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FULL-SCALE HIGHER HARMONIC CONTROL RESEARCH TO REDUCE HUB LOADS AND NOISE

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Abstract

Open loop higher harmonic control (HHC) has been researched in the 40- by 80-Foot Wind Tunnel of the National Full-Scale Aerodynamics Complex at NASA Ames. This test involved the modern, 5-bladed, moderate thrust Sikorsky Bearingless Main Rotor. The present HHC effort involved obtaining reductions in dynamic hub loads (1P, 5P) and separately, reductions in noise due to blade vortex interaction (BVI). A study was also made of the effect of 2P control on rotor performance. During dynamics testing, the maximum airspeed was 160 knots with the thrust kept constant at 14,000 lbs, with 1P and 5P control being exercised separately. The full-scale BVI experiments were conducted at 12,000 lbs thrust and at 60 and 80 knots, with 5P control. In both hub loads and noise experiments, testing was conducted with all three modes of control: collective, lateral, and longitudinal. The amplitude and phase in each of these modes were varied to determine their optimum values. It was found that in general, in cruise, the 5P inplane shears were reduced substantially by 5P lateral control. A substantial reduction in the 1P normal force was achieved with 1P collective control. Regarding acoustics testing, at the BVI flight condition (descent, 60 and 80 knots), a reduction in BVI-related noise up to 5 dB was consistently obtained; this was achieved by the application of lateral control.

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Introduction

Historically, higher harmonic control (HHC) has been experimentally researched with two goals: to reduce hub loads and to reduce noise due to blade vortex interaction (BVI). References 1 to 15 provide a fairly complete picture of these experimental efforts.

The present open loop HHC experimental effort, conducted in the 40- by 80-Foot Wind Tunnel of the National Full-Scale Aerodynamics Complex (NFAC) at NASA Ames, is the first of its kind. This is due to:

1. its full-scale nature.
2. its use of a modern, Sikorsky bearingless main rotor (five-bladed).
3. a moderate thrust level, 12,000 to 14,000 lb.
4. the use of a new, dynamic rotor balance system.
5. its exploration of the effect of two "types" of control (1P and 2P) on the hub loads; this is in addition to the application of 5P control for hub loads and BVI noise reduction.

Reference 16 contains more information on the full-scale wind tunnel evaluation of this rotor system at NFAC.

The Ames Rotor Test Apparatus (RTA) was used with a steady/dynamic rotor balance to measure the fixed system hub loads. The BVI noise levels were recorded with a microphone traverse. The first part of this paper covers hub loads and the second part covers BVI noise.

HHC Input Definition

In the present work, the definition of an HHC input is defined for blade one as:

$$\text{HHC Input} = A \sin [n (\psi + \phi)]$$

where "A" is the amplitude, "n" refers to an integer (1 or 5), ψ is the azimuth, and ϕ is the phase that is referred to in this paper. This input is introduced in the fixed system and can be applied either individually or as a combination of three different input modes: collective, longitudinal or lateral cyclic. This paper presents experimental results based on individual, open loop HHC inputs.

Rotor Description

The rotor tested was a five-bladed bearingless main rotor with the same diameter as the four-bladed, articulated Sikorsky S-76 rotor (44 ft). The blade chord was 15.6 inches. Outboard of the hub arrangement (flexbeam and torque tube), the test rotor blades were the same as S-76 blades.

Part I: Hub Loads

Introduction

The rotor hub forces and moments that are shown in this paper were directly obtained from dynamic rotor balance measurements transferred to the hub centerline. These do not include any corrections that are dependent on the excitation frequency. However, at any given frequency (presently 26.25 Hz, the 5P frequency at 100% NR for the five-bladed rotor under consideration), the hub loads trends with and without HHC should not change due to these corrections. The "delta" (incremental effect) due to HHC should also remain basically unchanged. Thus, the data presented here are reliable for trend studies.

Vibration

As a background to this application of HHC to a five-bladed rotor, the use of a five-bladed rotor design is intended in part to have low vibration levels.

In the present test, the following airspeed sweep was conducted: 80, 120, 140, 160 knots. All of these runs were carried out at a moderate thrust of 14,000 lbs. The rotor speed was 315 RPM (100%NR). Both the rotor balance dynamic hub shears and moments were considered. The current emphasis is on the shears (in addition to the hub moments, the balance moments involve the hub shears). In any case, important conclusions regarding the balance moments are duly noted.

Open loop higher harmonic control was applied in individual 5P collective, lateral and longitudinal control modes.

HHC 5P Phase Sweep

Figures 1 and 2 show the effect of a lateral cyclic phase sweep on the inplane forces (axial and side). The 5P HHC amplitude was kept constant at approximately 0.6 deg. The wind tunnel was operating at an airspeed of 80 knots. The baseline case is denoted as "Without HHC". A phase of 90 deg is the optimum for both the axial and side forces.

A study was made of the effect of a lateral cyclic phase sweep on the normal force and the pitching and rolling moments. Though not shown here, the trends can be described as follows.

