

Analytical Estimation of UH-60A Helicopter Pilot Vibration with Active Control

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In the absence of actual flight test data for the UH-60A helicopter with active controls, the objective of the present study is to obtain analytical estimates of the UH-60A pilot vertical vibration with active control from available experimental data. The particular form of active control considered in this study is “individual blade control” (IBC). This initial study presents an approximate, first order perturbation type of model that estimates the effects of IBC on the pilot vertical vibration (PVV). Two full-scale experimental databases are used. The first database is the NASA/Army UH-60A Airloads Program flight test database that does not contain IBC effects. The second database is the low speed full-scale UH-60A rotor-only wind tunnel database that was acquired in the NASA Ames 80- by 120-Foot Wind Tunnel with the Large Rotor Test Apparatus (LRTA) with an IBC system installed. The measured wind tunnel data include both the rotating system hub accelerations and the fixed system hub loads from the LRTA dynamic rotor balance system. The low speed, level flight PVV with a single IBC input is considered using two methods. The first method uses the wind tunnel rotating system tangential (in-plane) hub accelerations. The second method uses the wind tunnel fixed system N/rev balance hub loads. Using each of the six components of the balance hub forces and moments separately, six different estimates of the PVV have been obtained. In addition, two more estimates of the PVV have been obtained using the in-plane hub force (obtained from the axial and side forces) and the hub moment (obtained from the rolling and pitching moments). The PVV variations that are based on the wind tunnel in-plane hub measurements (the rotating system in-plane hub accelerations and the fixed system in-plane hub force) show similar trends.

Nomenclature

A_n	= amplitude of n'th harmonic of u_{IBC}
C_w	= helicopter gross weight coefficient
f	= function, represents PVV
g	= function, represents T3
h	= function, represents T5
IBC	= Individual Blade Control
IF4	= 4P wind tunnel in-plane hub force, square root of the sum of the squares of the 4P axial and side hub forces
LRTA	= Large Rotor Test Apparatus, NASA Ames
N	= number of main rotor blades, N = 4 for the UH-60A
N/rev	= integer (N) multiple of main rotor speed
NP	= integer (N) multiple of main rotor speed, same as N/rev
P	= per revolution
PVV	= peak, NP pilot floor vertical vibration, g's
T3	= 3P wind tunnel tangential (in-plane) hub acceleration, g's
T5	= 5P wind tunnel tangential (in-plane) hub acceleration, g's
u_{IBC}	= IBC control input, $\sum_{n=2}^7 A_n \cos(n\psi_1 - \phi_n), \text{ for blade no. 1, deg}$

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μ	=	rotor advance ratio
σ	=	rotor solidity ratio
ϕ_n	=	phase of n'th harmonic of u_{IBC}
Subscripts		
0	=	"No IBC," baseline
IBC	=	"With IBC"

I. Introduction

In Ref. 1, neural networks and ground based wind tunnel test data were used to model full-scale UH-60A helicopter flight test N/rev pilot floor vibration for low speed level flight conditions without any active control inputs. Reference 1 noted that it might be possible to quantify the anticipated benefits of active control in flight from wind tunnel testing alone. This study is a follow on study to Ref. 1. The present analytical study includes the effects of active control in the form of individual blade control (IBC) on the UH-60A pilot vertical vibration. This initial study introduces an analytical methodology to connect (relate) the "with IBC" wind tunnel parameters and the "no IBC" flight test data, and thus can increase the value of wind tunnel testing. This is because wind tunnel testing is less expensive than flight testing and a range of steady flight conditions can be easily explored. In the present study, the measured wind tunnel parameters under consideration include both rotating system parameters (hub accelerations) and fixed system parameters (hub loads from the dynamic rotor balance system).

II. Flight Test and Wind Tunnel Databases

The NASA/Army UH-60A Airloads Program flight test database is used (Ref. 2, the "no IBC" database). The creation of the "no IBC" pilot floor vertical vibration, PVV_0 , database was separately described (Ref. 3). The low speed full-scale UH-60A rotor-only wind tunnel database that was acquired in the NASA Ames 80- by 120-Foot Wind Tunnel with the LRTA and with an IBC system installed is used (Refs. 4-6, the "with IBC" database). The IBC related wind tunnel testing was described in Ref. 5. The wind tunnel database includes the rotating system hub accelerations and the fixed system N/rev hub loads obtained from the LRTA dynamic rotor balance system.

III. Objectives

In the absence of actual IBC flight test data for the UH-60A, the general objective of the present study is to obtain analytical estimates of the UH-60A pilot vertical vibration (PVV) with IBC from available experimental "no IBC" flight test pilot vibration data and "with IBC" measured wind tunnel data. The present study has the following two specific objectives:

- 1) Using the measured wind tunnel rotating system hub accelerations, obtain analytical estimates of the PVV with IBC.
- 2) Using the measured six components of the wind tunnel fixed system N/rev balance hub loads, obtain analytical estimates of the PVV with IBC.

