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RECENT LANGLEY HELICOPTER ACOUSTICS CONTRIBUTIONS

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SUMMARY

The helicopter acoustics program at NASA Langley has included technology for elements of noise control ranging from sources of noise to receivers of noise. This paper discusses the scope of Langley contributions for about the last decade. Specifically, it reviews the resolution of two certification noise quantification issues by subjective acoustics research, the development status of the helicopter system noise prediction program ROTONET, and presents highlights from research on blade rotational, broadband, and blade vortex interaction noise sources. Finally, research contributions on helicopter cabin (or interior) noise control are presented. A bibliography of publications from the Langley helicopter acoustics program for the past 10 years is included.

INTRODUCTION

Acoustics research at Langley Research Center covers sources of noise, propagation of noise, and receivers of noise. That portion of acoustics research aimed at helicopters has the same total scope and begins with understanding, predicting, and reducing noise generated by the most important sources, considers propagation of noise from source to receiver through the atmosphere or vehicle structure, and includes technology to determine criteria for controlling the impact of noise on receivers. Two classes of helicopter receiver problems are being addressed. The first class of research concerns the control of noise impacting residents in heliport communities--the "exterior" noise problem. The second class of concerns relates to the control of the noise environment of helicopter passengers and crew--the "interior" noise problem.

Helicopter acoustics research at Langley Research Center has been ongoing for about three decades. The level of activity was relatively small until the last decade when national and international concerns with the environment and quality of life resulted in proposals for noise certification of helicopters. The stimulus of impending noise certification requirements led to the recognition of limitations of existing noise control technology and to a push to expand the noise control technology base. Therefore, beginning in the late 70's, Langley helicopter acoustics research expanded significantly to respond to this need. The thrust of the expanded program has been to create the capability to design to a noise goal in order to make U.S. helicopters more competitive in the world-wide civil marketplace. Most of the effort has gone into the exterior, or community, noise problem at which noise certification is directed. A lesser, but still significant effort has gone towards control of the interior noise environment of passengers and crew.

An appreciation for the scope of acoustics research necessary to create design-to-a-certification-noise-goal capability comes from considering the complexity of helicopters as noise sources. This complexity is illustrated conceptually in figure 1 which shows a helicopter noise spectrum to be made up of contributions from several different noise sources. Sound at lower frequencies tends to be dominated by blade rotational tones arising from rotor loading and thickness. At higher frequencies, the sound becomes broadband in character and is generated by mechanisms that involve turbulence inflow or the rotor blade boundary layer. Of course, these sources exist on both main and tail rotors which generate noise at differing frequencies due to different shaft speeds. In intermediate frequency ranges, interaction noise sources tend to dominate the spectrum. Probably the most significant is blade vortex interaction (BVI) which occurs when the tip vortex shed from one blade is intersected by a following blade. Another such source is main rotor-tail rotor (MR-TR) interaction occurring when the tail rotor is loaded by the unsteady downwash field of the main rotor. The relative levels and frequencies of the various sources shift with operating condition, forward speed, and observer location relative to the vehicle. To determine which of the noise sources are in most need of research, the end goal of noise certification must be considered. The noise scale used for designing and certifying helicopters is the Effective Perceived Noise Level, or EPNL, that incorporates the A-weighted filter to approximate the response of the human ear and reflect people's perception of noise. The filter provides greatest weight to sound energy in the 1000 to 5000 Hz frequency range and filters out much of the low frequency sound energy associated with blade rotational noise. The filtered noise spectra is shown to be much "flatter" than the unfiltered spectra and to increase the relative importance of higher frequencies. For this reason, civil helicopter noise research must include the higher frequency sources even though their absolute noise levels are significantly less than the noise levels in the lower frequency range.

This paper will discuss the most significant of Langley's recent contributions to the technology of helicopter noise control. The first section describes research to resolve international issues associated with noise measurement for quantifying noise during helicopter certification and during heliport operations. Then, the program to develop design-for-noise capability centered on the ROTONET noise prediction system will be described. The research to understand, predict, and reduce the most important individual noise sources follows. The last section of the paper shifts attention from exterior to interior noise concerns and discusses Langley research on cabin environment. Finally, a bibliography is included which lists Langley helicopter acoustics research publications of the past decade.

NOISE MEASUREMENT SCALES

The prime requirement for noise measurement scales, or a noise metric, for noise certification or for assessing impact of noise on communities is that the scale adequately quantify those characteristics of the noise which influence human perception. During the past decade, NASA Langley has conducted a number of subjective acoustic studies to answer specific questions related to the ability of noise scales to quantify helicopter noise. Two studies which have had major impact on FAA and ICAO noise certification procedures (FAR-Part 36) and community noise assessment regulations (FAR-Part 150) are described in the following sections.

Noise Certification

A major concern in choosing a measurement scale for helicopter noise certification was the need for an impulse correction to account for the blade-slap phenomenon. Prior to the formulation of the ICAO noise certification rule and FAA notice of proposed rule making (NPRM), some laboratory studies had indicated that the standard aircraft noise certification scale, effective perceived noise level (EPNL), underestimated the annoyance due to helicopter noise containing appreciable blade-slap. As a consequence, an impulse correction was proposed which would have significantly complicated the EPNL calculation procedure and which would have severely penalized some U.S. manufactured helicopters. To provide data in a realistic setting, the FAA requested that Langley conduct a flight experiment using a jury of people to evaluate actual helicopter overflight sounds.

In the experiment conducted at NASA Wallops Flight Facility in the spring of 1978 and reported in reference 1, 91 people made judgments on the noise of 72 helicopter and propeller airplane flyovers. Some of them were located inside houses and others were out-of-doors during the tests. A photograph of the outdoor subjects and the test area is presented in figure 2. The impulsive characteristics of one of the two helicopter types was systematically varied by changing the main rotor speed while maintaining a constant airspeed and holding other characteristics of the noise relatively constant.

Results from the experiment indicated that, at equal noise levels as measured by EPNL, the more impulsive helicopter was judged less annoying than the less impulsive helicopter. This result is illustrated in figure 3 where the average annoyance rating given by the outdoor listeners is plotted against EPNL for the two helicopter types and the propeller airplane. Least square linear regression fits to the data for the impulsive and non-impulsive helicopters are indicated by the solid and dashed lines respectively. The more impulsive helicopter was judged very similar to the propeller airplane. These and other results from the experiment indicated that the proposed impulse correction did not improve the annoyance prediction ability of EPNL. Based on these results and a number of additional carefully controlled laboratory studies conducted at Langley or under NASA contract, the United States delegation convinced the ICAO to drop the impulse correction requirement for helicopter certification.

Community Impact

The total community impact of aircraft or helicopter noise is generally considered to depend on the number of overflights as well as the noise level from each overflight. The equivalent noise level (LEQ) scale, which integrates or sums the noise from a number of overflights on an energy basis, has been shown by both community surveys and laboratory studies to effectively quantify the total noise impact around large airports or along major roads with a large number of noise events per day. However, does LEQ adequately reflect annoyance around the growing number of heliports with a low number (1 to 10) of flights per day? Because of the difficulty in obtaining sufficient statistical accuracy, standard community survey techniques applied to naturally occurring heliport environments are inappropriate for answering this question. In addition, the necessity for testing very low numbers of events for extended time periods made the validity of laboratory experimentation questionable. With the support of the FAA, a new methodology was used to address this issue that combined the home environment with controlled noise exposures, reference 2.

The survey was conducted by telephone in a community near Fort Eustis, Virginia that is normally exposed to helicopter noise. The participants were repeatedly surveyed on evenings following days in which the helicopter noise levels and number of flights were closely controlled by arrangement with Army heliport officials. Noise exposure was controlled by using two different types of helicopters on different days in the tests. A UH-1H helicopter provided a relatively impulsive noise exposure and a UH-60A provided a relatively low impulsive exposure. On any given day overflights were made at either 500 ft. or 1500 ft. to provide nominal peak noise levels of 85 dB(A) or 75 dB(A). The number of planned flights per day varied from 1 to 32. Noise measurements were made at a number of locations in the community on test days to ensure accurate noise exposure estimates. The community residents participating in the survey were paid an honorarium to maintain interest but were told only of a general interest in transportation noise and given no hint of the true purpose of the test. A total of 338 residents were interviewed on each of 17 controlled exposure days.

Results from the survey indicate that community residents could discriminate days with noise exposures resulting from a very low number of flights per day from days with only a few more flights per day. Average annoyance scores for days with different noise exposures are shown in figure 4 on the noise scale sound exposure level (SEL) with number of flights as a parameter. SEL is a measure of the noise exposure of a single flight which includes A-weighting for frequency content and is corrected for the duration of the flight. An increase in annoyance with exposure is seen over the range of both noise level and number of flights. The data were also examined to determine the applicability of single number noise exposure indexes to quantify the respondents annoyance. Results for LEQ, the scale used to assess airport noise exposure in the FAR-Part 150 and by the EPA for any type of community noise exposure, is shown in figure 5. Except for the very lowest noise exposure condition, a linear increase in annoyance with exposure is evident, thus demonstrating that the LEQ scale is indeed applicable to heliport community situations with low numbers of flights per day.

Although not illustrated in this paper, several other interesting findings were obtained in the survey. One, consistent with the results of the field study described previously, was that impulsive helicopters are not inherently more annoying than non-impulsive helicopters when their noise is measured on a scale corrected for duration and noise level.

ROTONET

The aim of noise certification is to force the incorporation of the best available noise control technology in new helicopter designs. For this to happen in a rational manner, manufacturers must be able to conduct sensitivity analyses that predict, with confidence, the effects of design variables on the noise generated under certification conditions. As pointed out earlier, this requires methodology for determining noise from several helicopter noise sources and then predicting their combined effects in certification measurement units under specified conditions. ROTONET is a modular testbed computer program that predicts noise at a specified receiver location of a helicopter system that aims to meet this need. The elements of ROTONET are depicted in figure 6. Inputs include the configuration variables (such as rotor and tail rotor geometry and rotational speeds), flight path (such as level flyover or landing descent), and observer location (such as certification measurement sites). The ROTONET computer program itself has three major functional computer code groups. The first, rotor performance, predicts the airfoil section and rotor force coefficients for isolated main and tail rotors and generates aerodynamic loads and motions for inputs to source noise prediction. The second code grouping contains several source noise modules that are required to account for all contributors such as blade rotational noise, broadband noise, and blade vortex interaction. Finally, the propagation cluster of modules accounts for effects such as source to observer geometry, atmospheric absorption, spherical spreading, and ground reflection and attenuation, and computes the noise on any desired scale such as overall sound pressure level (OASPL), A-weighted sound pressure level (L_A), and effective perceived noise level (EPNL).

The modular approach to ROTONET permits the newest technology to be incorporated in the computer system. The prediction procedure for any given noise source may be analytical or empirical and can be replaced by a better procedure that subsequently becomes available. A user's proprietary method can be incorporated by meeting well defined interface requirements. A phased development of ROTONET is being followed, with each phase representing a more complete and advanced modeling of the helicopter noise prediction problem. The Phase I baseline system described in reference 3 is operational and contains blade rotational and broadband noise modules. The Phase II version now being evaluated adds better broadband source noise capability, accounts for non-uniform inflow, uses a prescribed wake, expands the harmonic range of the blade rotational source module, and generally inproves utility. The Phase III version under development is building towards including a BVI capability and a rotor free wake along with other improvements. In addition to operating on Langley's mainframe CDC computers, ROTONET operates on VAX minicomputers and in that form has been delivered to all four major helicopter companies.

At least three of the companies have exercised the Phase I and Phase II systems, have verified that proprietary modules can be interfaced and operated with ROTONET, and are planning to evaluate the more advanced versions.

Initial applications of ROTONET indicate the kinds of results that are possible. Table I, from reference 3, compares predictions with measurement of EPNL for a Bell 222 in level flyover for four combinations of speed and altitude. The prediction with just rotational noise sources is directly from the Phase I system and is uniformly low compared to measurement by about 6-7 EPNdB. The broadband source module used in the second prediction is a partial version of the full broadband source module in Phase II. The addition of the broadband source significantly improves the overall agreement with measurement, bringing it to within 3-4 EPNdB. This comparison demonstrates that the broadband source is a significant contributor when noise is measured on the EPNL scale. However, it also shows that system noise prediction must be further improved before it can be routinely applied with confidence. The goal continues to be to predict EPNL to within $\pm$1.5 EPNdB. For the case presented, addition of the BVI source is believed to be necessary for further significant improvement in prediction.

While the EPNL predictive ability just discussed is the desired product of ROTONET, determination and assessment of weak links in prediction of the complex quantity EPNL is extremely difficult. The comparison with data just discussed relates output for a given input but gives no information on the efficacy of the myriad of intervening steps. Therefore, a series of helicopter flight tests are underway to obtain a data base that not only relates input (flight condition) to output (EPNL) but also permits assessment of the intervening steps. This data base will be used to validate the predictive ability of ROTONET, develop confidence in its utility, and identify improvement needs.

