DESIGN OF HELICOPTER ROTORS TO NOISE CONSTRAINTS

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SUMMARY

Results from the initial phase of a research contract, "Study of Design Constraints on Helicopter Noise," NAS1-15226, sponsored by the NASA Langley Research Center are presented. A description of the overall program is included. Basic calculations of nonimpulsive rotor harmonic and broadband hover noise spectra, over a wide range of rotor design variables were accomplished; and the sensitivity of PNL to changes in rotor design parameters are presented. Measured rotor noise data were used to correlate the calculations in verifying the prediction methodology.

INTRODUCTION

Increased emphasis on reducing the noise generated by helicopter rotors to minimize aural detection times in military applications, and increase community acceptance during commercial operations, now require the helicopter manufacturer to consider noise constraints of his product early in the design phase. Impending noise regulations, such as the FAA/ICAO possible noise limits for certification of helicopters, are forcing designers to implement noise control measures during preliminary design performance studies when the sizing of rotors is being determined.

Basic rotor design parameters such as total thrust, blade tip speed, disk loading, number of blades per rotor, and rotor solidity, which invariably affect the noise produced by the rotor, have generally been decided long before noise restrictions are considered. One reason is that most preliminary designers do not have simplified guidelines for predicting rotor noise which can be meaningful during early rotor design decisions stages. Consequently, most designs are semi-finalized, before noise estimates of the configuration can be made. Subsequent changes that may be required in reducing the noise to comply with certain regulations find themselves in conflict with designs that have already been set.

This study, when completed, will result in a general method, and sets of design charts, which will permit evaluations of the noise and performance tradeoffs of single rotors during the early design stage. The measure of performance will be the percentage of available rotor thrust which must be expended in lifting the drive system (rotor blades, hub, and rotor transmission).

Given a desired thrust and noise limit, the charts can be used to define the corresponding radius, chord, and tip speed for 2, 3, 4, 5 or 6 bladed rotors. The rotor which requires the lowest drive system weight is the optimum design. Conversely, given a completely defined rotor the charts can be used to predict the noise.

Results from the completed initial phase of the study, which includes the calculation of both rotor harmonic and broadband, nonimpulsive hover noise and the relative importance of various rotor design parameters that influence changes in Perceived Noise Level (PNL) are discussed in this paper.

SYMBOLS AND ABBREVIATIONS

Values are given in both SI and U.S. Customary Units. The calculations were made in U.S. Customary Units.

T	thrust, N (lb)
V_T	blade tip speed, m/sec (ft/sec)
f_p	peak frequency, Hz
A_b	blade area, m^2 (ft^2)
σ	angle between centerline of rotor shaft and line to observer, deg
S_j	one-third octave frequency band correction
C_L	lift coefficient
r	distance to observer, m (ft)
SPL	Sound Pressure Level, dB (re 2×10^{-5} N/m^2)
PNL	Perceived Noise Level, in PNdB
dBA	A-weighted network
dBC	C-weighted network
BB	Broadband noise
PNLT	Tone-corrected Perceived Noise Level
NOY	Unit used in the calculation of Perceived Noise Level. It is the noisiness of a noise for which the Perceived Noise Level is 40 PNdB. The noisiness of a noise that is judged by a subject to be n times that of a 1-NOY noise is n NOYS.

PROGRAM

he objective of the program is to provide a "handbook" for helicopter designers nd configuration managers to evaluate the noise of rotors during the prelimnary design phase, and to estimate the effect on rotor payload.

n order to produce an effective designer's tool that can be used during noise nd performance tradeoff evaluations, the total rotor noise signature has to e represented accurately. All major sources of rotor noise are included in eveloping the design charts for the handbook. Figure 1 shows an example of hese sources and their contribution to the overall noise signature. The subective weighting of these noise sources; harmonic, broadband (nonharmonic), nd impulsive, which is the prelude to determining the PNL, are shown in igure 2 as total NOY values per octave band. The engine noise minor contriution is shown for completeness only. Examination of this figure indicates hat in terms of annoyance, rotor impulse is the major factor; but if the otor did not have an impulsive characteristic then broadband noise predomiates the Perceived Noise Level (Figure 2) to a much greater extent than the ound Pressure Level Spectrum (Figure 1).

he overall study consists of the following phases:

1. Calculating the nonimpulsive rotor harmonic and broadband noise spectra using established prediction procedures recognized and used by industry and found in open literature. The range of rotor physical parameters included in the calculations are: thrust, 44 to 356 kN (10 000 to 80 000 lb); disk loading, 287 to 575 N/m^2 (6 to 12 lb/ft^2); solidity, 0.04 to 0.12; number of blades, 2 to 6; and tip speed, 152 to 244 m/sec (500 to 800 ft/sec). Calculations are for a sideline distance of 150 meters from rotor and a height of 150 meters (which corresponds to the measurement locations being considered in the regulations). Combining the noise signatures into one-third octave frequency bands calculating PNL, dBA and dBC.