The pitching moment trends are somewhat similar to the axial force trends, Fig. 1. The optimum phase value was 90 deg, with a reduction in pitching moment at 90 deg compared to the baseline moment.

The normal force and rolling moment phase sweep trends were similar to each other. Again, the lowest force and moment values were obtained at 90 deg. For these components, introduction of HHC always resulted in an increase (over their respective baseline values). This adverse effect could be due to the present use of a lateral cyclic. Or, it may be characteristic of this five-bladed bearingless main rotor operating at this moderate thrust level and low airspeed.

HHC Amplitude Variation

Since the same, clear optimum phase was obtained for both inplane shears, the effect of amplitude variations was studied keeping this phase constant.

Figure 3 shows the effect of an increase in the amplitude of a 5P lateral cyclic input at 90 deg phase. These trends were obtained at an airspeed of 140 knots. The axial force shows an almost linear reduction with increasing amplitude. The trend for the side force at this airspeed is not so clear, though possibly tending to increase with amplitude. The axial force is more sensitive (in the desired direction) compared to the side force.

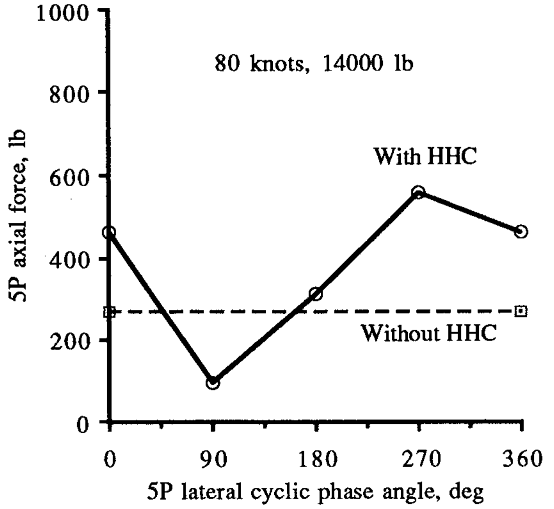

Fig. 1 HHC phase sweep, axial force variation, 80 knots

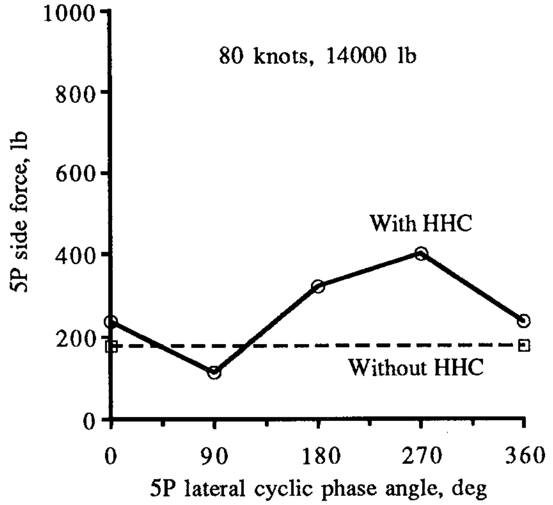

Fig. 2 HHC phase sweep, side force variation, 80 knots

Airspeed Variations With and Without HHC

The second variation that was studied was with respect to airspeed. Five balance components (axial force, side force, normal force, pitching moment and rolling moment) were considered. Figure 4 shows the baseline ("Without HHC") trend and "With HHC" trend for the axial force when the rotor is subjected to a 5P lateral cyclic at 90 deg phase. Open loop HHC is effective up to 160 knots at moderate thrust.

The side force trends with airspeed are shown in Fig. 5. Again, open loop HHC is effective up to 160 knots.

The axial force and side force trends have exhibited crossovers in the 120 and 140 knots regions. These crossovers may be characteristic of this rotor system or due to the optimum phase angle not being constant (90 deg) with airspeed.