The first test in the series has been completed at Wallops Flight Facility and was conducted cooperatively with McDonnell-Douglas Helicopters using the 500E helicopter shown in figure 7. The configurations tested had a 5-blade main rotor, either 2- or 4-blade tail rotors, and sometimes included an engine exhaust muffler to insure uncontaminated main and tail rotor noise. A specially designed rotor head telemetry system transmitted rotor blade data for on-board recording along with other vehicle data, thus eliminating slip rings for obtaining high frequency data off the rotor. Laser radar tracking provided precise helicopter position and velocity data. Microphone array techniques, time correlated with the on-board data, were used to measure a hemispherical far field noise directivity pattern underneath the vehicle with a high level of statistical confidence. A typical result from the May 1986 test is illustrated in figure 8 and compared with a ROTONET prediction. In this case, the 1/3 octave band noise spectrum radiated from near the overhead position is shown. The prediction of the details of the spectrum are reasonable at low frequencies, very good at mid-frequencies, and poor at higher frequencies. However, EPNL (which makes use of the spectrum time history throughout the flyover) is predicted to within 1.7 EPNdB, illustrating the forgiving nature of the EPNL scale. Such detailed spectral information shows clearly that improved noise source models must be included in the system model. The acoustic data from the MD 500E flight test will include EPNL and narrow band spectra as well as 1/3 octave spectra such as this for measurement locations beneath the helicopter covering nearly a hemisphere. The data base will also include operating and dynamic state data and layered atmospheric weather data and will be available to the industry for comparison with company prediction methods as well as ROTONET.

NOISE SOURCES

Helicopter external noise is generated by a large number of distinctively different sources and mechanisms. Among the most important are high speed impulsive noise associated with transonic rotor tip speeds, tonal rotational noise from main and tail rotors, broadband noise of various types, blade-vortex interaction noise, main rotor-tail rotor interaction noise, and engine noise. With the exception of engine noise, all these sources are related to moving aerodynamic surfaces of helicopters. Therefore, their intensity and spectral characteristics are functions of system configuration, flight speed, maneuvers, and rotor dynamics. Thus, the analysis, prediction, and measurement of individual source components, which are needed as part of the total helicopter system noise prediction in ROTONET, are complex and difficult. However, significant progress has been made in the quantitative understanding of the most important source mechanisms. Research to understand the high speed impulsive noise source has been led by the Army Aeromechanics Directorate at Ames Research Center. Langley Research Center's most significant accomplishments are related to three important sources for civil noise certification, blade rotational noise, broadband noise, and blade vortex interaction noise.

Rotational Noise Theory

The generation of noise by bodies in arbitrary motion is governed by the Ffowcs Williams Hawkings (FW-H) equation which may be derived from first principles of mass and momentum conservation. It can be simply interpreted as a wave equation with three source terms commonly identified as the thickness, loading, and quadrupole noise sources. At Langley, Farassat obtained and reported a general solution to the FW-H equation and adapted it to rotor noise prediction, reference 4. His analytical development is unique in several ways. Mathematics aside, perhaps most important is that the solution is obtained in the time domain, rather than the frequency domain, as an acoustic pressure time history. The solution is expressed in an integral form that can be numerically evaluated and permits full description of rotor blade geometry and kinematics. Since the noise spectrum is obtained by Fourier transform of the time history, the method predicts amplitudes of the fundamental and all its harmonics and is not limited to predicting only one or two tones. More recent developments have shown that the time domain solution can also be adapted for linearized unsteady aerodynamic analysis, reference 5, and extended to obtain a practical solution for supersonic tip speed propeller noise analysis, reference 6.

A comparison between prediction by the Farassat formulation and measured noise data from the Operations Loads Survey (OLS) Bell helicopter were conducted and reported in references 7 and 8 to evaluate the prediction capability. Typical results from that validation study are shown in figures 9 and 10. Shown are noise spectra measured and predicted ahead of the helicopter, near the plane of the rotor. Figure 9 is at relatively low speed, 66 fps, and 8.5 degrees below the rotor plane. The fundamental rotor tone and 16 harmonics are illustrated. Three tail rotor tones are also identified over the frequency range. For the predictions, measured aerodynamic loads were used as inputs. The results demonstate that full scale rotor rotational noise can be predicted with good accuracy at modest forward speeds using only thickness and loading source components, if aerodynamic loading is known with confidence. Figure 10 is a result at higher flight speed, 200 fps, 13.3 degrees below the rotor plane. At this higher speed, the amplitudes of the fundamental tone and lower harmonics were underpredicted, indicating the need to consider quadrupole sources, transonic aerodynamics near the advancing blade tip, or nonlinear effects. This particular methodology for predicting rotational noise, demonstrated to work very well except at high forward speeds, is part of the Phase I ROTONET system described earlier.

Recently, substantial effort has been devoted to improving the computational codes for rotor blade rotational noise prediction. The theory has been reformulated to permit faster and more accurate computations. Other improvements in the numerical algorithms and geometrical modeling have improved speed and robustness. The complete, updated version of the blade rotational noise prediction code, known as the Brentner-Farassat code or WOPWOP, is described in reference 9 and has been distributed to the industry. Two results using the code from a recent validation effort in reference 10 are shown in figures 11 and 12. The comparisons are with wind tunnel data for a 1/4 scale UH-1 helicopter. The noise code was coupled to an existing rotor performance code, C-81 from Ames Research Center, to generate input data. Figure 11 shows the acoustic pressure time history and spectrum for a case where thickness noise dominates. Agreement in time history and for a broad frequency range are felt to be good and of the same order of agreement obtained with earlier codes. Figure 12, however, is the time history for a flight condition where loading noise is dominant and BVI occurs. Agreement is not good for this case for two reasons--first, BVI prediction is not included in the analysis, and secondly, the aerodynamic loads from C-81 are inadequate. This highlights the necessity of using the best available aerodynamic loading information if blade rotational noise is to be predicted for arbitrary locations and flight conditions. The robustness, high resolution, and stability of the new code make it ideal for studying noise effects of detailed rotor dynamics, such as lead-lag and random impulsive blade loads, and rotor geometry variations. Therefore, Langley efforts are directed at coupling the noise code to newer and better aerodynamic codes including Ames' CAMRAD and TFAR codes.

Broadband Noise

Broadband noise is of concern for its contributions to total noise measured on the certification scale EPNL at higher frequencies. It is especially important for large, low rotor-speed rotor systems. Numerous broadband sources and generating mechanisms have been identified. Unsteady, non-deterministic loading on the rotor produces the random part of blade rotational noise. Of more concern at higher frequencies is the self-noise generated by a rotor blade and its boundary layer and shed vortices. Dominant broadband source mechanisms recognized in the survey of reference 11 are turbulence ingestion, trailing edge-turbulence interaction, trailing edge bluntness, separated flows, and blade tip vortex shedding.

The Langley program has addressed these sources over the past decade so that the relative importance of each is understood. An example of this research from reference 12 is illustrated in figures 13 and 14. As seen in the photograph, relatively small models were tested at low velocities in Langley's Quiet Flow Facility. Most tests were two-dimensional and varied Reynolds numbers over a wide range by changing both velocity and airfoil chord. The data show how the scaled noise level for the trailing edge-boundary layer interaction source collapses into a single curve through the boundary layer laminar to turbulent transition flow region. Such measurements were a key in developing an empirical prediction method for the broadband sources that has been incorporated into ROTONET.

An opportunity to assess broadband prediction methods occurred during the joint NASA/DFVLR/FAA rotor noise test in the DNW wind tunnel in the Netherlands during May 1986. Figure 15 shows the 40% scale BO-105 rotor being tested in that facility. The unique DNW aeroacoustic wind tunnel is the only facility in the world with an acoustic environment permitting broadband noise to be measured on a model of realistic size. Noise was measured with microphones above the rotor plane and external to the flow. Prior to tunnel entry, the broadband noise for each test condition had been predicted using the newly developed method for ROTONET. One of the best comparisons from reference 13 is presented in figure 16. Four 50 Hz bandwidth measured spectra are shown for constant thrust coefficent, C_T, and advance ratio, μ. The parameter, angle of attack of the tip path plane, α_{TPP}, is a measure of rate of descent which is known to be major variable in blade vortex interaction, or BVI. The broadband noise prediction in the figure uses all of the previously mentioned source mechanisms except trailing edge bluntness which is not important for this case. As expected, at low frequencies where rotational and blade vortex interaction noise dominate, the prediction falls far below the measured spectra. However, at high frequencies, the prediction agrees remarkedly well with experiment. While complete data from the experiment are still being analyzed, this early result is very encouraging and suggests that the prediction procedure truely incorporates the important noise generation mechanisms. The agreement is surprising when considering the 2-dimensional basis for the prediction method. However, the availability of data from a carefully conducted basic research experiment, even though 2-dimensional, is the key to the good prediction.

At intermediate frequencies, up to about 6000 Hz model scale, noise levels in figure 16 change drastically with the parameter α_{TPP}, thus indicating interaction is dominating the noise at these frequencies. The state of understanding of the interaction noise is still poor, and is the focus for on-going research, some of which is discussed in the next section.

Blade-Vortex Interaction Noise

Blade vortex interaction (BVI) noise arises from the impulsive load when a rotor blade intersects or passes near the tip vortex shed by a preceeding blade. It depends on operating conditions, observer position, and frequency range. As just pointed out on figure 16, it's energy usually shows in the spectrum between lower frequency blade rotational noise and higher frequency broadband noise. Research on this very complex noise source is not nearly as advanced as on the other sources discussed. Langley's approach to the problem has been to study it in a very fundamental way with 2-dimensional experiments and analysis as well as to conduct wind tunnel experiments on rotating blade systems. Figure 17, from reference 14, shows a 2-dimensional flow visualization experiment in the Langley Quiet Flow Facility which examined details of vortex interaction with an airfoil and determined the bounds of three zones of interaction for BVI. A distributed vortex may deflect its trajectory but will retain its shape if it is more than one chord length away from the airfoil. When the encounter distance is within a half chord, the vortex will deform as well as deflect. If the encounter distance is within an airfoil thickness, collision occurs and viscous interaction splits the incident vortex and may induce secondary vortices. Parallel computational acoustic studies using an Euler Code to model the interaction process are reported in reference 15 and illustrated in figure 18. A vortex is injected 1.5 chord lengths upstream from and 0.5 chord lengths below the airfoil leading edge and then tracked as it washes downstream. It both distorts and accelerates as it passes a lifting airfoil and these processes generate the noise. The predicted acoustic pressure time history is seen to closely approximate the familiar impulse noise of BVI.

Such fundamental studies provide insights into the fluid mechanics that generate BVI. However, experiments with rotating blade models are necessary to develop noise prediction capability and noise reduction approaches. The most recent such Langley experiment on BVI was conducted jointly with the broadband noise experiment in the DNW wind tunnel in May 1986. The test configuration for BVI noise testing is shown in figure 19 and is reported in reference 16. In this case, an array of microphones is mounted on a traversing carriage beneath the rotor, with the microphones inside the wind tunnel flow, to map the BVI noise on a plane beneath the rotor. A typical result is shown in figure 20 for a rotor tip-path-plane angle of 2.3°. The contours are constant peak-to-peak BVI pressure on a plane 2.1 m beneath the 4-meter diameter rotor. The area covered by the rotor disk is shaded. The unsymmetric character of the BVI radiated noise is immediately apparent, with the most intense noise appearing under the advancing side of the rotor. This is believed to result from a vortex interaction with an advancing rotor blade in the aft quadrant. On that basis, the square shaded area is the noise source shadow cast by the fuselage which makes BVI noise levels in the shadow questionable. The very steep gradients of acoustic pressure demonstrate the sensitivity of microphone placement in any experimental assessment of BVI. Data from this experiment are being used to evaluate prediction methods for the BVI source which are urgently needed in the ROTONET noise prediction system.

CABIN ENVIRONMENT

The final section of this paper will discuss recent Langley contributions toward understanding and controlling the noise and vibration environment in cabins of helicopters. The interior noise and vibration levels of current helicopters are very high relative to other air and ground transportation systems due to proximity of the crew and passenger spaces with the rotor gearbox which is the dominant interior noise and vibration source. The result of the high noise and vibration levels is poor passenger acceptance compared to other aircraft and, in the case of military helicopters in particular, possible degradation in pilot performance and increased risk of hearing loss. The Langley program has included numerous studies of ride quality due to noise and vibration in helicopters and other transportation systems as well as a number of studies for predicting and controlling helicopter interior noise. The model developed for predicting ride quality due to combined interior noise and vibration will be described first, followed by a discussion of two helicopter interior noise studies.

Ride Quality Model

A series of experimental studies that used Langley's Passenger Ride Quality Apparatus (PRQA), figure 21, and over 3000 test subjects generated a data base from which a comprehensive model for estimating discomfort/acceptance of passengers exposed to complex interior noise and vibration was developed. The model, reference 17, accounts for multi-degree of freedom vibrations combined with interior noise. The basic outputs of the model are numerical indices representing total absolute discomfort (or acceptance) of a given environment as well as indices representing the relative contributions of noise and vibration to total discomfort. The indices are measured on a ratio scale, called DISC's, such that DISC = 2 corresponds to twice the discomfort as DISC = 1, etc. The absolute value of DISC = 1 represents a threshold level rated uncomfortable by 50 percent of the subjects tested. The model has been incorporated into a commercially available device, called the Ride Quality Meter, which samples the noise and vibration environment and reads out the numerical discomfort indices, reference 18.

