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RESEARCH ON HELICOPTER ROTOR NOISE.(U)

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This report summarizes the results of studies in the following areas: (1) applications of generalized functions to aeroacoustics and aerodynamic problems, (2) bounds on thickness and loading noise of rotating blades and the effects of blade sweep on reduction of the noise of rotating blades, (3) study of nonlinear effects relevant to the rotor noise problem and (4) computational aspects of high speed rotor noise.

JOINT INSTITUTE FOR ADVANCEMENT OF FLIGHT SCIENCES

RESEARCH ON HELICOPTER ROTOR NOISE

ARO Grant DAAG 629-78-G-0152

FINAL REPORT

June 1, 1976 to August 31, 1979

School of Engineering and Applied Science
The George Washington University
Washington, DC 20052

This report covering the period of June 1, 1976 to August 31, 1979 consists of four parts as follows:

i) applications of generalized functions to problems of aerodynamics and aeroacoustics.

ii) bounds for thickness and loading noise of rotating blades and the effect of blade sweep on reduction of the noise of rotating blades.

iii) study of nonlinear effects relevant to the rotor noise problem.

iv) computational aspects of high speed rotor noise.

In the following pages a summary of important conclusions and results will be presented.

i) Applications of generalized functions to aeroacoustics and aerodynamic problems.

In 1969 Ffowcs Williams and Howkings developed an equation for determining the noise of bodies in motion. They used generalized function theory extensively to find various forms of the solutions of this equation. Due to the unusual success of their method, an attempt was made to systematize and apply the technique to other aeroacoustic and aerodynamic problems. The results were published in the Journal of Sound and Vibration, vol. 55, 1977.

The basic idea behind the method is as follows. For problems involving discontinuities such as shock waves, the Green's function approach can be used provided that the differential equation governing the phenomenon is rewritten with generalized derivative replacing the ordinary derivatives. The manipulations involved in the application of Green's function technique are straight forward and easy in most cases. The operational properties of the generalized functions help in this respect. For example, the equation of transonic flow around a thin wing in three dimension is

$$\nabla^2 u = \frac{\partial^2}{\partial x_1^2}\left(\frac{u^2}{2}\right) \tag{1}$$

where u is the perturbation velocity in the direction of the free stream. If $k(\vec{x})=0$ is the equation of the surfaces of discontinuities (wing surface, wake and the shock waves), then the above equation should be written as follows:

$$\bar{\nabla}^2 u = \frac{\bar{\partial}^2}{\partial x_1^2}\left(\frac{u^2}{2}\right) + \Delta\left[\frac{\partial u}{\partial n} - \frac{\partial}{\partial n_1}\left(\frac{u^2}{2}\right)\right]|\nabla k|\,\delta(k) \tag{2}$$

$$+ \bar{\nabla}\left[\Delta\left(u\vec{n} - \frac{u^2}{2}\vec{n}_1\right)|\nabla k|\,\delta(k)\right]$$

In this equation, the bar on the derivative indicates generalized differentiation, $\vec{n} = (n_1, n_2, n_3)$ is the unit normal to k=0 and $\vec{n} = (n_1, 0, 0)$. Now the use of the Green's function for the three dimensional Laplace equation results in Oswatitsch integral equation of transonic flow which was obtained originally using classical mathematics. The present method is more direct and systematic.

In the derivation of Oswatitsch integral equation, the regularization of the following divergent integral was required.

$$I_1 = \int \frac{u^2}{2} \frac{\bar{\partial}^2}{\partial y_1^2} \left(\frac{1}{r} \right) dy; \tag{3}$$

where $r = \vec{x}-\vec{y}$. Let $f(\vec{x}) = 0$ be a small closed surface around the point $\vec{x}$ with maximum dimension ε such that $f>0$ inside this surface. It was shown that

$$I_1 = \frac{1}{2} \lim_{\varepsilon \to 0} \int [u^2(\vec{y})-u^2(\vec{x})h(f)] \frac{\partial^2}{\partial y_1^2} \left(\frac{1}{r}\right) d\vec{y} - \frac{1}{2} \alpha u^2(\vec{x}), \tag{4}$$

where $h(f)$ is the Heaviside function. The constant α is a strong function of the shape of the surface $f=0$. If $f=0$ is a sphere with center at $\vec{x}$, then $\alpha = 4\pi/3$ and if $f=0$ is a flat cylinder whose axis is parallel to x_1-axis, then $\alpha=4\pi$ as ε goes to zero. This has important implication in numerical calculations of transonic flow around airfoils. If the three dimensional lattice points form a cube or other geometric shapes, the value of α changes accordingly. This fact is not widely known and to the author's knowledge it was first explicitly stated the article appearing in the Journal of Sound and Vibration. This result was again obtained using generalized function theory.