2. Applying impulsive corrections developed by the Boeing Vertol Co. and subjective adjustments from Reference 1 to adjust dBA, dBC and PNL values to a subjectively equivalent broadband level.

3. Preparing a set of design charts to permit direct determination of values of dBA, dBC and PNdB for range of rotor physical parameters. An example of a possible design chart format is shown in Figure 3 for determining the PNdB in hover and, providing a rationale showing the effects of rotor configuration on forward flight noise.

4. Evaluating the performance penalty for each main rotor configuration and tip speed combination. The ratio of drive system weight to rotor thrust shall be used as an index of the design efficiency.

RESULTS AND DISCUSSION

Prediction of Nonimpulsive Rotor Hover Noise

The harmonic rotation noise calculation was based on the method developed in Reference 2. This widely accepted rotor noise calculation includes the design variables of thrust, disk loading, tip speed, and number of rotor blades. The only change made to the equations of Reference 1 was that an airloads harmonic decay exponent of 1.3 was used instead of 2.0, as specified by the original authors. This modification reflects a more realistic airload harmonic decay of 15 dB per octave which has been measured by other researchers and provides better agreement with measured data in the higher harmonic range.

The broadband, or nonharmonic, rotor noise calculation used was from the unpublished semiempirical prediction made by Robert J. Pegg of the NASA Langley Research Center. The equation from this prediction,

$$f_p = -240 \log T + .746\, V_T + 786$$

$$SPL = 10 \log A_b + 60 \log V_T + 10 \log (\cos^2\sigma + .1)$$
$$+ S_j - 20 \log r + f(C_L) - 53.29$$

$$f(C_L) = 10 \log \frac{\overline{CL}}{.4} \quad \text{for } \overline{CL} \leq .48$$

$$f(C_L) = .9 + 80 \log \frac{\overline{CL}}{.48} \quad \text{for } \overline{C_L} \geq .48$$

has as its design variables, thrust (T), tip speed (V_T), blade area (A_b) and lift coefficient (C_L).

A computer program was written to include all of the design variables and to provide an automatic calculation of both the harmonic and broadband noise, then combine them into one-third octave frequency bands and print-out the resultant dBA, dBC and PNL. Figure 4 shows a sample of this output. Nine hundred sixty computer cases were run during the initial phase of the program to provide adequate definition of the design variables for preparation of the "handbook" charts.

Prediction-Data Correlation

Measured noise data, shown in Figures 5 and 6, from a nonimpulsive and moderately impulsive rotor were directly compared to the calculated one-third octave SPL using the developed computer program. The agreement between predictions and measurement for the nonimpulsive case (fig. 5) are generally quite good, the discrepancy in the 500 Hz octave band is probably due to destructive interference between the direct and first ground reflected waves which calculates to occur at 556 Hz. In the case of the impulsive rotor (fig. 6) good agreement is attained in the first two harmonics and higher frequency broadband noise since the harmonic noise prediction method does not account for the increase in mid-harmonic loading which typifies impulsive rotor noise.

Perceived Noise Level Sensitivity to Rotor Design

To provide an indication of the sensitivity of PNL to changes in design variations, five baseline rotor designs representing different classes of helicopters were investigated. For each baseline configuration the rotor parameters of thrust, disc loading, tip speed and number of blades were varied one at a time (at constant lift coefficient) and the resultant PNdB calculated.

Figure 7 shows an example of the calculated nonimpulsive hover SPL for one particular case (3-bladed, 89-kN (20 000-lb) thrust rotor). Taking this configuration as a baseline design and varying each of the parameters one at a time results in the PNL sensitivity chart shown in figure 8. Similar studies have been done for four other baseline designs which cover a wide range of values and the resultant summary (table I) indicates some rough guidelines which can be used pending release of the final design charts which will result from this study.