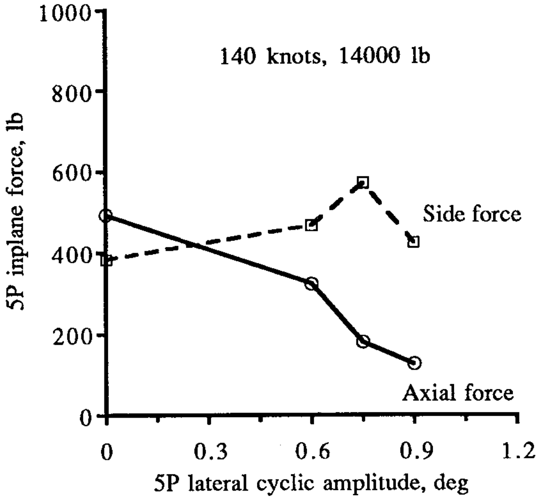

Fig. 3 Effect of lateral HHC amplitude on inplane forces

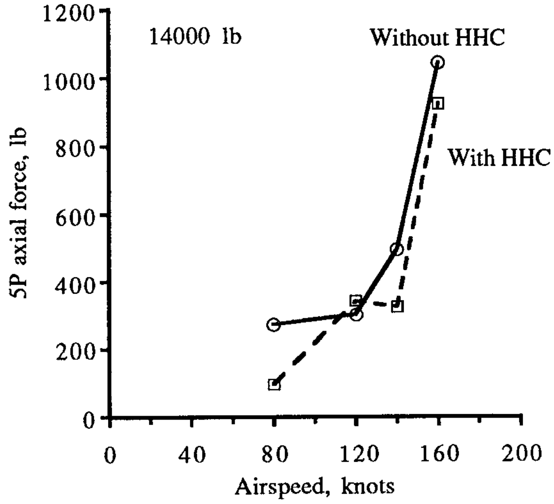

Fig. 4 Airspeed trends for axial force, effect of HHC

The pitching moment airspeed trends were somewhat similar to the axial force trends. The rolling moment trends were different from these two trends, and similar to the normal force trends. Since presently, the normal force is not optimized (the present optimum HHC input being associated with minimum inplane forces), it was found, not surprisingly, that the 5P lateral, 90 deg phase HHC input had an adverse effect on the normal force.

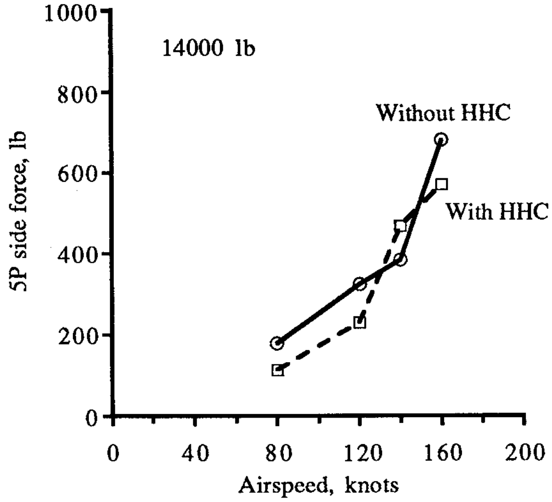

Fig. 5 Airspeed trends for side force, effect of HHC

Hub Loads Spectra

Prior to presenting the results from non-NP HHC control, it is useful and interesting to study the harmonic content of the experimental hub loads.

As an example, consider the baseline side force spectra as shown in Fig. 6. The spectra appear reasonable, the steady and 5P components dominating. Figure 7 shows that with the introduction of 5P lateral control, the 5P component of the side force is reduced (see also Fig. 5, 120 knots).

1P Control and 2P Control

Introduction

These unconventional, new applications brought out some interesting results. The 2P control in the rotating system was achieved through 1P lateral and longitudinal cyclic variation. 2P control changes the rotor trim to a new "state" that involves additional considerations that are absent in the 5P or the 1P collective case.

1P Control

Here the objective was one of reducing the 1P normal force. The baseline 1P axial and side forces were relatively small and trends for these force components are not presented here.

As an example, Fig. 8 shows the baseline normal force spectra, with a large 1P component. Figure 9 shows that with the introduction of 1P collective control of 0.15 deg at 270 deg phase, the 1P normal force is substantially reduced.

Figure 10 shows the 1P normal force variation (120 knots, 14000 lb) due to a change in the phase of the 1P collective input. A phase of 270 deg is the optimum. The amplitude of the collective mode was kept constant at 0.15 deg.

The effect of this 1P control on the other hub forces was also studied. It was found that the 1P axial force was reduced by more than half and the 1P side force was reduced to a very small value.

The effect of 1P collective mode amplitude was studied next. This is shown in Fig. 11 (140 knots, 14000 lb). It appears that in the present 1P application, there exists a best value of the amplitude which gives the smallest normal force.

2P Control

Here the objective was one of improving rotor performance. A sequence of test runs was made to isolate the 2P cause and effect relationships.

It was found experimentally that even though 2P control has a significant effect on some of the rotor hub loads, it can improve rotor performance.

The hub loads results arising from 2P control require a brief, general discussion in order to put them in perspective. An outline of the calculation of the benefit in rotor performance follows the discussion on hub loads.

Second harmonic (2P) control on this five-bladed rotor brought about dynamic hub load trends that were complicated and difficult to interpret. A 2P control will alter the "track state" for a five-bladed rotor. The crucial question is, can a five-bladed rotor remain in good or satisfactory track when subjected to 2P control?