For aeroacoustic problems, it was shown that for an arbitrary surface $f=0$ in motion, there is a simple relation for the acoustic pressure $p'(\vec{x},t)$. Let $F(\vec{y}; \vec{x},t)=[f(\vec{y},\tau)]_{ret} = f(\vec{y},t - r/c)=0$. Then, in far-field

$$4\pi p'(x,t) = \frac{1}{r} \frac{\partial}{\partial t} \left(Q + \frac{1}{c} T_r\right). \tag{5}$$

where $Q(\vec{x},t)$ is the rate of mass injection from the surface $F=0$ defined by the relation

$$Q(\vec{x},t)= \int_{f=0} \rho V_n d\Sigma \tag{6}$$

Here $d\Sigma$ is the element of surface area of $F=0$. The symbol T_r stands for the net force in the radiation direction on the surface $F=0$. Equation (5) is interpreted as follows. In the far-field the acoustic pressure $p'(\vec{x},t)$ is dependent on fluctuations in the net rate of mass injection based on the local density on the surface F=0 and the net force in the radiation direction on this surface. This result is for noncompact sources extending a similar result for compact sources.

In connection with the above result, it was shown that the thickness noise in the far-field is related to the second time derivative of the volume Ψ enclosed by the surface F=0 through the relation

$$4\pi p'(\vec{x},t) = (\rho_o/r)\partial^2\Psi/\partial t^2 \ . \qquad (7)$$

This equation was used successfully by Dr. G. P. Succi of the Department of Aeronautics and Astronautics of MIT in a program to calculate the thickness noise of general aviation aircraft. It was published in "Design of Quiet Efficient Propellers" SAE paper 790584, 1979.

Another related result was that Isom's thickness noise formula for the far-field is valid for an arbitrary motion (not necessarity a rotating motion) of a body. This formula states that in the far-field, the thickness noise is equivalent to the noise from a uniform pressure distribution over the entire body surface. The source strength has the magnitude $\rho_0 c^2$. This work was published as Letter to the Editor, Journal of Sound and Vibration, Vol. 64, 1979. Professor Ffowcs Williams proved very recently that this result is also valid in the near-field. A new Letter to the Editor of JSV describing this extension will appear in Vol. 66 Part 4, 1979. The various expressions for the thickness noise based on this result are:

$$4\pi p'(\vec{x},t) = -\frac{\partial}{\partial x_i}\int_{f=0}\left[\frac{\rho_0 c^2 n_i}{r|1-M_r|}\right]_{ret} dS, \qquad (8\text{-a})$$

$$= \frac{\partial}{\partial t}\int_{f=0}\left[\frac{\rho_0 c\cos\theta}{r|1-M_r|}\right]_{ret} dS + \int_{f=0}\left[\frac{\rho_0 c^2\cos\theta}{r^2|1-M_r|}\right]_{ret} dS \qquad (8\text{-b})$$

$$= \frac{\partial}{\partial t}\int_{\substack{f=0\\g=0}}\frac{\rho_0 c^2\cot\theta}{r}\, d\Gamma\, d\tau + \int_{\substack{f=0\\g=0}}\frac{\rho_0 c^3\cot\theta}{r^2}\, d\Gamma d\tau \qquad (8\text{-c})$$

In these results, dS is the element of surface area of the body f=0 and $g=\tau-t+r/c$. The element of length of the curve of intersection of the surfaces f=0 and g=0 is denoted by $d\Gamma$ and the source time is τ. The angle θ is between the normal to the body surface and the radiation direction $\vec{x}-\vec{y}$.