A recent study to assess the validity of the ride quality model is reported in reference 19. The study was conducted in the PRQA using measured helicopter interior noise and vibration as inputs and experienced military pilots as test subjects. The interior of the simulator was configured to resemble a modern jet transport with four first class seats. The noise and vibration inputs were measured on OH-58C, UH-1H, AH-1S, UH-60A and CH-47C helicopters. Military pilots (35 from Fort Eustis, VA and Naval Air Station, Norfolk, VA) served as passengers who rated each of 120 different ride conditions. The noise conditions represented levels and spectra inside current flight helmets.

Typical results from the study are shown in figure 22 for the range of noise and vibration simulated for the OH-58C helicopter. Average discomfort rating, in DISC's, is plotted versus interior A-weighted noise level for low, moderate, and high vibration conditions. Open symbols represent mean discomfort ratings given by pilots, and closed symbols show predicted discomfort ratings from the NASA model. The agreement is good over the range of conditions and the data show the typical interactions between noise and vibration that determine total discomfort. Because of the good agreement between predicted and actual ratings in this and other studies, the U.S. Army Aviation System Command has recently incorporated the NASA ride quality model into the human factors vibration requirement of their Aeronautical Design Standard ADS-27.

Interior Noise Prediction and Control

NASA Langley Research Center has conducted several programs to investigate aspects of helicopter interior noise control. In one early program, the Civil Helicopter Research Aircraft (CHRA), the modified CH-53A shown in figure 23, was outfitted with a 16-seat passenger cabin and state-of-the-art noise control treatment. Acoustic measurements, reference 20, were made over a wide range of operating conditions before and after the installation of the acoustic treatment. A comparison of the noise environment in the treated and untreated interior volume is shown in figure 24. Both before and after treatment, the subjectively dominant noise sources were identified as first-stage planetary and main bevel/tail take-off gear clash. Although acoustic treatment reduced interior noise levels about 30 dB, the levels were still considerably in excess of current jet transports. Subsequent flight demonstrations confirmed that interior noise remained excessive.

The experiences from the Civil Helicopter Program demonstrated the shortcomings of helicopter interior noise control technology. Langley has since contracted with Sikorsky to develop advanced, but practical, helicopter interior noise predictive techniques and control concepts. Extensive flight and laboratory measurements of cabin noise and structural vibrations at acoustic frequencies have been made on a modern helicopter, figure 25, and are reported in reference 21. These measurements were used to validate a statistical energy analysis (SEA) model of the directly radiated and structure-borne interior noise originating from the gearbox which dominates the cabin noise. In the SEA model, the S-76 fuselage is represented by 95 subsections (35 frames, 53 panels, and 7 acoustic spaces) and 235 junctions. The only main elements not modeled are the propulsion system, tail cone and landing gear.

A comparison of the predicted and measured in-flight cabin noise is presented in figure 26 for the four subjectively most important octave bands centered at 500, 1000, 2000 and 4000 Hz. Also shown is the Speech Interference Level (SIL), a noise scale which sums the energy in these bands and which is frequently used for specifying cabin noise levels. The maximum and minimum noise measured at various locations in the cabin as well as the data averaged over the cabin is presented. Excellent agreement was found between the predicted and measured interior noise for SIL and for each octave band when experimental data were averaged over measurement locations. Since the

SEA model provides a volume average of the acoustic energy level, the averaging of the levels at many locations is appropriate and demonstrates that predictive tools are available for this class of problems.

Analytical studies using the SEA model have shown that the most efficient interior noise reduction for this vehicle can be achieved with high frequency vibration isolation between the gear box and the fuselage. Therefore, a resilient, load-limiting, fail-safe isolator has now been designed and will be evaluated in ground experiments in the final phase of the contract to complete the cycle of noise prediction, diagnosis, and reduction.

CONCLUDING REMARKS

This paper summarizes the major helicopter acoustics research activities of Langley Research Center over the last decade. Individual projects are described that address a variety of issues covering the span of acoustics disciplines from noise generation by individual sources to the propagation of noise and the effects of noise on receivers. Most of this research has been driven by civil sector requirements for noise certification and heliport operations.

Langley research was a major factor in resolving national and international issues on noise measurement scales used to quantify helicopter noise. Certification issues involving a "penalty" for blade slap noise proposed by U.S. competitors were resolved, and, in another case, the ability of LEQ to quantify community environmental impact around heliports with very limited numbers of operations was demonstrated.

The ROTONET testbed helicopter noise prediction computer system has become a reality with operational codes delivered to the four major manufacturers for evaluation during 1986. This prediction capability includes blade rotational and broadband sources and operates at each company on VAX computers. However, confidence must be established in prediction ability before ROTONET is widely used. A series of validation flight tests are planned to acquire the data for this purpose, but only the first test using a MD-500E helicopter has been completed. In addition, Phase III ROTONET is under development to improve prediction capability by including additional, as well as improved, source noise models.

Langley research on individual helicopter noise sources is focused on the requirements for ROTONET. Rotor blade rotational source noise theory is highly developed but needs to be expanded to include quadrupole sources and nonlinear effects to treat higher tip speeds. A big increment in blade rotational noise prediction ability will come from improved high frequency unsteady aerodynamic load predictions, expected to come from CFD codes, which are a main ingredient in noise prediction. Excellent progress in defining and developing semi-empirical predictions for broadband noise has also been made in the last 5 years. This technology has been made available to the industry through ROTONET. Progress on interaction noise is urgently needed but is coming much slower. The interaction noise generation mechanisms are extremely complicated and are the subject of studies by Langley and other research groups. As results become available, the technology will be included in ROTONET.

The internal noise and vibration environment in helicopter cabins has been studied less extensively. A ride quality model has been developed which predicts passenger and crew acceptability of combined noise and vibration environments. Recently, this model was incorporated in the Army Aviation System Command's aeronautical design standards. On-going research on interior noise control has resulted in an interior noise prediction methodology which provides, for the first-time, a tool for design sensitivity analyses. Combined with new materials and concepts, an opportunity now exists for significant progress in this difficult area.

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Altitude (ft)	Speed (kts)	EPNL (EPNdB)		
		Predicted rotational only	Predicted rotational & broadband	Measured
404	137	88.0	90.1	92.5
417	123	85.6	88.4	91.6
452	110	83.0	86.7	90.4
977	123	79.4	82.1	85.8

Notes: Overhead flyover

Microphone 4 feet above ground

TABLE I.- EFFECTIVE PERCEIVED NOISE FOR HELICOPTER IN LEVEL FLYOVER

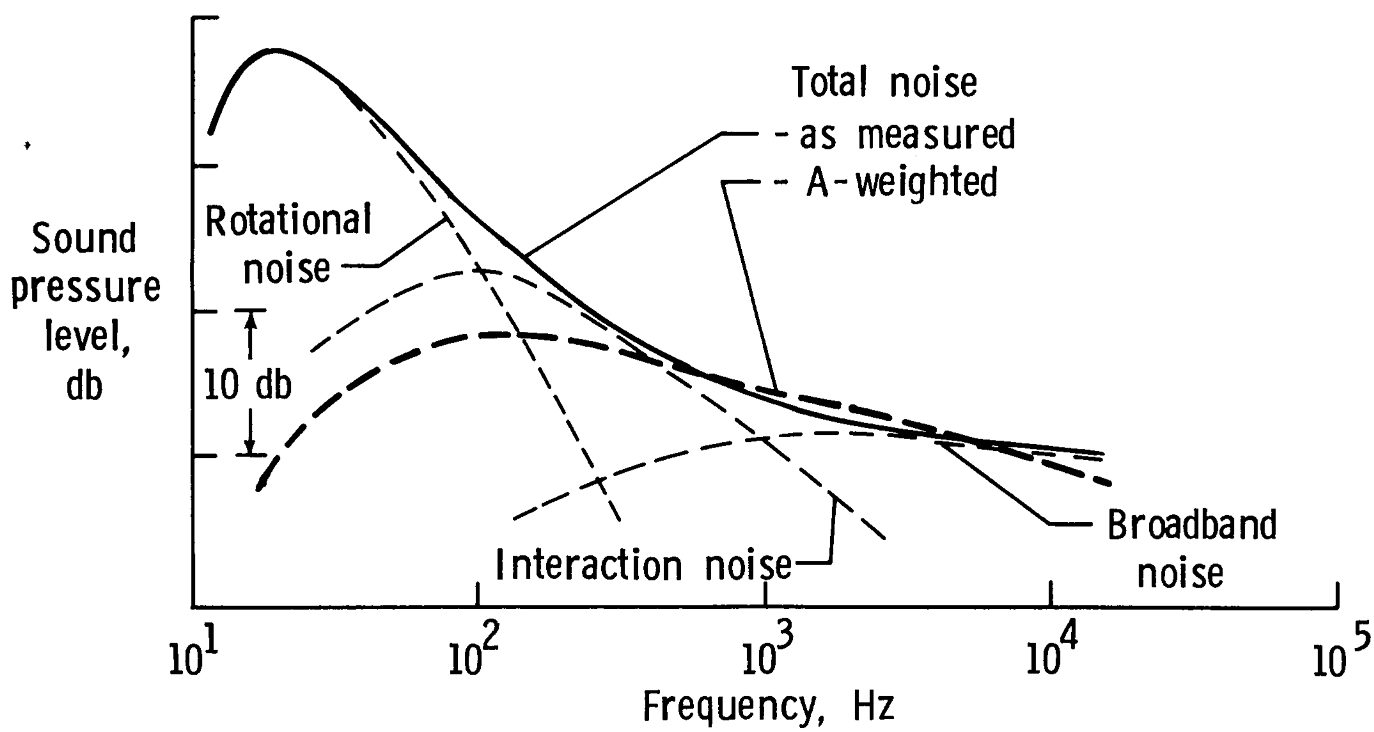

Figure 1.- Typical helicopter noise spectrum.

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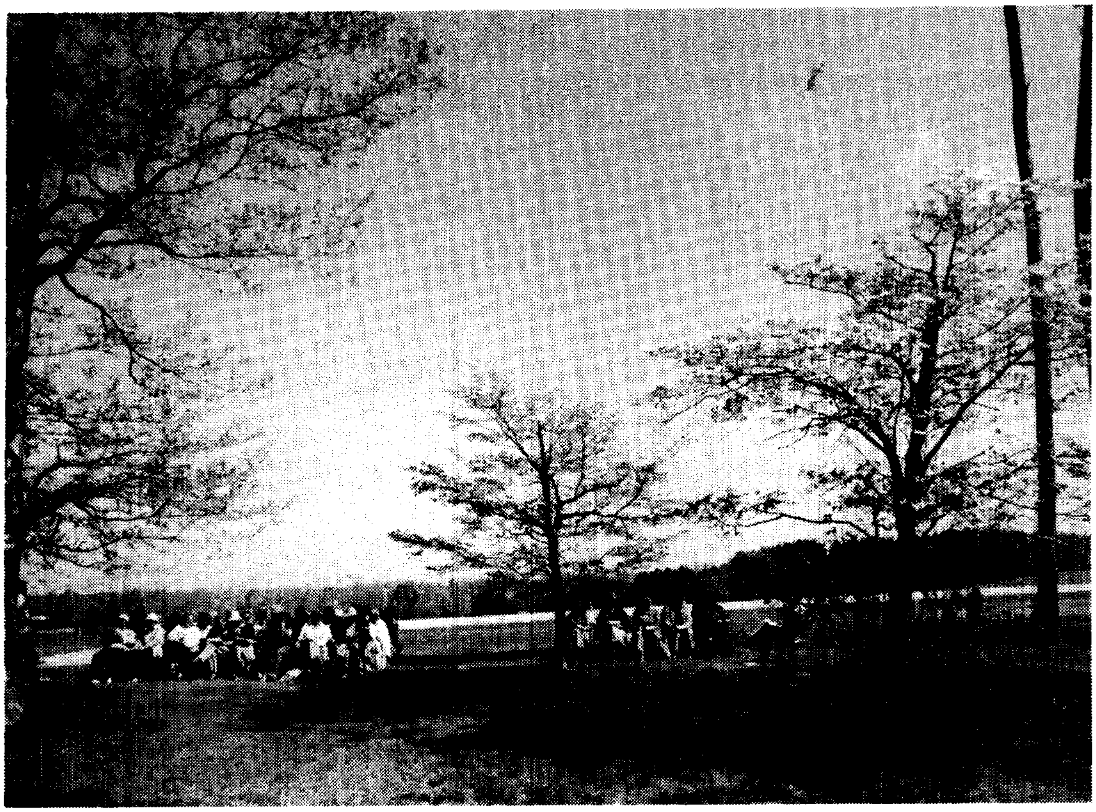


Figure 2.- Outdoor listening site for helicopter overflight experiment.