Present test data (not included in this paper) imply the following. A 2P control on the present rotor will induce a rough "track", with a resulting variation in the hub loads. In the present case, where the baseline state

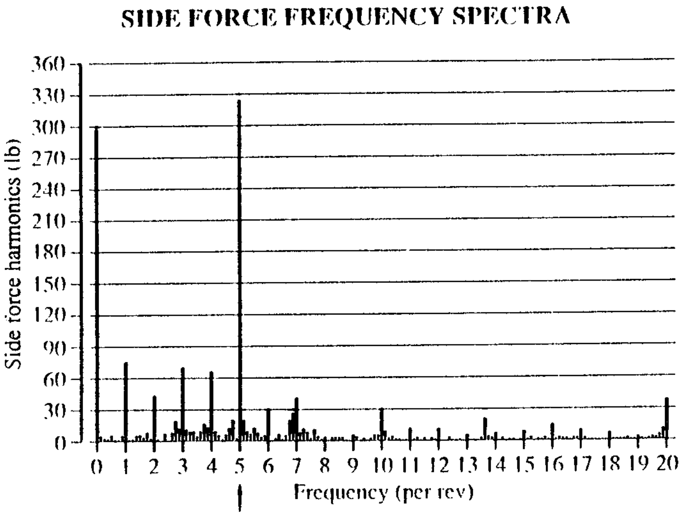

Figure 6. Baseline (no HHC) side force, 120 knots, 14,000 lb.

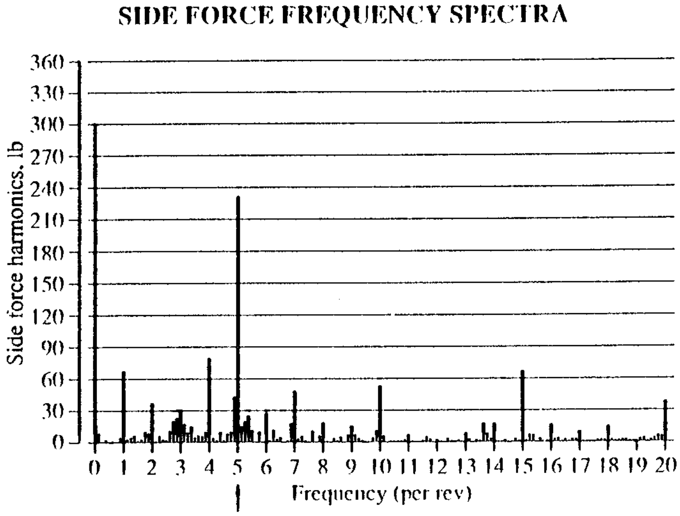

Figure 7. Side force with 5P HHC (lateral 0.6 deg, 90 deg phase), 120 knots, 14,000 lb.

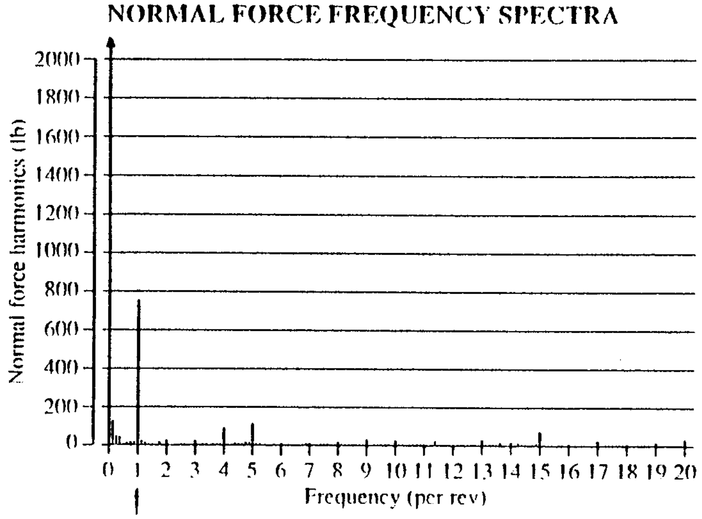

Figure 8. Baseline (no HHC) normal force, 120 knots, 14,000 lb.

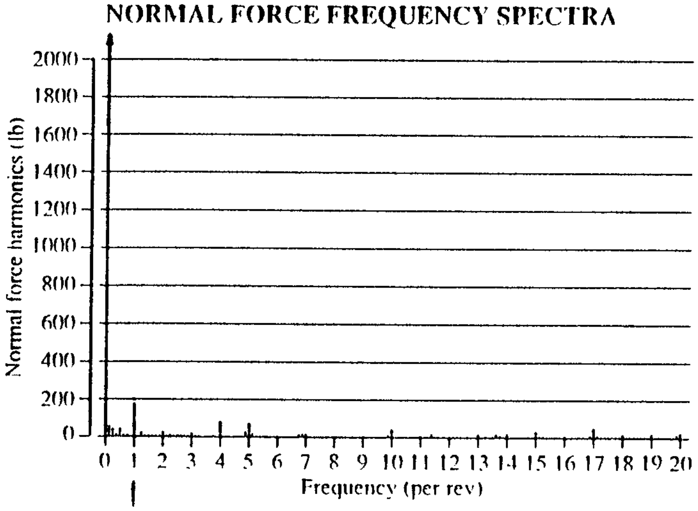

Figure 9. Normal force with 1P HHC (collective, 0.15 deg, 270 deg phase), 120 knots, 14,000 lb.