The above equations can be used to show that thickness noise level is larger than the skin friction noise. Both of these components of the noise of rotors and propellers peak in the plane of the disk. For skin friction noise the term $\rho_0 c^2 \cos\theta$ must be replaced by $\frac{1}{2}\rho_0 V^2 \sigma' = \frac{1}{2}\rho_0 c^2 M^2 \sigma'$ in the above equations where σ' is the skin friction coefficient on the blade. For Raynolds numbers encountered in rotor and propeller operation, the range of variation of σ' is between 0.001 to to 0.002 for laminar flow and between 0.004 to 0.01 for turbulent flow. For the observer in the plane of the disk $\cos\theta \simeq \frac{1}{2}$(thickness ratio) $\approx$ 0.05. Therefore the source strength for thickness noise in the plane is approximately $0.05\rho_0 c^2$ while for skin friction noise the source strength is at most $0.005\ \rho_0 c^2 M^2$. For subsonic blade speeds, therefore, thickness noise level is much larger than skin friction noise. This was also shown by an exact numerical method and published as AIAA paper No. 79-0608, 1979 and also in NASA Technical Memorandum 80059, 1979.

ii) Bounds on thickness and loading noise of rotating blades and the effects of blade sweep on reduction of the noise of rotating blades.

For high speed rotors, the two dominant components of the radiated noise are thickness and loading noise. It was thought that establishing bounds on these would be very useful as a quick check of noisiness of a rotor. Since bounds are only approximations, any formulation that would require as much effort as the exact calculation of thickness and loading noise must be rejected. Unfortunately, this proved to be very difficult.

One formulation for a bound on thickness noise was published in proceedings of 14th Annual Meeting, Society of Engineering Sciences, 1977. It was shown that the bound on thickness noise was proportional to the maximum of second time derivative of the acoustic planform. To determine this maximum, the program reported in NASA TMX-74037 can be used. An interesting conclusion from this formulation is that planform variation can be used to control the noise of high-speed rotating blades.

Other formulations in frequency domain, which were for both thickness and loading noise, have been published in the proceedings of an International Specialists Symposium held at NASA Langley Research Center, 1978 (NASA CP-2052). For a given harmonic of the noise, a blade thickness and loading distribution were found to maximize the level of the noise. Since these distributions were functions of harmonic number, these bounds turned out to be very coarse. When the acoustic pressure spectrum of a real rotor is compared with individually-maximized harmonic levels, the latter were substatilly higher than the former. No simple and useful bounds for thickness and loading noise were found despite considerable amount of work on this subject.

In the above paper, a rigorous proof for the effectiveness of blade sweep in the reduction of the level of rotor noise was presented. For a blade with continuously increasing sweep, it was proved that no optimum sweep existed. Thus, increasing the blade sweep lowers the generated noise level. Large blade sweep appears to be impractical for helicopter rotors but idea has been used for advanced propellers in recent years.

iii) <u>Study of nonlinear effects relevant to the rotor noise problem</u>

In recent years several researchers such as Hanson and Fink and also Boxwell, Schmitz, Yu and Caradonna, have pointed out the importance of nonlinearities as the cause of discrepancies between linear acoustic calculations and measured data. For high speed rotating blades, linear acoustic calculations have two shortcomings. The theoretical level and the width of the main pulse of the acoustic pressure signature are both smaller than the measured values. Many comparisons with experimental data, particularly for propellers, are available at present. With the exception of a model rotor noise data for four tip speeds (M_t=0.8 to 0.96) collected at Ames, for blades with subsonic tip speeds the underestimation of the level of the acoustic pressure signature is small. Some comparison with experimental data supporting this fact will be published by the author and Dr. G. P. Succi shortly. The underestimation of the width of the main pulse of the signature can be pronounced at high (transonic) speeds.

The two methods of approach to include the nonlinearities of flow around the blades both rely on the inclusion of quadrupole sources around the blades (Hanson and Fink; Yu, Caradonna and Schmitz). Both these methods require some means of determining the quadrupole strength around the rotating blades. Hanson and Fink use two dimensional transonic flow calculations while Yu et al also use three dimensional flow calculations around the blade tip region. Apparently the appeal of the acoustic analogy is the simplicity of the formulation of the problem. However, the calculated results depend on how well the quadrupole sources are approximated.

Since the full nonlinear aeroacoustic equation for rotating blades is very complicated, the question of approximation of quadrupole strength was studied for a simpler problem. The nonlinear wave propagation around a pulsating sphere is ideal for this purpose since its exact solution can be obtained by several methods such as nonlinearization technique discussed by Whitham (Linear and Nonlinear Waves). It was shown that if the quadrupole strength was based on first order (linear) velocity of the fluid, then the solution correct to second order does not exhibit the characteristics of the exact nonlinear solution. Thus the quadrupole strength must be known to an accuracy better than that from linear solution. The implication of this result is that acoustic analogy is not appropriate for the study of nonlinear effects around the blades since the determination of quadrupole strength alone by a theoretical method would make the acoustic calculations redundant. This is so because any calculations which determines the velocity field around the blade also can determine the pressure field.