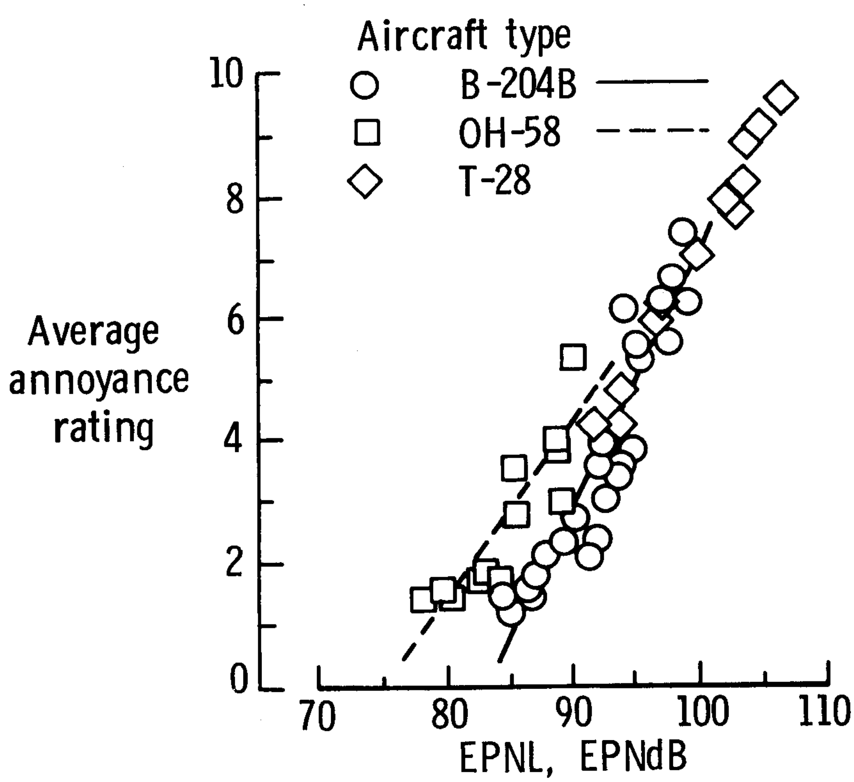


Figure 3.- Average noise annoyance ratings of outdoor listeners during helicopter overflights.

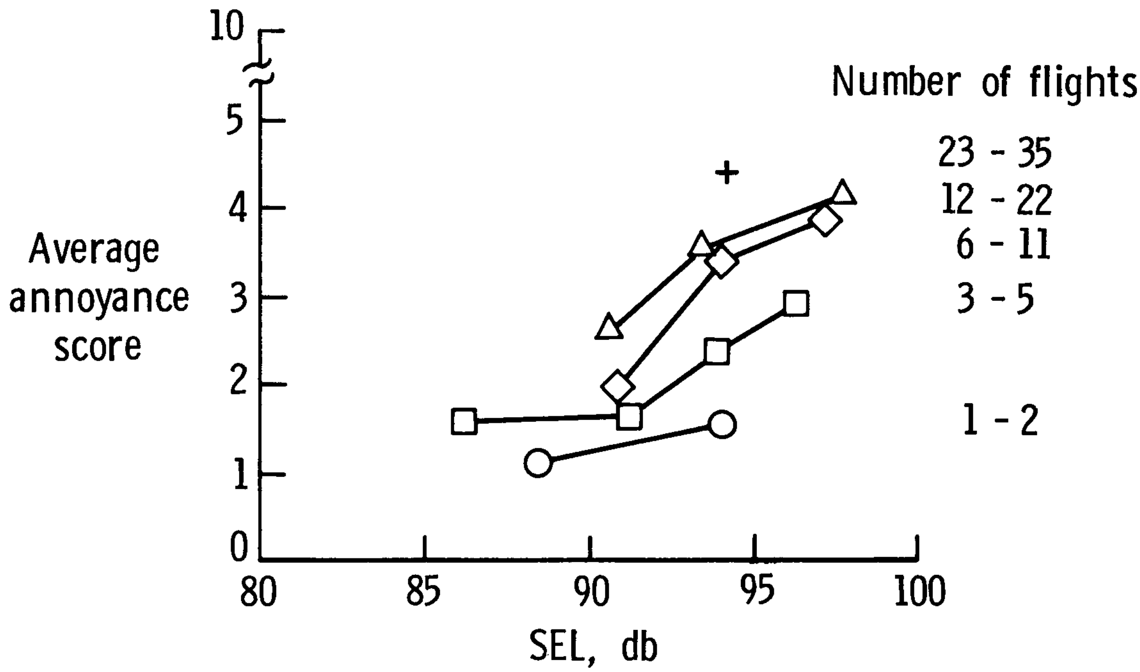


Figure 4.- Effect of noise level and number of flights on annoyance.

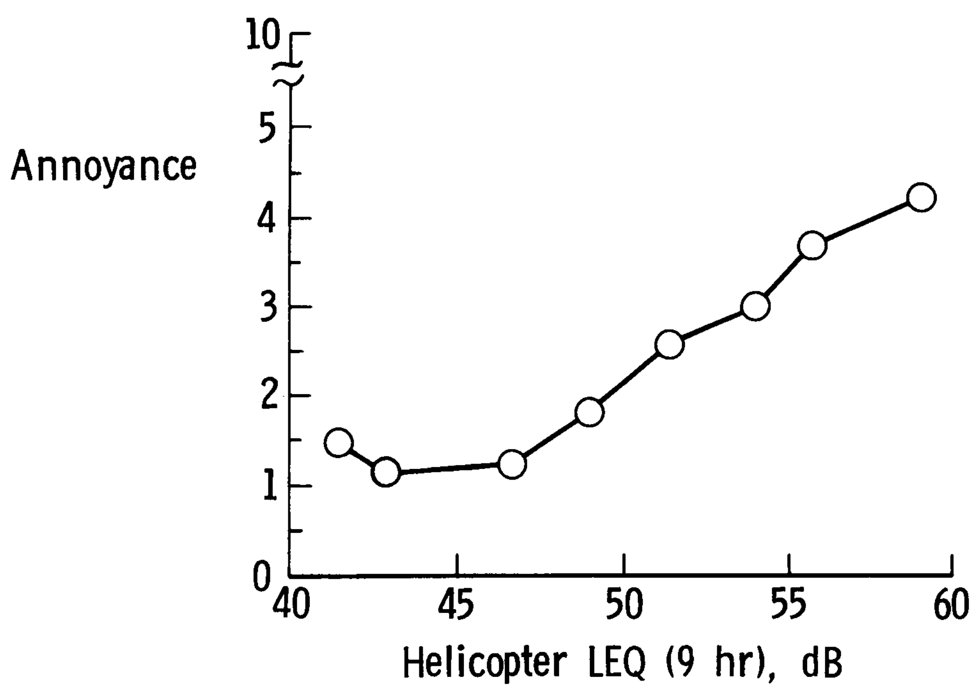


Figure 5.- Relationship between annoyance and Equivalent Noise Level (LEQ).

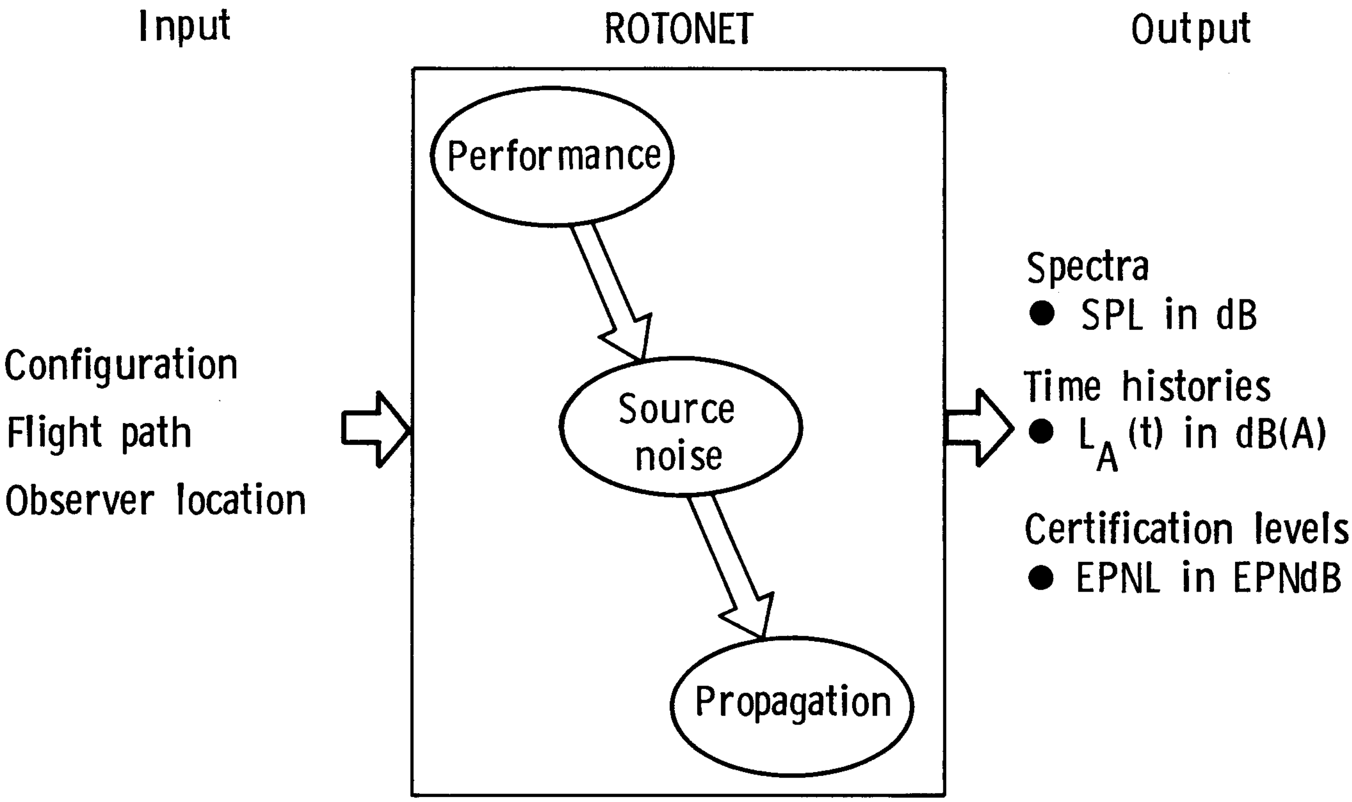


Figure 6.- ROTONET computer program for helicopter system noise prediction.

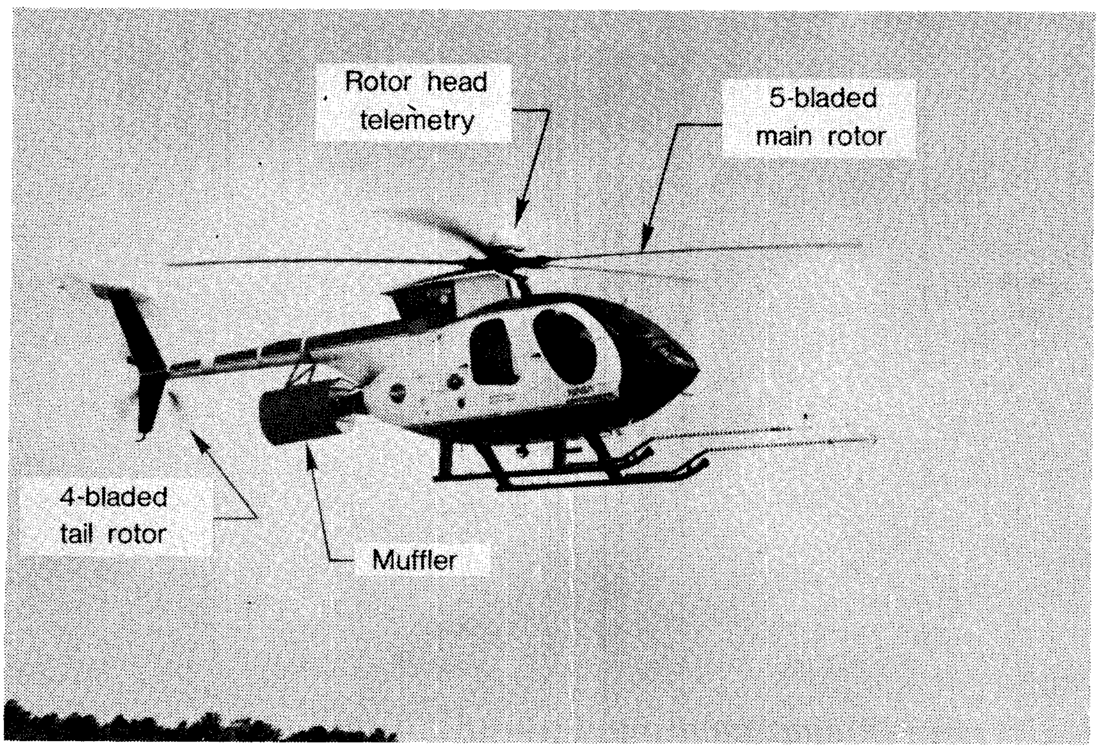
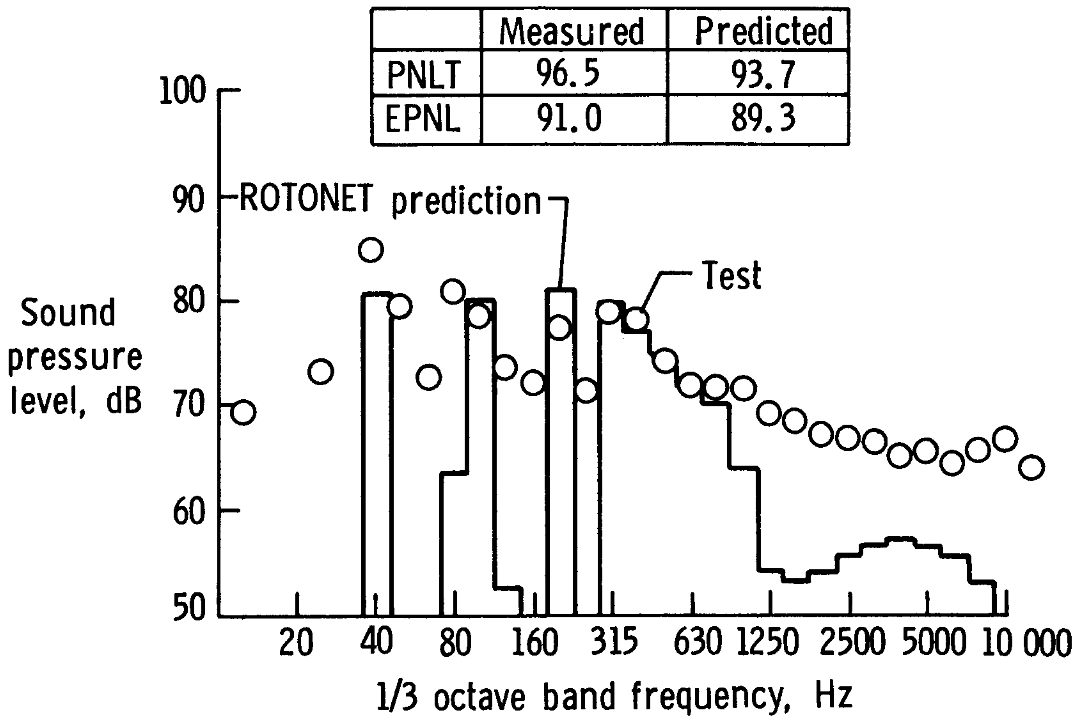