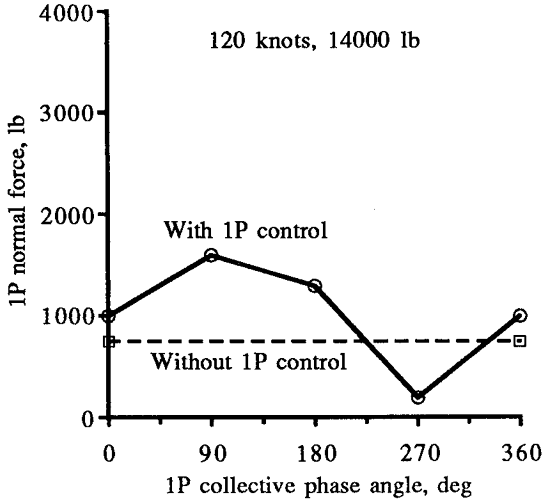

Fig. 10 1P phase sweep, normal force variation

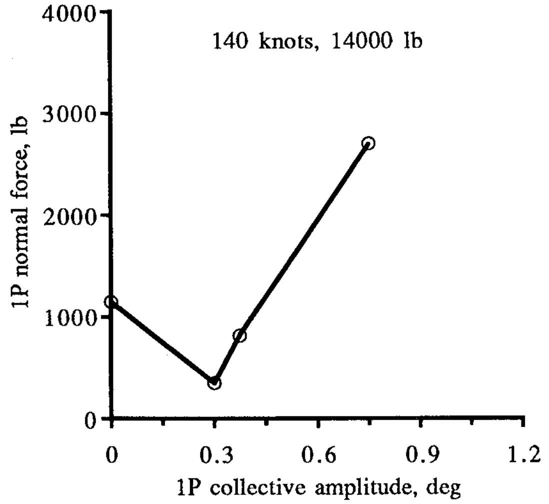

Fig. 11 Effect of 1P collective amplitude on 1P normal force

exhibits high levels of 1P loads, the effect of 2P control on hub loads is genuinely complicated.

Rotor Performance Lateral 2P control at a phase of 315 deg and 1.05 deg amplitude was found to be promising. There was a measurable improvement in the rotor lift. When converted into an "equivalent" reduction in the rotor power, this increase in rotor lift of 568 lb was obtained with a slight power reduction for a baseline 14000 lb operating condition at 140 knots.

It is possible to obtain the "equivalent" power reduction (while maintaining the same thrust) associated with 2P control. Present experimental data can be used to calculate this power reduction. A brief description of this procedure follows.

For the run condition under consideration, the baseline rotor was operating at an airspeed of 140 knots, a thrust of 14360 lb, and an associated power of 1167 HP. The present "equivalence" has been derived from these baseline values and test data obtained from collective pitch sweeps.

From the collective pitch sweep test run, it was found that, roughly, a 1 deg increase in collective pitch brings about a 1109 lb increase in thrust, and at the same time a 263 HP difference in the power.

It is inferred from this that 1109 lb of thrust increment is "equivalent" to 263 HP of power increment (keeping other parameters the same). Or, 1 lb of thrust is "equivalent" to (263/1109) HP, i.e., 0.237 HP. Using the observed improvement in lift of 568 lb results in the present power benefit to be (0.237 x 568), i.e., 135 HP or, a rotor performance improvement of over 10 percent.

Part II: Blade Vortex Interaction Noise

Introduction

To determine the effect of open loop HHC on rotor noise due to BVI, acoustic data were acquired during the test at two different descent conditions. Comparisons of data with and without HHC highlight its effect on BVI noise. Fixed system 5P inputs were individually applied in the collective, lateral and longitudinal modes while varying the amplitude and phase angle. In addition to HHC control sweeps, a wide range of rotor azimuth and elevation angles were examined using the new NFAC Acoustic Survey Apparatus (ASA). The ASA was used to position a vertical array of micophones around the tunnel floor in the lateral and longitudinal directions.

Experimental Set Up and Procedure

Acoustic data were measured with 5 1/2-in condenser-type microphones. These were mounted in a vertical array with elevations of 2.45, 3.24, 12.84, 14.01, and 17.65 feet below the rotor plane (0 deg shaft angle). The microphones array was attached to the ASA and was moved in the lateral and longitudinal directions thus acquiring data for a wide range of azimuth and elevation angles. Table 1 lists the array locations (in cylindrical coordinates; the RTA tail is at 0 deg azimuth) at which data were typically acquired.

The acoustic data were passed from the microphones to amplifiers and recorded as raw data onto a digital tape recorder deck. A time code and 1/rev signal were also recorded. Real-time analysis and post-test analysis were completed using high-pass and low-pass analog filters in conjunction with signal analyzers to efficiently generate time traces and frequency spectra. Initially, data were acquired without HHC inputs, at several descent rates. Time traces for the different conditions were studied to identify those that gave the strongest BVI signatures. Frequency spectra were generated from the time traces and power levels determined for the frequency band between 200 to 800 Hz where BVI dominates, when it exists. These power levels were used as the basis for evaluating the effects of HHC on the BVI noise levels at all descent rates and microphone locations.

