length remained at the tip. The propeller noise increased toward the unmodified propeller noise levels as the serration length was reduced from 1/4 span to 1/8th span and 1/16th span. Thus, in support of some longstanding speculation on the subject[15] we conclude that for low tip speed propellers and rotors in smooth flow the dominant region of nonrotational noise generation is the outer one-quarter of the blade radius.

Conclusions

The principal conclusions from this study are:

1) Predominant, distinct tones are generated by NACA 0012 shaped airfoils and propellers operating at low angles of attack in smooth flow with chord based Reynolds numbers ranging from $8.33 \times 10^4 \leq R_c \leq 3.33 \times 10^5$. The tones are generated by periodic fluctuating forces, acting on the airfoils and propellers near the trailing edge as a result of forces induced by wake vortex shedding. It is suspected, although not verified, that the wake induced fluctuating pressures are well-correlated along the airfoil and propeller span. At higher angles of attack, corresponding to stall where the wake vortex shedding is broadband, the tones disappear.

2) The tones are reduced or eliminated by attaching properly designed and properly located serrations near the leading edge of the airfoil and propeller lower surface. The serrations generate chordwise trailing vortices on the suction surface and also trip the laminar boundary layer on the pressure surface thereby changing the character of the wake vortex shedding from periodic or almost periodic to broadband—hence the reduction or elimination of the tones. At high angles of attack corresponding to stall, the serrations also reduce the broadband noise.

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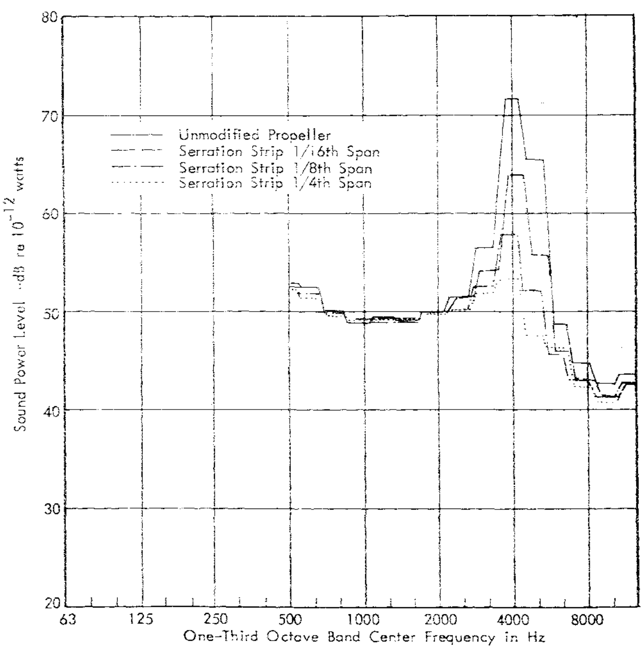

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X2048, A High Strength, High Toughness Aluminum Alloy for Aircraft Applications

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X2048 is an aluminum alloy which retains all of the desirable properties of 2024 or 2124-T851, but exhibits fracture toughness equal to or greater than that of 2219-T851. Testing of 3-in. thick plant-produced plate has shown that the strength, corrosion resistance, fatigue resistance, and elevated temperature stability of 2024-T851 are maintained. Through control of chemistry and processing, the level of brittle second-phase particles is substantially reduced for the new alloy. The resulting fracture toughness is above 33, 30, and 24 KSI $(in.)^{1/2}$ for the L-T, T-L, and S-L directions, respectively. Short transverse elongations as high as 8% have been obtained for X2048.

I. Introduction

FRACTURE toughness and fatigue crack propagation rates may presently be regarded as the two principal design limiting parameters for aircraft materials. In the future these two parameters will play an even greater role as aircraft are designed on fail-safe principles which incorporate fracture toughness and fatigue crack propagation criteria. In spite of considerable fundamental and applied research, major improvements in the fatigue performance of the high-strength aluminum alloys have not occurred. Major fracture toughness improvements, without loss of strength, have recently been achieved. A second generation of aircraft alloys have recently emerged which are basically variations of the alloys 7075 and 2024, with carefully controlled chemistry and processing to optimize fracture toughness. The purpose of the present paper is to introduce a new Al-Cu-Mg alloy which retains the desirable properties of 2024-T851, but provides a 50% improvement in fracture toughness.

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Index categories: Aircraft Structural Materials; Materials, Properties of.

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The first major step in the direction of improving the toughness of 2024-T851 was the development of 2124-T851. The major difference between these two alloys is that the latter alloy is produced with reduced levels of the impurity elements iron and silicon, and with improved processing practices. The toughness and short transverse elongation of the 2124 is equal to or better than that which had been obtained with 2024 only when a costly preforging operation was employed.

X2048 is the next step in the attainment of high fracture toughness, without sacrificing the other important properties of either 2024 or 2124-T851. Thus, plane strain fracture toughness exceeding 33, 30, and 24 KSI $(in.)^{1/2}$ have been obtained for the L-T, T-L, and S-L directions (ASTM-E399 designations), while maintaining the strength, stress corrosion resistance, fatigue resistance, and thermal stability of 2024-T851 or 2124-T851. Short transverse elongations as high as 8% have been obtained for the new alloy, where 1.5% was difficult to achieve consistently with unpreforged 2024. Reynolds Metals Co. now has produced eight plant lots of the new alloy. The majority of the data has been gathered for 3-in.-thick plate, but other thicknesses are currently being evaluated. At present the product is available as plate with a finished weight of up to 8000 lb. Larger ingots have recently been cast and the ability to provide the properties described below, for larger finished plates, is currently being evaluated. The latest standard or recommended ASTM testing methods were employed to determine the properties of the alloy.