Figure 7.- Experimental helicopter used in noise prediction validation flight test.



	Measured	Predicted
PNLT	96.5	93.7
EPNL	91.0	89.3

Figure 8.- Noise spectrum during overhead flyover at peak tone-corrected perceived noise level (PNLT), 95 knots flight speed, 250 ft. altitude, 2-blade tail rotor.

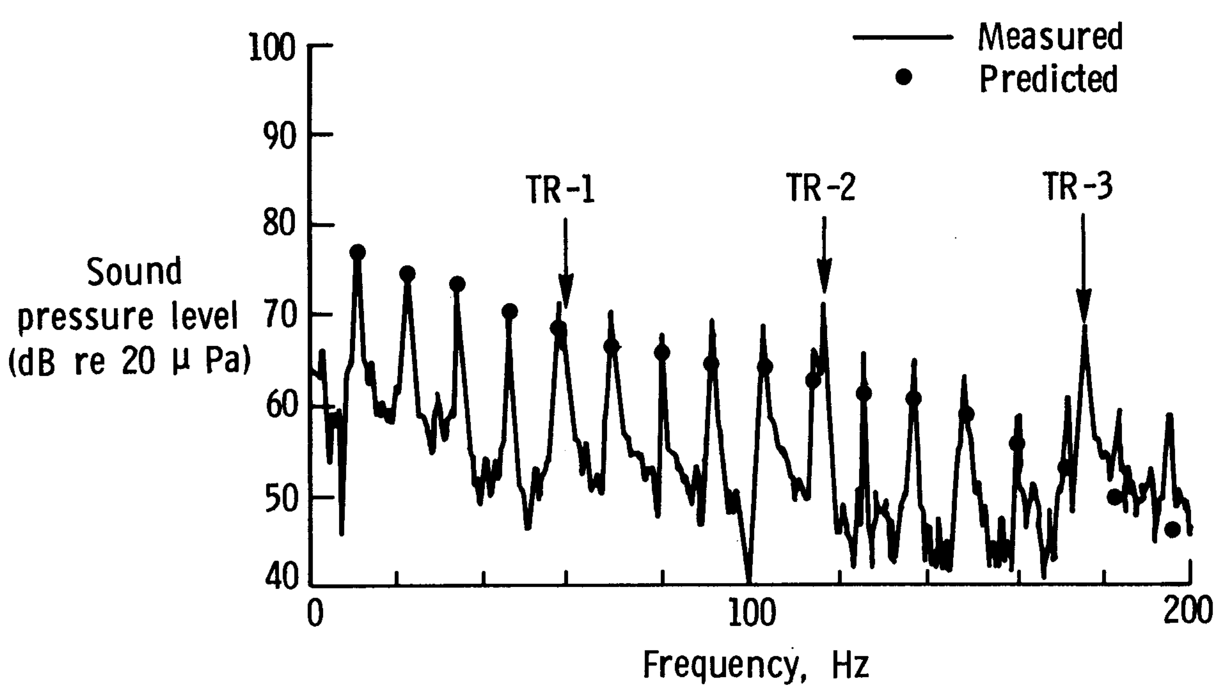


Figure 9.- Noise spectrum of OLS helicopter, 66 fps flight speed, 8.5° emission angle from rotor plane.

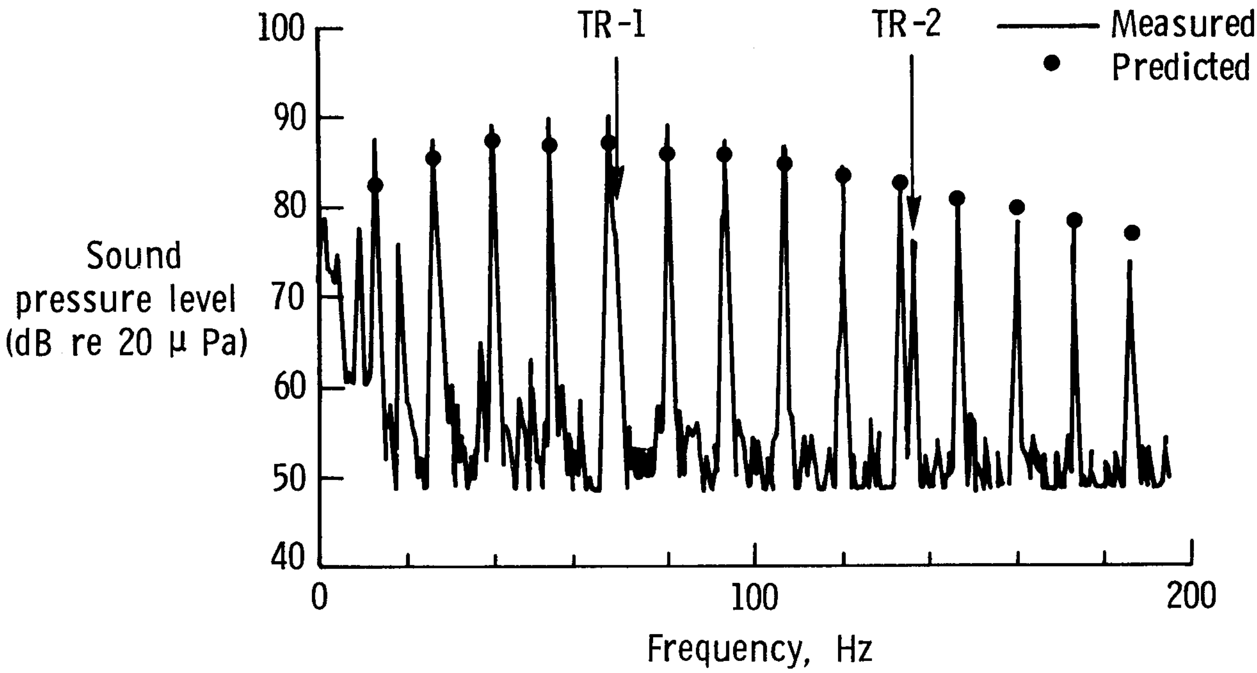


Figure 10.- Noise spectrum of OLS helicopter, 220 fps flight speed, 13.3° emission angle from rotor plane.

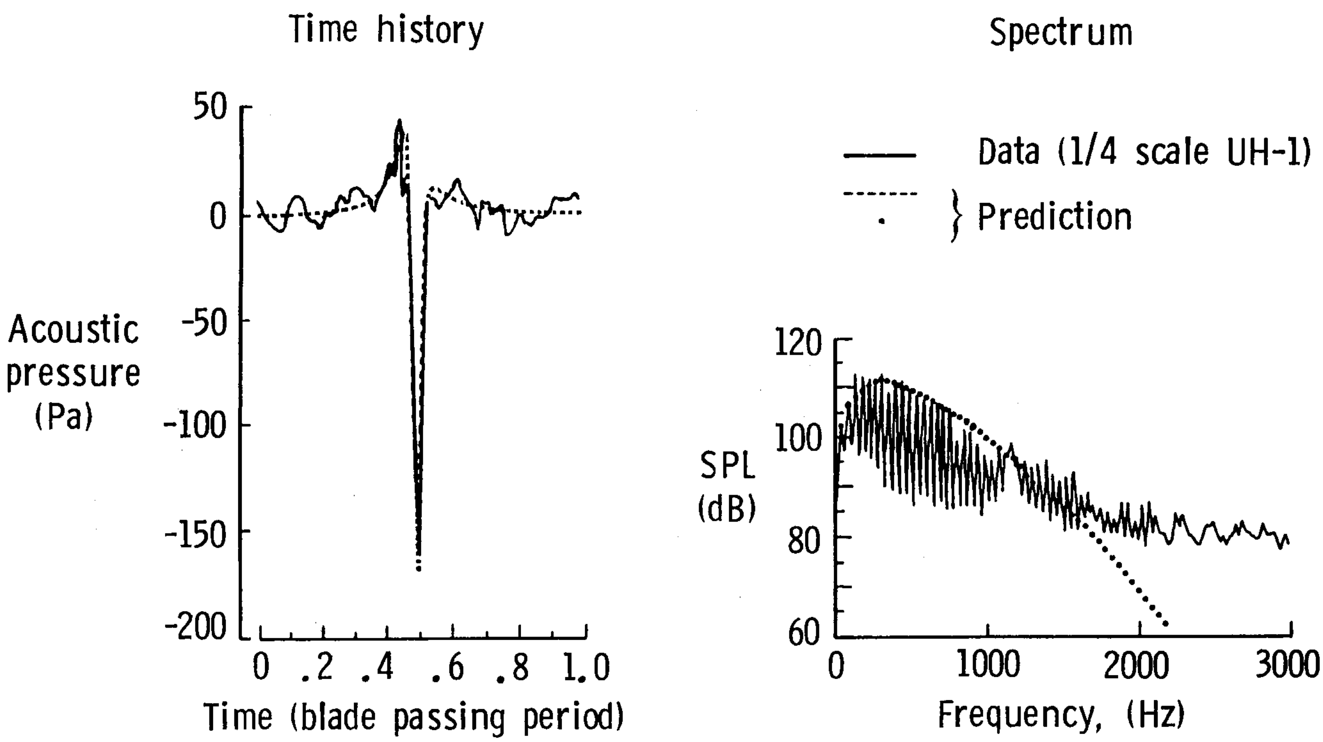


Figure 11.- Noise prediction for 1/4-scale UH-1 model when thickness noise dominates, tip Mach Number = 0.86, 100 knots, 140° azimuth in tip path plane.

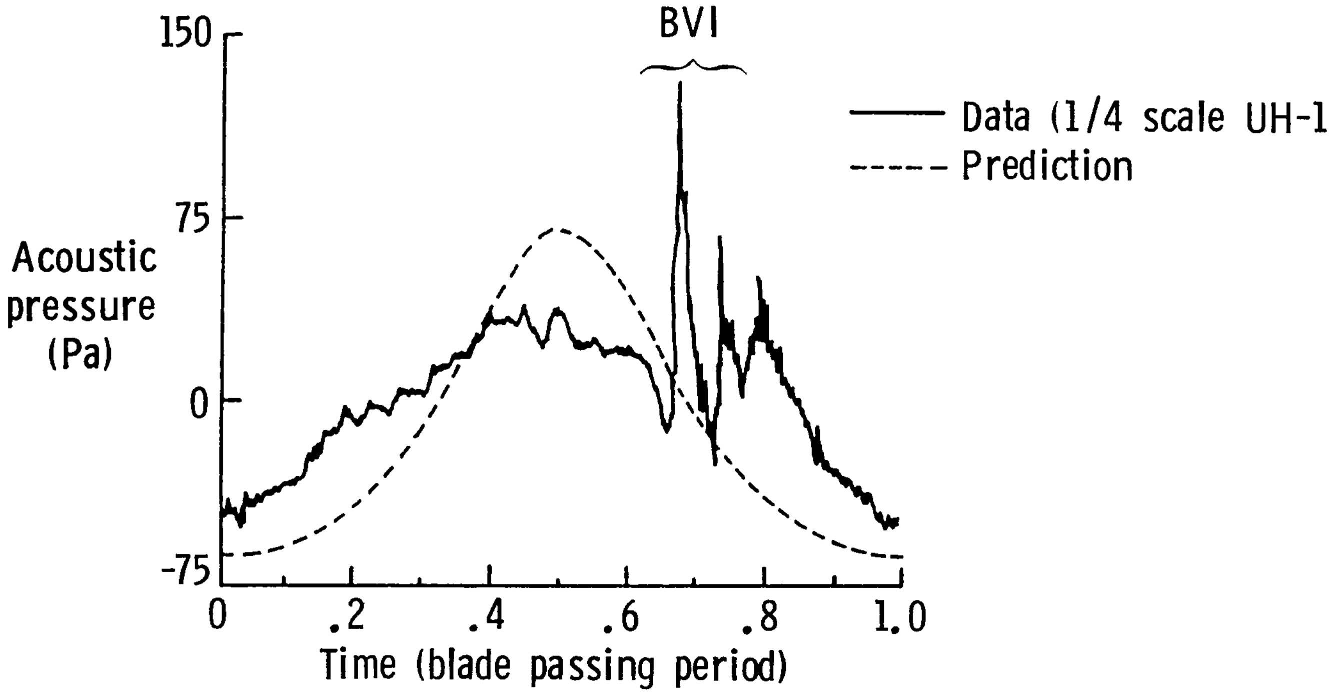


Figure 12.- Noise prediction for 1/4-scale UH-1 model when loading noise dominates, tip Mach Number = 0.82, 60 knots, 140° azimuth in tip path plane.