Table 1. Typical array locations

Radius (%dia.)	Azimuth (deg)
73.6	150,142,137
77.5	140
79.6	180,135,150,145,142 140
84.4	145

Results

HHC Effects on BVI Noise

From the initial sweep of descent rates, two were found to have high BVI noise signatures: 450 fpm (at 80 knots) and 511 fpm (at 60 knots). These descent rates were calculated for a representative aircraft similar to the Sikorksy S-76B, which has a flat plate area of 14.5 sq-ft. Several HHC input sweeps were conducted and data acquired for these two descent rates. Other wind tunnel conditions were: a hover tip Mach number (Mtip) of 0.599; an advance ratio (Mu) of 0.20; a thrust coefficient ratio (Ct/s) of 0.08; and a tip path plane angle (αtpp) of 0.3 deg.

Figures 12 and 13 are time histories of the baseline data (450 fpm) without HHC inputs and with optimum HHC input settings (5P lateral, amplitude 0.6 deg phase 90 deg). These time histories were recorded at the microphone array location of radius 79.6% dia., azimuth 142 deg, and an elevation 20 deg below the rotor plane. This HHC input reduced the noise levels associated with BVI by 5 to 7 dB. In particular, it can be seen from the time traces that this HHC input virtually eliminated the first and second vortex interactions and reduced the magnitude of the third BVI peak.

5P HHC Control Type Sweep

As a first cut at examining the effects of 5P HHC on rotor acoustics, the phase angle of the input was swept at 90 deg increments. To speed up the acquisition process, data were compared at one microphone location (radius 79.6% dia., azimuth 142 deg, and 30 deg below the rotor plane). Figure 14 shows the 200 to 800 Hz sound power levels (SPL) for these different inputs at a descent rate of 450 fpm. The collective input has little effect on the BVI noise levels. This may be in part due to the small amplitude used (0.15 deg). With the longitudinal control input, there were small increases and decreases in sound power levels. One case of lateral inputs (phase 90 deg) gave the only significant SPL reduction. For this case, a 7 dB reduction in the 200 to 800 Hz frequency band was achieved. This was accompanied however by a 5 dB increase in the SPL's of the first few rotor harmonics. In general, during this wind tunnel test, whenever the simple 5P HHC input was able to reduce BVI noise, an increase in the SPL of the lower rotor harmonics also took place.

5P HHC Phase and Amplitude Sweep

With the best control input determined, smaller increments in phase angle were introduced in order to refine the noise level reduction "map". Results for a descent rate of 450 fpm are shown in Fig. 15. For this condition, the best phase angle was in fact found to be 90 deg. For a descent rate of 511 fpm, the best phase angle was determined to be close to the 90 deg setting obtained earlier, i.e., 95 deg. A 5 deg difference in the best phase for two descent rates that are apart by 61 fpm is perhaps encouraging and at the same time, may also imply that different HHC settings are required for each descent rate. This supports the concept of either pre-programmed open loop control or closed-loop control with a microphone or other sensor acting as one of the inputs. Reference 15 discusses the latter approach in more detail.

With the best control input type and phase identified, the amplitude was varied to determine its optimum level. Figure 16 shows the results for a descent rate of 450 fpm, where the minimum noise levels were measured at an amplitude of 0.60 deg. At 511 fpm, the corresponding amplitude was 0.75 deg (this was the limit imposed by the test safety (loads) considerations).

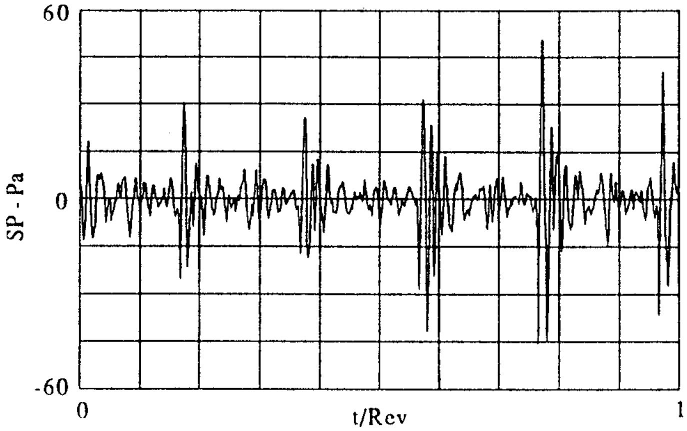

Figure 12. Time history of high BVI noise - baseline, no HHC (Mtip=0.599, Mu=0.20, Ct/s=0.08, αtpp=0.3 deg)