Thus, it appears that a direct method of flow-field calculations around the blades, such as that by Caradonna and Isom is the best way to study the nonlinear effects. The results related to this section were presented in AIAA Paper No. 79-0608, 1979 and in more detail in NASA Technical Memorandum 80059, 1979.

iv) Computational aspects of high speed rotor noise

Because of need for accurate prediction of rotor noise to meet the noise standards, computational aspect of rotor noise has become an important problem. Much work has been done in developing theories to explain rotor noise while little effort has been spent on applying these results as precisely as possible using computers. It is the characteristic of noise formulations that there are always some restrictions such as singularities or the position of the observer. It is also a common practice to make simplifying assumptions for both the input data or the rotor geometry. In most cases intuitive arguments as to the effect of these assumptions are not reliable or convincing. To test the validity of any noise theory, rotor geometry and the input data must be described as precisely as possible.

A study of different formulations the calculation of the noise of rotating blade was done to find a formulation with least restrictions such as singularities or the observer position. The formulation that was selected is based on the collapsing sphere technique:

$$4\pi\, p'(x,t) = \frac{\partial}{\partial t} \int_{\tau_1}^{\tau_2} \int_{\Gamma} \frac{\rho_o c v_n + p \cos\theta}{r \sin\theta}\, d\Gamma\, d\tau$$

$$+ \int_{\tau_1}^{\tau_2} \int_{\Gamma} \frac{cp \cot\theta}{r^2}\, d\Gamma\, d\tau$$

A computer program was developed at NASA Langley Research Center in collaboration with Mr. Thomas J. Brown of U.S. Army, Langley Directorate. The program Logic is very complicated and the computation time is long. Nevertheless, many calcutions and comparisons with experimental data convinced the author of the soundness of this approach. The results have been published in NASA Technical Memorandum 74037, 1977.

One problem associated with the above formulation in addition to excessive computation time, is increased numerical error for low rotor tip speeds. Therefore, the above formulation is only suitable for high subsonic and supersonic tip speeds. To remedy this problem, another formulation was selected as follows:

$$4\pi\ p(\vec{x},t) = \frac{1}{c}\frac{\partial}{\partial t}\int_{f=0}\left[\frac{\rho_0 c v_n + p\cos\theta}{r|1 - M_r|}\right]_{ret} dS$$

$$+ \int_{f=0}\left[\frac{p\cos\theta}{r^2|1 - M_r|}\right]_{ret} dS$$

This formulation has been used to develop a new rotor noise program at NASA Langley Research Center. The new program has a precise rotor geometry and motion description, for example the rotor angle of attack, blade flapping and azimuthal pitch change. The observer can be stationary or in motion with the helicopter. This program is at present being validated by Bell Helicopter Textron and Sikorsky Aircraft. Both these companies will use realistic input data, blade geometry and motion for comparison with measured data. Preliminary evaluation of the program at Langley appears very promising.

Based on the experience gained on the calculation of the noise of rotors, another program for high speed propellers was developed. Both of the above formulations are used depending on the value of M_r. For $M_r \approx 1$ or $M_r > 1$, the collapsing sphere technique is used for panels on the blade. Otherwise the formulation involving the Doppler singularity is used. This program uses a curvilinear coordinate system to describe the blade geometry for advanced propellers. It has been used successfully at NASA Langley Research Center to calculate the Hamilton standard propfan noise and also the noise of general aviation aircraft.

Because of the complexity of noncompact source calculations, other possible formulations have been carefully studied. One new formulation in time demain which does not require retarded time calculation has been obtained. This formulation involves a two dimensional integration within a wedge shaped region in a plane. It will be published in a NASA Technical Memorandum in the near future.

Even for high speed rotors, there are regions of space where the acoustic sources are compact. In these regions, the unsteady blade loading noise can dominate. Research in this area, particularly on the input data to the acoustic calculations is continuing elswhere. However, for high speed rotors and propellers, when both steady and unsteady sources should be considered in the acoustic calculations, a combined noncompact source calculation for steady sources and a compact source calculation (such as one based on Lowson's formula) appears to be the best approach. This work was reported in ASME Paper 77-GT-70, 1977.

PUBLICATIONS OF F. FARASSAT
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