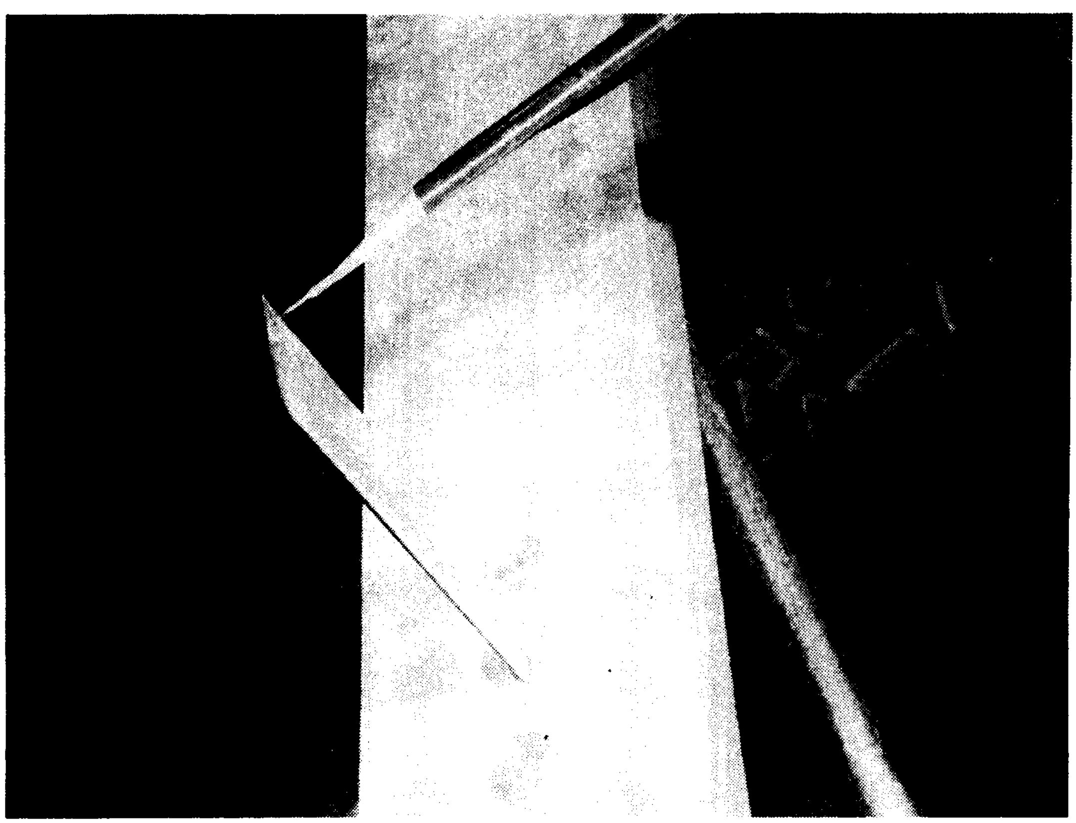


Figure 13.- Broadband noise experiment in Langley Quiet Flow Facility.

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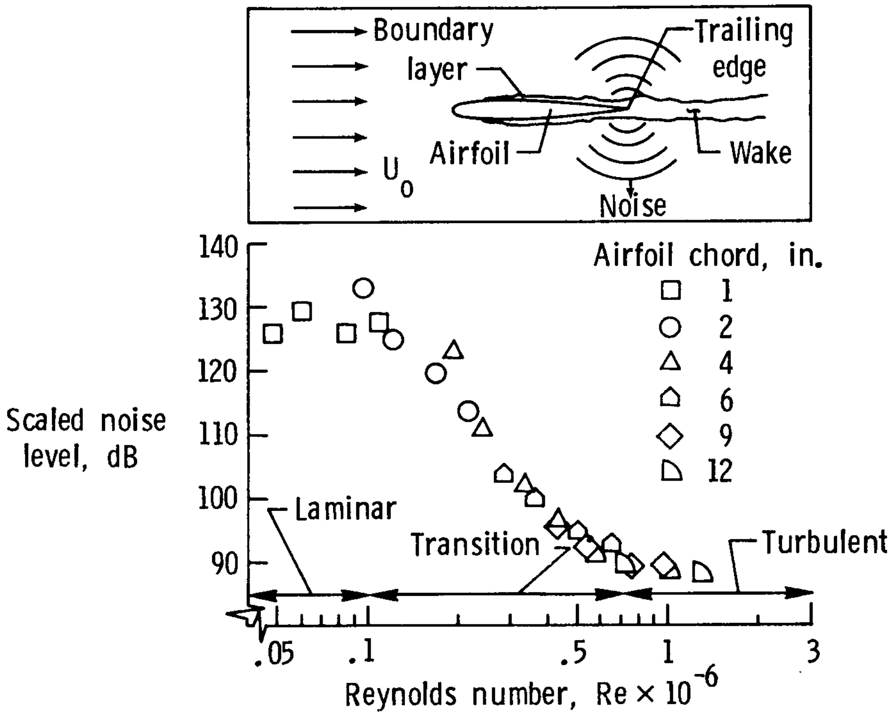

Figure 14.- Scaled level of trailing edge-boundary layer interaction noise through boundary layer transition region.

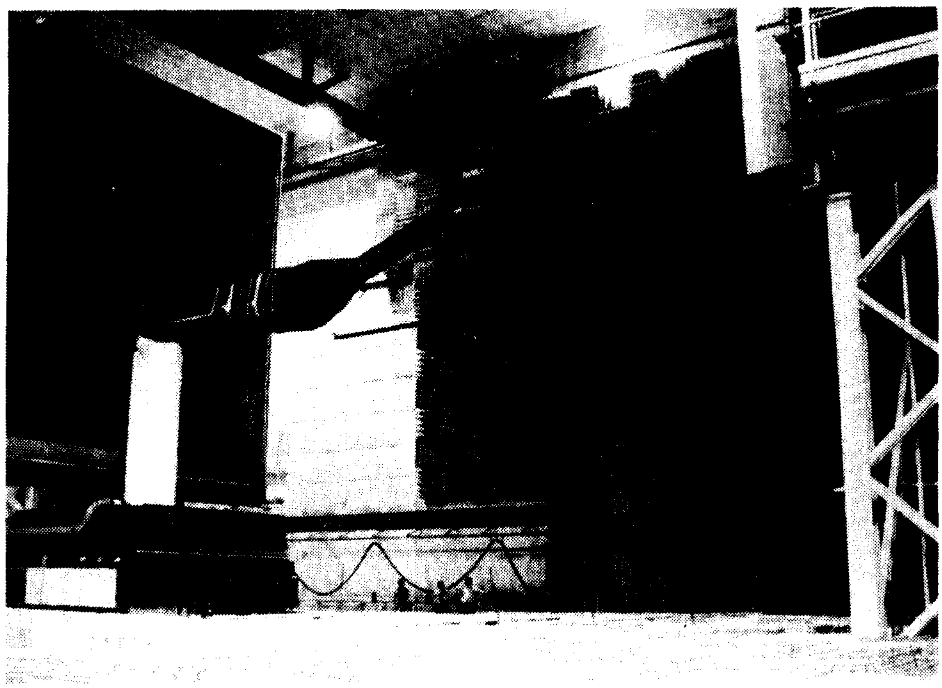

Figure 15.- Rotor broadband noise experiment in the DNW wind tunnel.

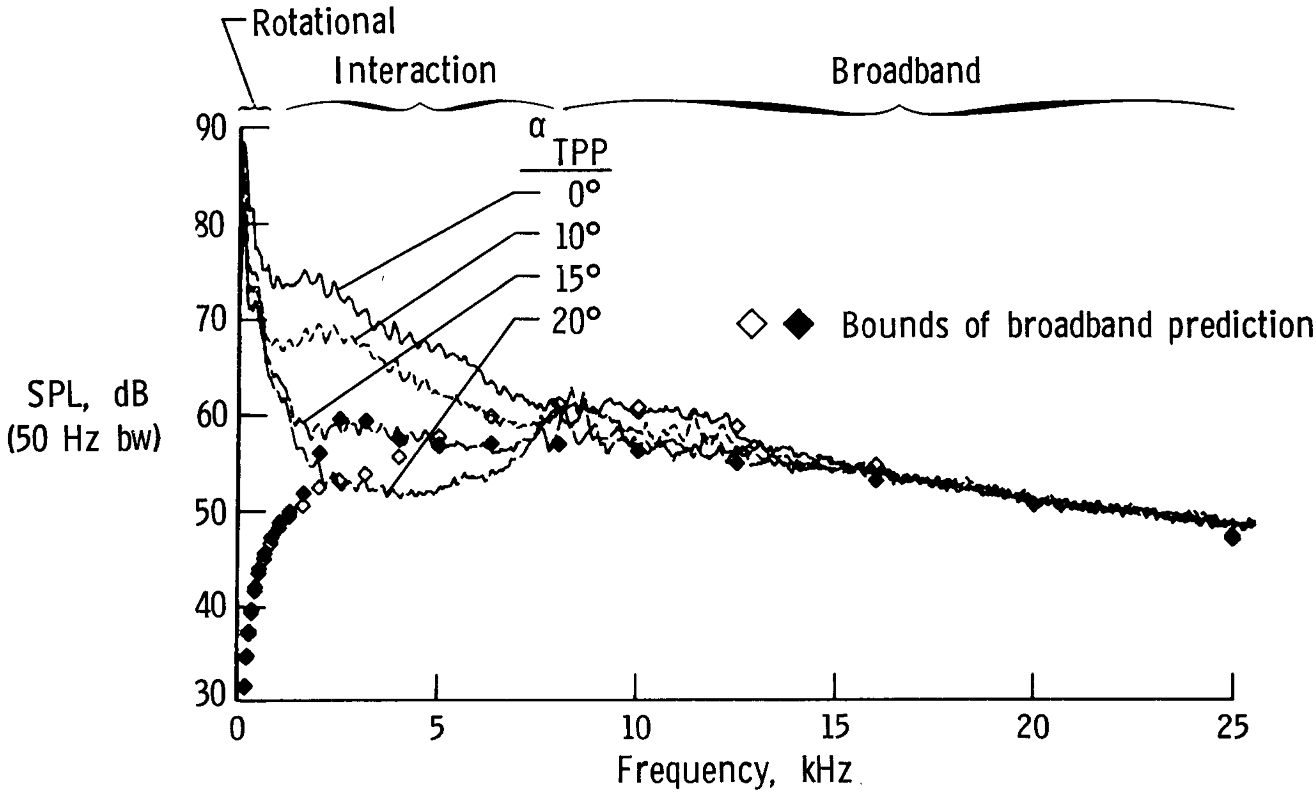

Figure 16.- Rotor broadband noise spectra from DNW test for varying rotor tip path plane angles, 40% scale rotor, C_T = 0.0044, μ = 0.086, 1050 rpm.