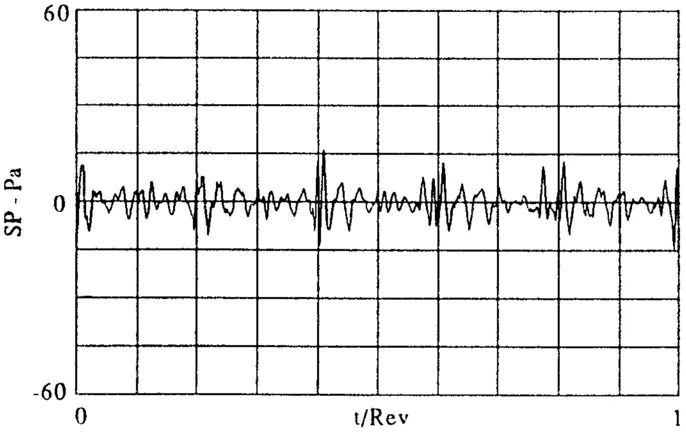

Figure 13. Time history of high BVI noise - with HHC (Mtip=0.599, Mu=0.20, Ct/s=0.08, αtpp=0.3 deg)

This again indicates that different inputs are likely to be required for each flight condition.

Microphone Position Sweep

Use of the ASA during the test allowed for the movement of the microphones along the test section floor. With this capability, data were recorded on the advancing side of the rotor with and without HHC inputs. Figure 17 is a comparison of the SPL's with and without HHC for the typical microphone locations where data were acquired. For each of these locations, the SPL was reduced by 5 to 7 dB in the 200 to 800 Hz band by an application of the optimum HHC input. This implies that HHC reduces the degree of the interaction between the blade and the vortex, thus reducing the noise source. The preceding implies that the directivity of the pulse is not being changed significantly. Further testing of this rotor system with pressure instrumented blades is recommended in order to correlate noise, and blade pressures, with and without HHC.

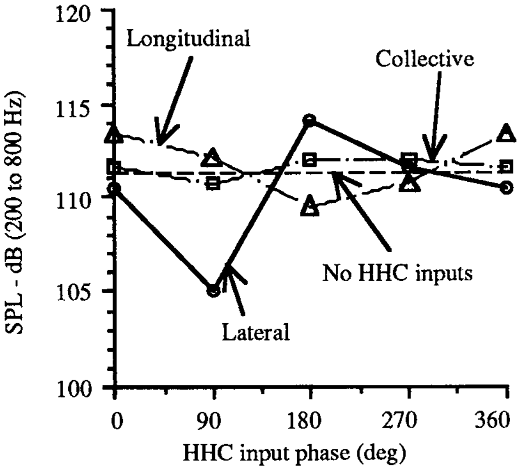

Fig. 14 HHC control sweep

These data also show that the use of a single microphone in a closed loop system may be effective in reducing the overall noise levels even if it were not located at a point of maximum noise. It is important to note that no attempt was made to evaluate the retreating side BVI levels and as such, these may or may not have been affected by the HHC inputs. Further, only a simple 5P input was applied in the present first-time application, which may account for the typical sound pressure level increase in the first several rotor harmonics at a condition when the BVI related noise is significantly reduced.

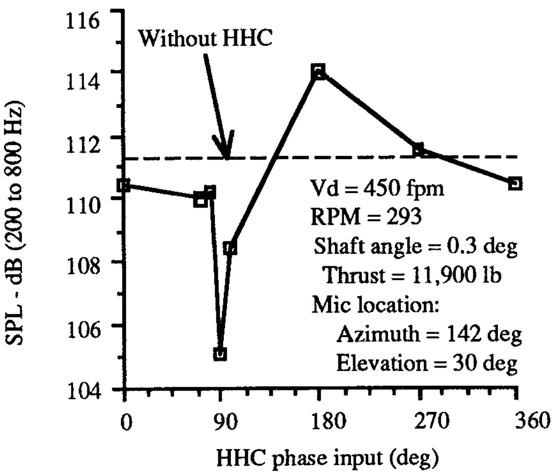

Fig. 15 HHC phase sweep

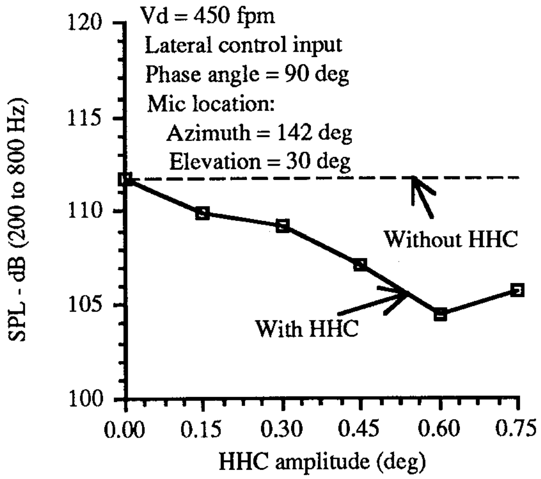

Fig. 16 HHC amplitude sweep

Recommendations

Slightly different HHC settings were required to minimize BVI noise at the two different descent conditions. If one wishes to address the BVI noise problem more thoroughly, this variation in required HHC settings may necessitate the development of approaches more advanced than the present. The first such approach would be an incremental advance over the present and involves a pre-programmed "on board" computer that would input different open loop HHC settings at different flight conditions. The second such approach would involve the use of a microphone interactively as part of a closed loop HHC system.