CONCLUDING REMARKS

The calculation of the nonimpulsive harmonic and broadband hover noise for a wide range of rotor design variations was accomplished. The prediction methodology used correlated well with measured whirl tower data. Application of the predictions to variations in rotor design (thrust, tip speed, disc loading, and number of blades per rotor) has shown tip speed and thrust as having the most effect on changing the PNL.

REFERENCES

1. Sternfeld, Harry, Jr.; and Doyle, Linda Bukowski: Evaluation of the Annoyance Due to Helicopeter Rotor Noise. NASA CR-3001, 1978.

2. Lowson, M.V.; and Ollerhead, J.B.: Studies of Helicopter Rotor Noise. USAAVLABS Tech. Rep. 68-60, U.S. Army, Jan. 1969.

TABLE I.- INTERIM RESULTS SUMMARY OF SENSITIVITY OF PNL TO DESIGN PARAMETER VARIATION

Parameter	Range	Sensitivity*
Tip speed	137 to 290 m/sec (450 to 950 ft/sec)	2 to 5 PNdB per 30.5 m/sec (100 ft/sec)
Thrust	11 121 to 358 876 N (2 500 to 80 000 lb)	2 PNdB per doubling of thrust
Disk loading	96.1 to 574.6 N/m^2 (2 to 12 lb/ft^2)	0.5 PNdB per 96.1 N/m^2 (2 lb/ft^2)
Number of blades per rotor	2 to 6	<0.5 PNdB per blade addition

*Based on varying parameter under study while holding all others constant.

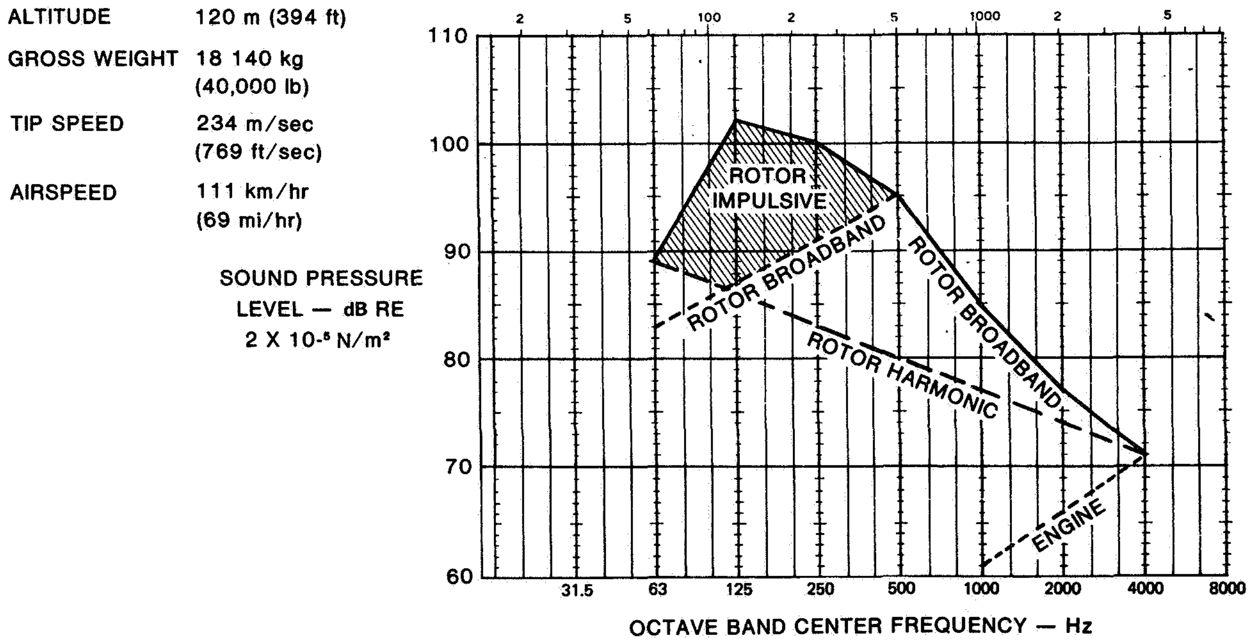

Figure 1.- Helicopter noise source contribution during 6-degree approach.