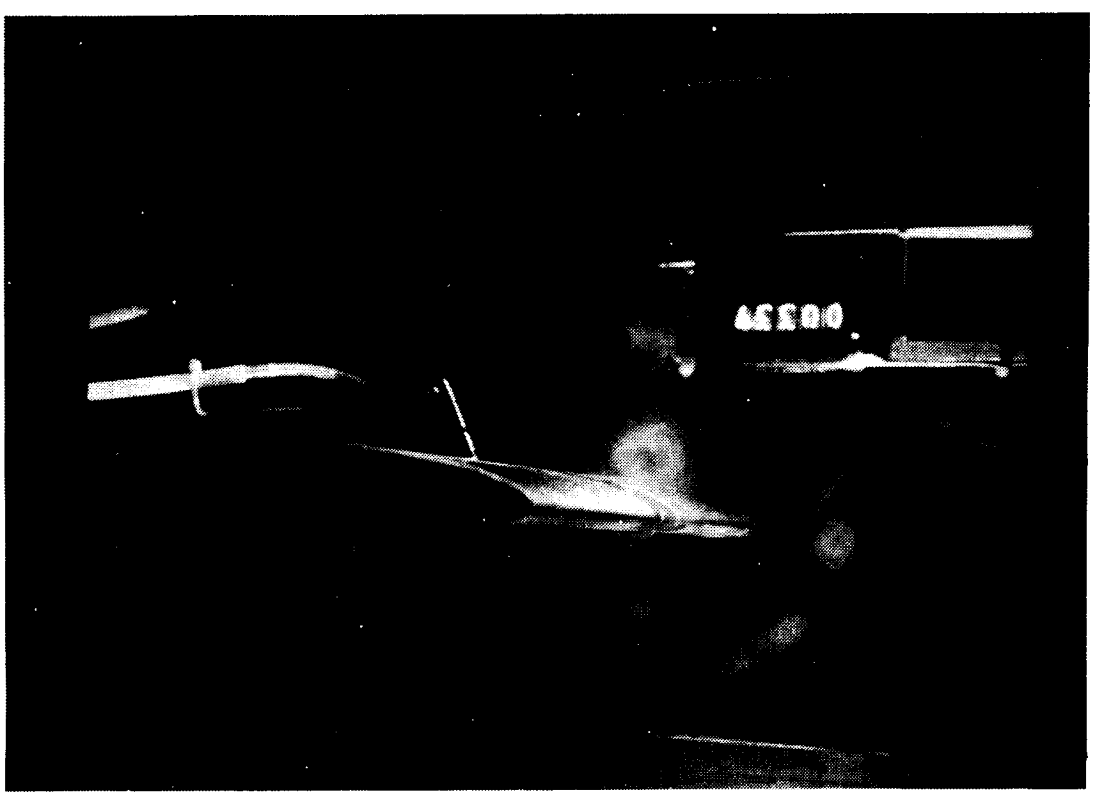

Figure 17.- Two-dimensional airfoil-vortex interaction experiment in the Quiet Flow Facility.

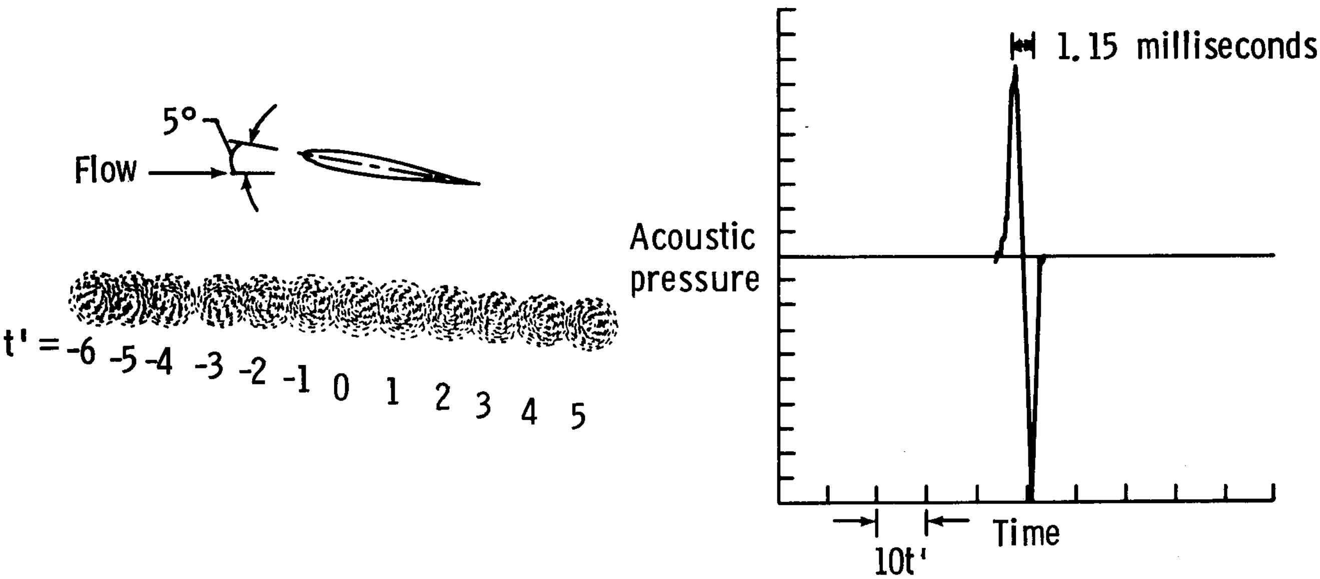

Figure 18.- Computational acoustics model of blade vortex interaction noise.

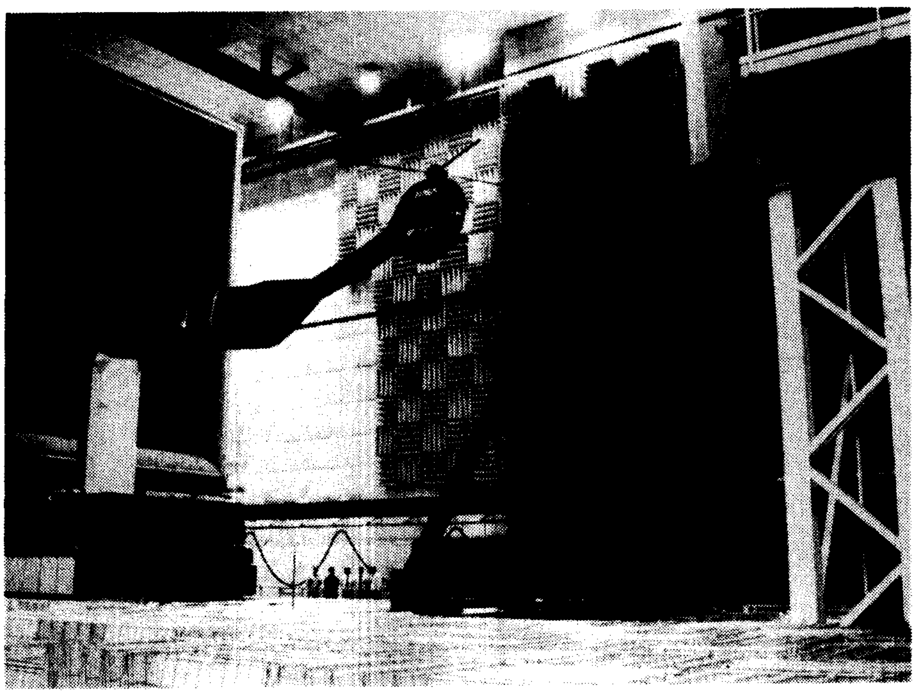

Figure 19.- Blade vortex interaction noise experiment in the DNW wind tunnel.

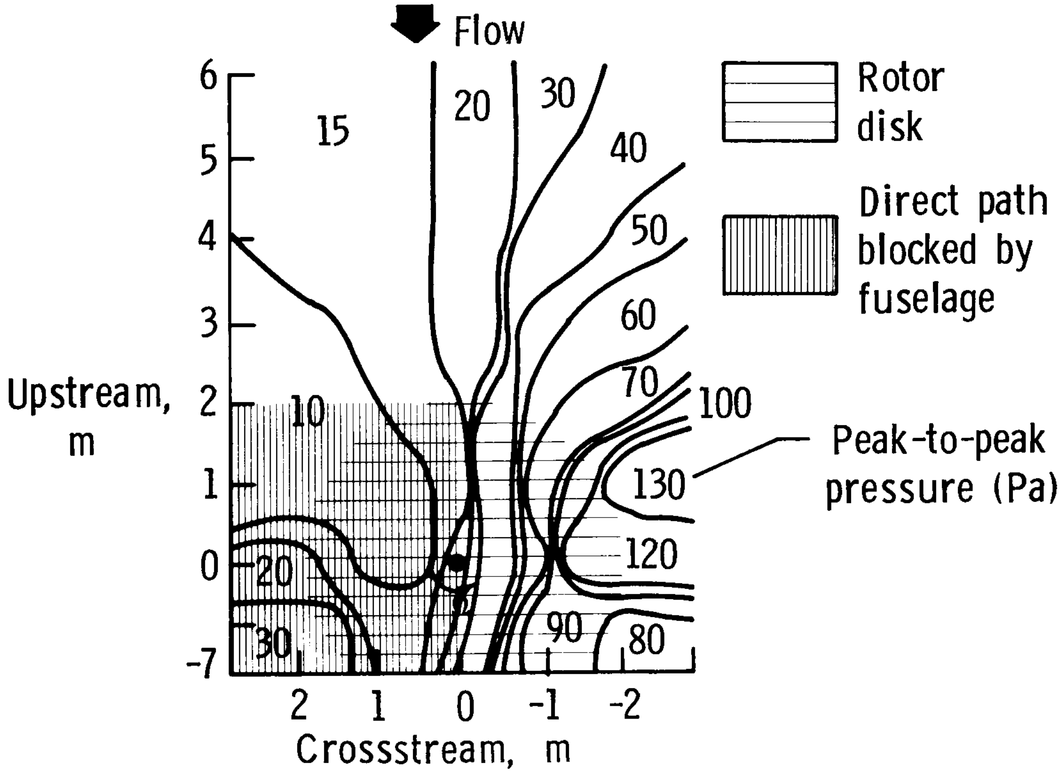

Figure 20.- Contours of constant impulsive noise beneath the rotor due to blade vortex interaction, α_{TPP} = 2.3°, 60 knots.

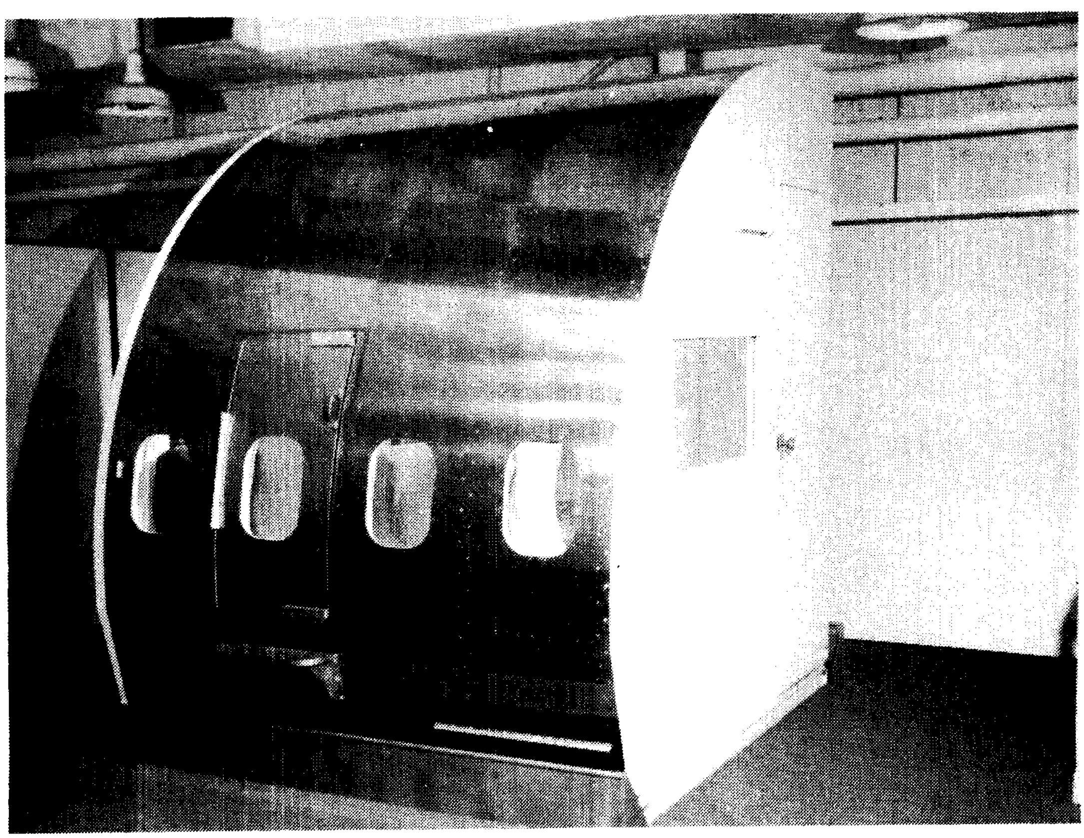

Figure 21.- Ride Quality Simulator

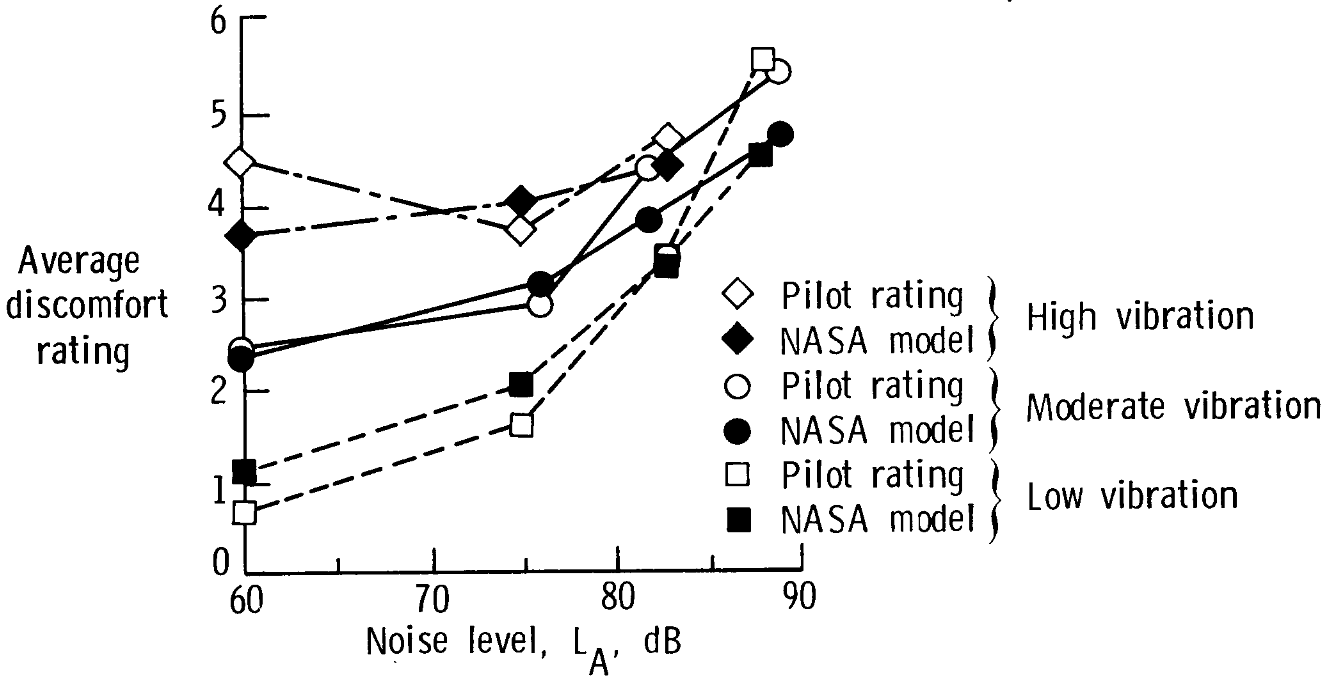

Figure 22.- Effect of noise and vibration level on pilot discomfort.