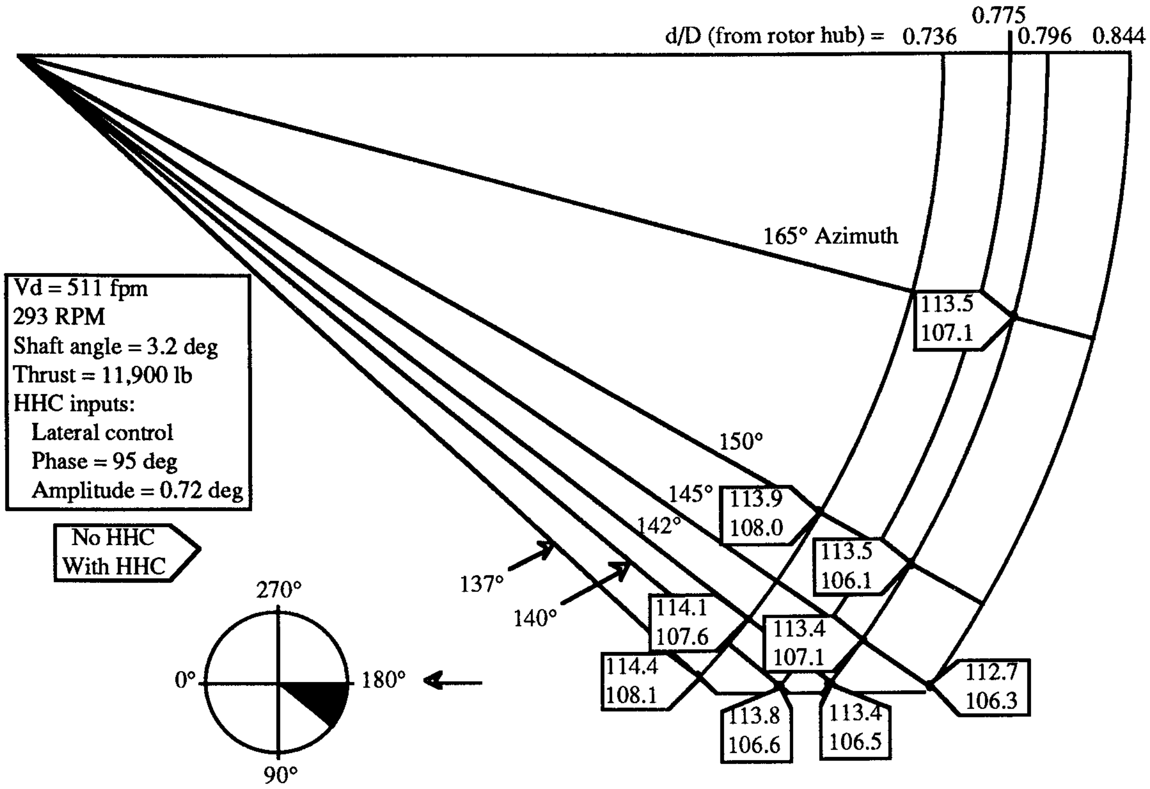

Fig. 17 Power levels in dB (200 to 800 Hz) at various microphone locations (17.65 ft below rotor plane), Baseline and with 5P lateral HHC input

Further HHC related work with pressure instrumented blades would be useful in correlating BVI noise reductions and associated blade pressure distributions.

At the optimum HHC setting for BVI noise reduction in the 200 to 800 Hz band, there was an increase observed during this wind tunnel test in the noise from the first few rotor harmonics. In this context, it would be useful to investigate the use of more advanced HHC inputs.

Conclusions

Higher harmonic control has been applied at various frequencies to a full-scale, moderate thrust, five-bladed bearingless main rotor. This was done in the 40- by 80-Foot Wind Tunnel of the National Full-Scale Aerodynamics Complex (NFAC). HHC testing was limited to a simple application of open loop control. The experimental research covered dynamic hub loads reduction and, separately, blade vortex interaction (BVI) related noise reduction. Substantial reductions in hub loads (1P, 5P) were obtained, with testing conducted up to 160 knots. Application of 2P control and its effect on rotor performance was researched in the wind tunnel with mixed results.

Full-scale research on BVI noise reduction was carried out at 60 and 80 knots. A 5 dB reduction in the BVI noise was obtained at the optimum HHC setting. For the two descent conditions tested, 450 fpm and 511 fpm, a lateral HHC input with a phase around 90 deg was found to be the best. Use of the Acoustic Survey Apparatus in order to examine a large area of the rotor advancing side, showed that HHC inputs reduce the degree of blade vortex interaction, and do not just change the directivity of the pulse.

Acknowledgments

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NASA Ames Research Center are gratefully acknowledged.

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