ALTITUDE	120 m (394 ft)
GROSS WEIGHT	18 140 kg (40,000 lb)
TIP SPEED	234 m/sec (769 ft/sec)
AIRSPEED	111 km/hr (69 mi/hr)
PNL - 107 **PNdB**	

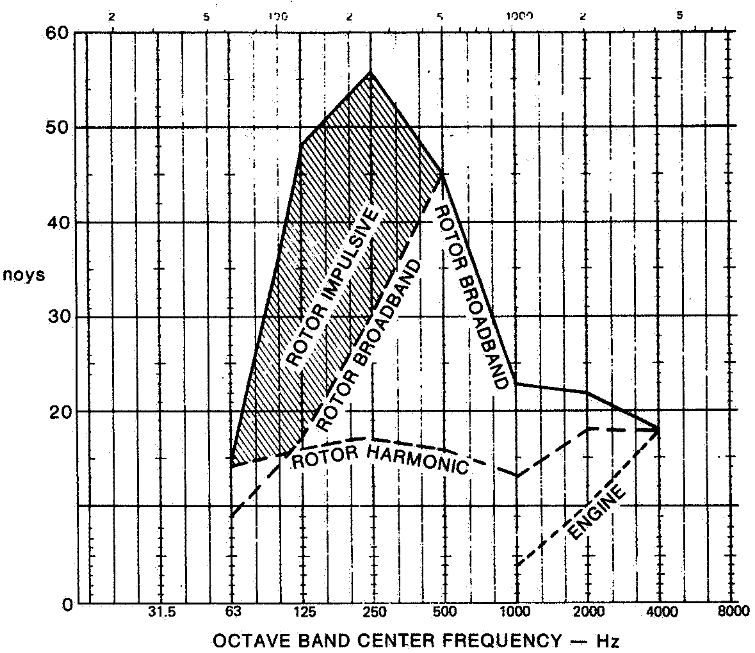

Figure 2.- Subjective weighting of helicopter noise during 6-degree approach.

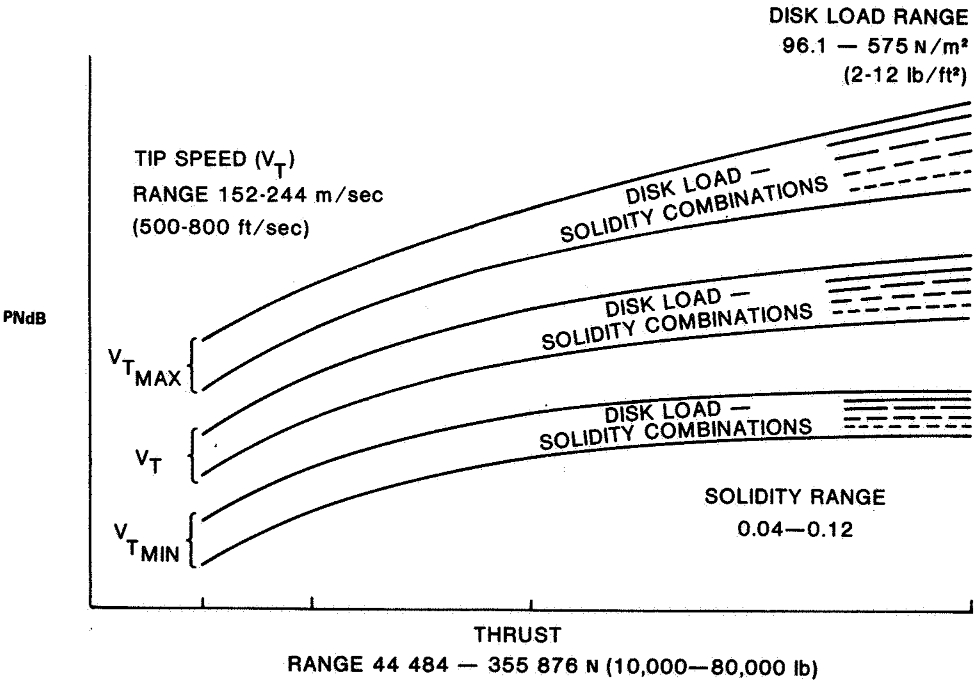

Figure 3.- Possible design chart format for 2-, 3-, 4-, 5-, and 6-bladed rotors.