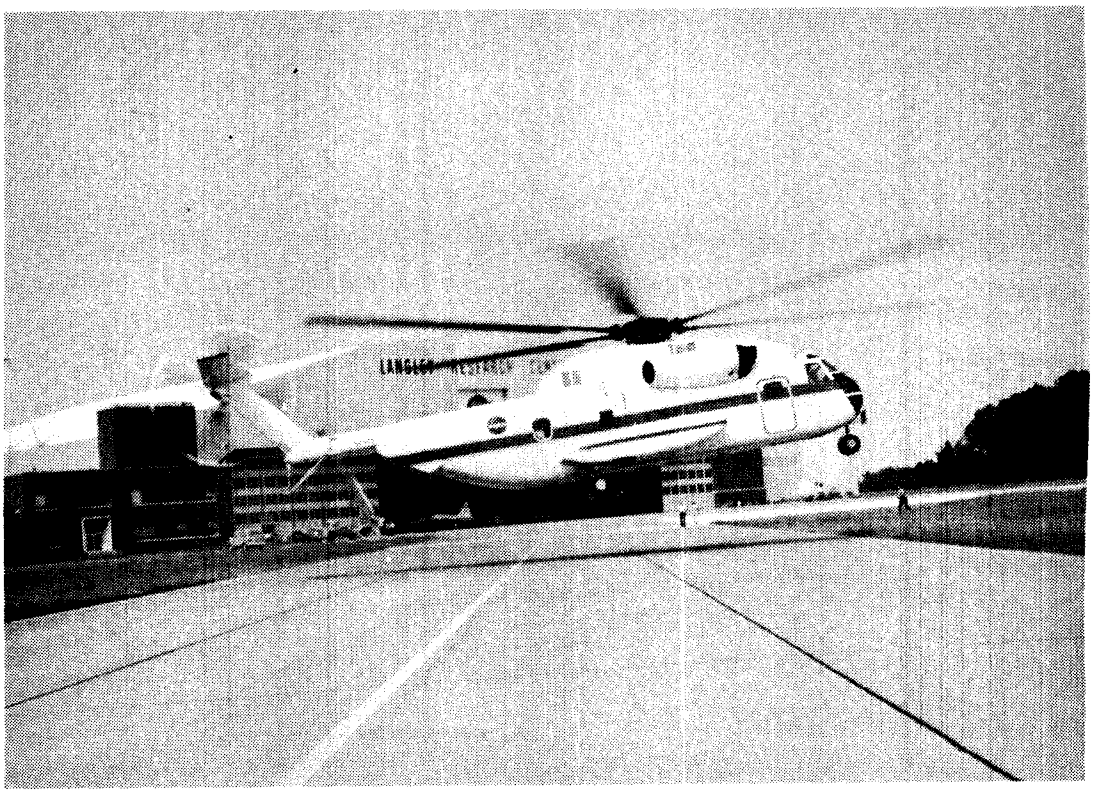

Figure 23.- Civil helicopter research aircraft (CHRA).

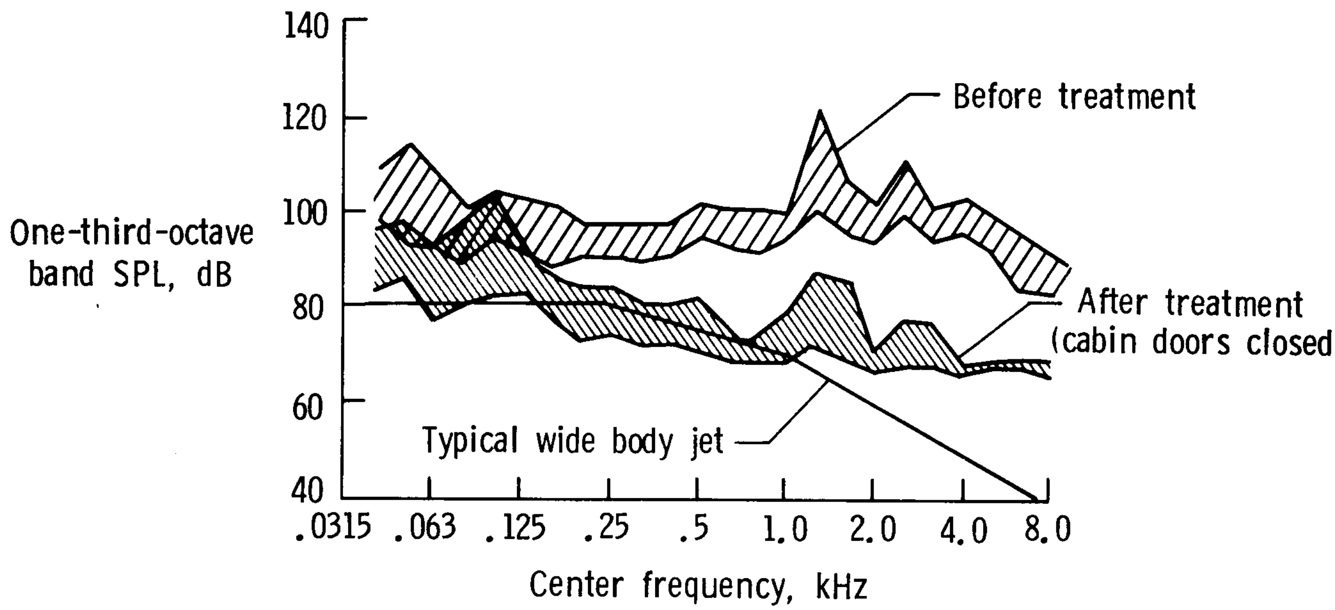

Figure 24.- Effect of acoustic treatment on interior noise in civil helicopter research aircraft.

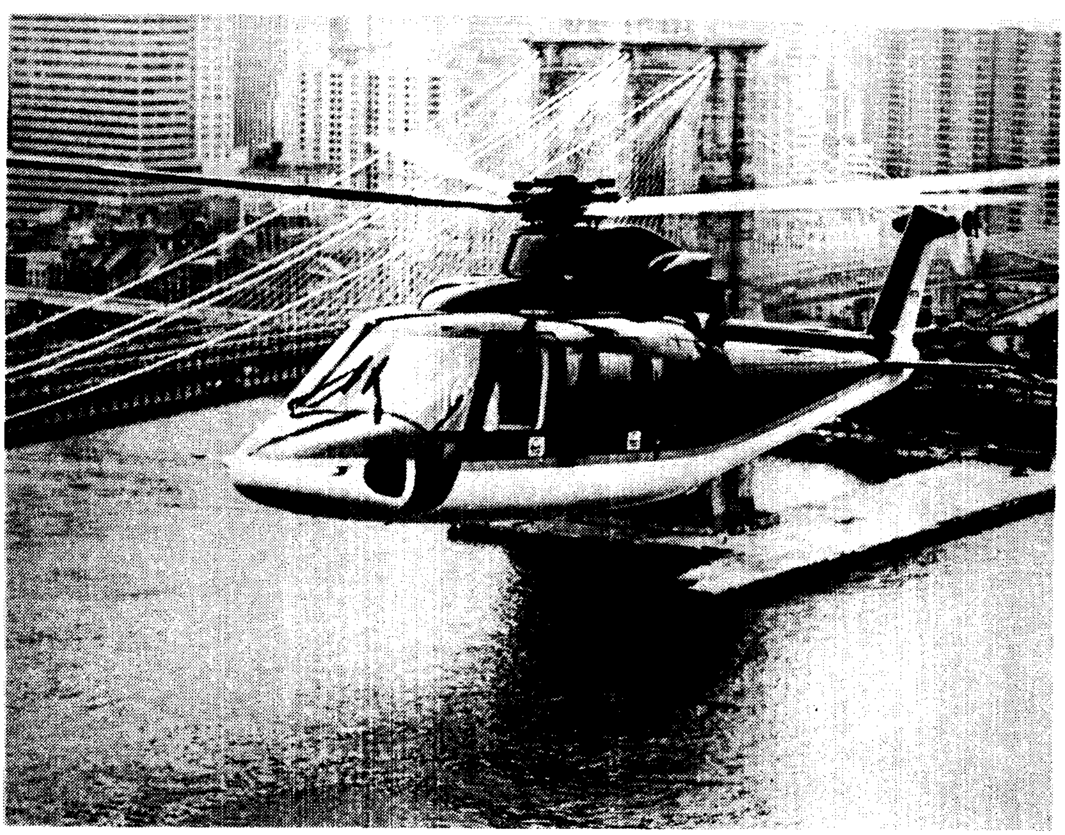

Figure 25.- Interior noise test helicopter.

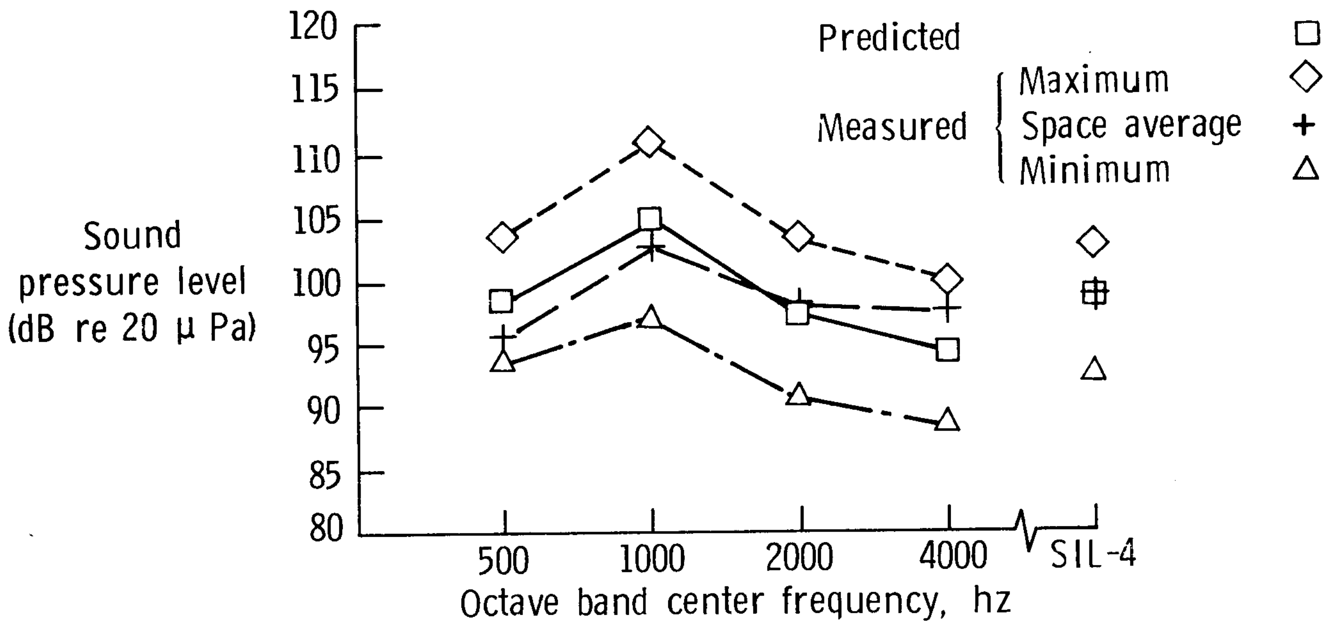

Figure 26.- Measured and predicted inflight sound pressure levels in test helicopter.

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