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                                                 *********************
                                                 *                   *
                                                 *     KASE  5141    *
                 INPUT DATA                      *                   *
                                                 *********************
ROTOR        ROTOR         ROTOR        DISC        NUM                       BB EFFECT.   HARMONIC
THRUST       TIP SPEED     SOLIDITY     LOAD        BLADES        KNOTS       TIP SPEED    FUND.FREQ
15000.        750.          .1000        8.00         4            0.           750.        19.54


BLADE        ROTOR         TIP          ROTATION    FLIGHT        EFFECT.     LIFT         PEAK BB      PEAK BB
RADIUS       RPM           MACH NO.     MACH NO.    MACH NO.      MACH NO.    COEIF.       FREQ.        SPL
 24.4        293.2          .671         .537        .000          .537        .359         343.2        70.4


BB           BB                         HARMONIC    HARMONIC                  TOTAL        TOTAL
DBA          DBC                        DBA         DBC                       DBA          DBC
 75.7         78.9                       70.7        84.9                      76.9         85.9
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A

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****** BROAD-BAND NOISE ******     ***************** ROTATIONAL NOISE *****************      * TOTAL  NOISE *

FREQ                                                                    FREQ                  FREQ
BAND       FREQ          SPL       HARMONIC    FREQ         SPL         BAND     SPL          BAND     SPL
****     ********      *******     ********   ******       *****        ****   ******         ****   ******
  20        21.5         53.4         1         19.5        87.1         20     87.1            20     87.1
  25        27.0         55.1         2         39.1        80.7         25       .0            25     55.1
  31        34.1         56.7         3         58.6        75.6         31       .0            31     56.7
  40        42.9         58.4         4         78.2        72.7         40     80.7            40     80.7
  50        54.1         59.8         5         97.7        70.9         50       .0            50     59.8
  63        68.1         61.2         6        117.3        69.4         63     75.6            63     75.8
  80        85.8         62.6         7        136.8        68.3         80     72.7            80     73.1
 100       108.1         63.8         8        156.4        67.3        100     70.9           100     71.6
 125       136.2         65.0         9        175.9        66.4        125     71.9           125     72.7
 160       171.6         66.2        10        195.4        65.6        160     69.9           160     71.4
 200       216.2         67.6        11        215.0        64.9        200     68.3           200     70.9
 250       272.4         69.0        12        234.5        64.3        250     68.5           250     71.7
 315       343.2         70.4        13        254.1        63.7        315     68.0           315     72.4
 400       432.5         69.1        14        273.6        63.2        400     66.9           400     71.0
 500       544.9         67.7        15        293.2        62.6        500     66.6           500     70.2
 630       686.5         66.4        16        312.7        62.2        630     66.1           630     69.3
 800       864.9         66.2        17        332.2        61.7        800     61.9           800     67.5
1000      1089.7         66.0        18        351.8        61.3       1000       .0          1000     66.0
1250      1373.0         65.8        19        371.3        60.9       1250       .0          1250     65.8
1600      1729.8         64.3        20        390.9        60.6       1600       .0          1600     64.3
2000      2179.4         62.9        21        410.4        60.2       2000       .0          2000     62.9
2500      2745.9         61.2        22        430.0        59.9       2500       .0          2500     61.2
3150      3459.6         61.1        23        449.5        59.5       3150       .0          3150     61.1
4000      4358.8         60.9        24        469.1        59.2       4000       .0          4000     60.9
5000      5491.8         59.4        25        488.6        58.9       5000       .0          5000     59.4
6300      6919.3         57.9        26        508.1        58.7       6300       .0          6300     57.9
8000      8717.7         56.1        27        527.7        58.4       8000       .0          8000     56.1
10000    10983.6         54.6        28        547.2        58.1      10000       .0         10000     54.6
                                     29        566.8        57.9
                                     30        586.3        57.6
                                     31        605.9        57.4
                                     32        625.4        57.2
                                     33        645.0        56.9
                                     34        664.5        56.7
                                     35        684.0        56.5
                                     36        703.6        56.3
                                     37        723.1        56.1
                                     38        742.7        55.9
                                     39        762.2        55.7
                                     40        781.8        55.6
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B

Figure 4.- Rotor noise calculation - computer program sample output.

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                    ********** COMBINED  BROADBAND  AND  HARMONIC  PERCEIVED  NOISE  DATA **********

FREQUENCY - HZ        LEVEL - DB           NOYS         CORRECTION
          50              59.8               .57             .00
          63              75.8              4.36            1.55
          80              73.1              4.27             .00
         100              71.6              4.86             .00
         125              72.7              5.85             .00
         160              71.4              6.03             .00
         200              70.9              6.79             .00
         250              71.7              7.75             .00
         315              72.4              8.79             .00
         400              71.0              8.55             .00
         500              70.2              8.10             .00
         630              69.3              7.60             .00
         800              67.5              6.74             .00
        1000              66.0              6.05             .00
        1250              65.8              6.85             .00
        1600              64.3              8.06             .00
        2000              62.9              8.41             .00
        2500              61.2              8.58             .00
        3150              61.1              9.13             .00
        4000              60.9              9.01             .00
        5000              59.4              7.58             .00
        6300              57.9              6.38             .00
        8000              56.1              4.58             .00
       10000              54.6              3.36             .00

      PNLT =   91.3
       PNL =   89.8
'CORRECTION =    1.55
```

C

Figure 4.- Concluded.

ROTOR THRUST	66,727 N (15,000 lb)
ROTOR TIP SPEED	229 m/sec (750 ft/sec)
ROTOR SOLIDITY	0.1
DISK LOAD	303 N/m^2 (8 lb/ft^2)
BLADE RADIUS	7.5m (24.5 ft)

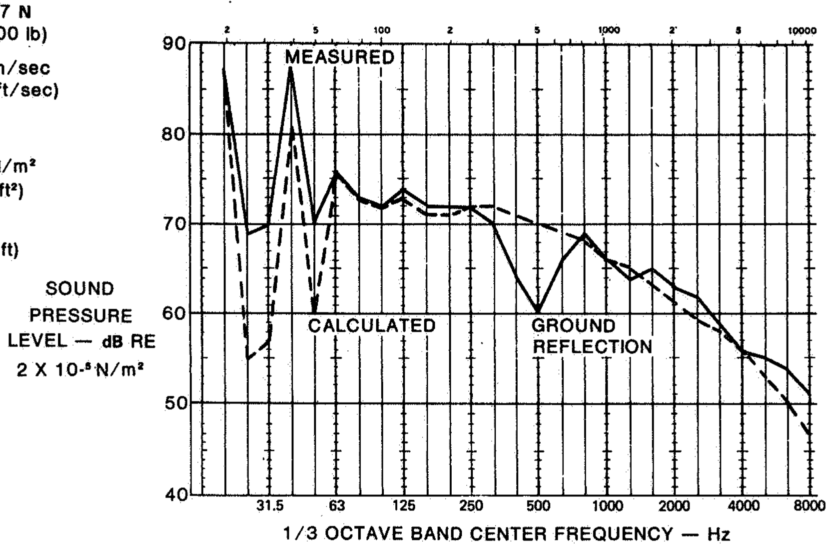

Figure 5.- Correlation of calculations with whirl tower nonimpulsive rotor noise at 152-m (500-ft) distance.

ROTOR THRUST	266,907 N (60,000 lb)
ROTOR TIP SPEED	229 m/sec (750 ft/sec)
ROTOR SOLIDITY	0.09
DISK LOAD	430 N/m^2 (9 lb/ft^2)
BLADE RADIUS	14m (46 ft)

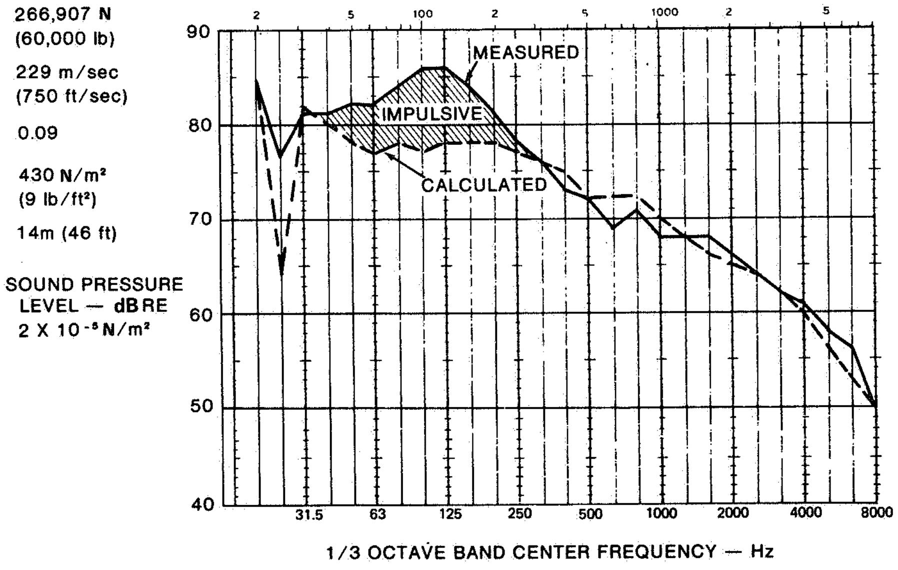

Figure 6.- Correlation of calculations with whirl tower impulsive rotor noise at 152-m (500-ft) distance.

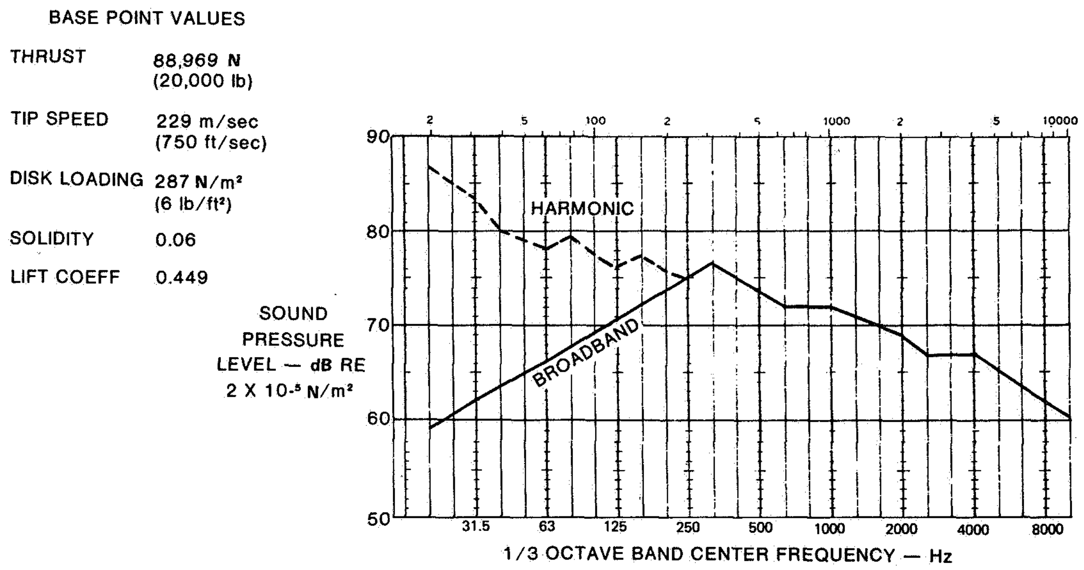

Figure 7.- Calculated - nonimpulsive hover noise 3-bladed rotor at 152-m (500-ft) distance.

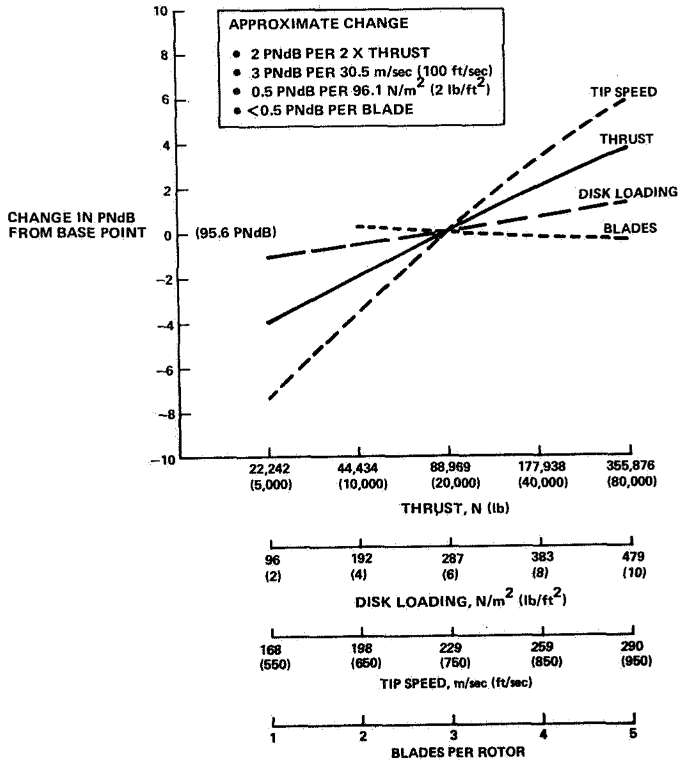

Figure 8.- Relative change in PNdB with design parameter variation.