IV. Approach

The pilot vibration is modeled using two different methods that involve, first, the wind tunnel rotating system in-plane hub accelerations and, second, the wind tunnel fixed system, balance-system N/rev hub loads. Both methods use the same analytical approach.

A. Pilot vibration prediction using wind tunnel rotating system hub accelerations

This method uses the (N-1)P and (N+1)P tangential (in-plane) rotating system wind tunnel hub accelerations to model the PVV. For the UH-60A, $N = 4$, resulting in the 3P and 5P components of the in-plane hub accelerations as the components of interest. The nonlinear functional representation of the "no IBC" pilot vertical vibration PVV_0 is based on the representation used in Ref. 1, and is as follows:

$$PVV_0 = f_0(\mu, C_w/\sigma) \quad (1)$$

The nonlinear functional representations for the measured "no IBC" wind tunnel 3P and 5P tangential hub accelerations, $T3_0$ and $T5_0$, respectively, are as follows:

$$T3_0 = g_0(\mu, C_w/\sigma) \quad (2)$$

$$T5_0 = h_0(\mu, C_w/\sigma) \quad (3)$$

In this initial study, the effects of IBC on the pilot vibration are modeled through the corresponding effects on the two tangential hub accelerations (the measured wind tunnel hub accelerations, $T3_{IBC}$ and $T5_{IBC}$). The nonlinear functional representation for the pilot vibration PVV_{IBC} is as follows:

$$PVV_{IBC} = f_{IBC}(\mu, C_w/\sigma, T3_{IBC}, T5_{IBC}) \quad (4)$$

The nonlinear functional representations for the above measured wind tunnel hub accelerations with IBC are as follows:

$$T3_{IBC} = g_{IBC}(\mu, C_w/\sigma, u_{IBC}) \quad (5)$$

$$T5_{IBC} = h_{IBC}(\mu, C_w/\sigma, u_{IBC}) \quad (6)$$

In the above two equations, u_{IBC} is the IBC control input.

The differential of PVV_{IBC} is as follows:

$$\begin{aligned} dPVV_{IBC} = & [(\partial f_{IBC}/\partial \mu) + (\partial f_{IBC}/\partial T3)(\partial g_{IBC}/\partial \mu) + (\partial f_{IBC}/\partial T5)(\partial h_{IBC}/\partial \mu)]d\mu + \\ & [(\partial f_{IBC}/\partial (C_w/\sigma) + (\partial f_{IBC}/\partial T3_{IBC})(\partial g_{IBC}/\partial (C_w/\sigma) + (\partial f_{IBC}/\partial T5_{IBC})(\partial h_{IBC}/\partial (C_w/\sigma))]d(C_w/\sigma) + \\ & [(\partial f_{IBC}/\partial T3_{IBC})(\partial g_{IBC}/\partial u_{IBC}) + (\partial f_{IBC}/\partial T5_{IBC})(\partial h_{IBC}/\partial u_{IBC})]du_{IBC} \end{aligned} \quad (7)$$

which results in the following partial derivative:

$$(\partial PVV_{IBC}/\partial u_{IBC}) = (\partial f_{IBC}/\partial T3_{IBC})(\partial g_{IBC}/\partial u_{IBC}) + (\partial f_{IBC}/\partial T5_{IBC})(\partial h_{IBC}/\partial u_{IBC}) \quad (8)$$

The partial derivatives $(\partial f_{IBC}/\partial T3_{IBC})$ and $(\partial f_{IBC}/\partial T5_{IBC})$ are not directly available. The above derivatives are approximated by $(\partial f_0/\partial T3_0)$ and $(\partial f_0/\partial T5_0)$, respectively, i.e., by $(\partial PVV_0/\partial T3_0)$ and $(\partial PVV_0/\partial T5_0)$, respectively. These two derivatives are calculated from the flight test data and the measured wind tunnel data. This results in the following approximation:

$$(\partial PVV_{IBC}/\partial u_{IBC}) \cong (\partial PVV_0/\partial T3_0)(\partial g_{IBC}/\partial u_{IBC}) + (\partial PVV_0/\partial T5_0)(\partial h_{IBC}/\partial u_{IBC}) \quad (9)$$

The pilot vertical vibration with IBC to first order is as follows:

$$PVV_{IBC} = PVV_0 + (\partial PVV_{IBC}/\partial u_{IBC})u_{IBC} \quad (10)$$

Using the wind tunnel rotating system in-plane hub accelerations (Eq. (9) above), and Eq. (10), the present estimate for the pilot vertical vibration with IBC is as follows:

$$PVV_{IBC} = PVV_0 + [(\partial PVV_0/\partial T3_0)(\partial T3_{IBC}/\partial u_{IBC}) + (\partial PVV_0/\partial T5_0)(\partial T5_{IBC}/\partial u_{IBC})]u_{IBC} \quad (11)$$

B. Pilot vibration prediction using wind tunnel fixed system balance hub loads

This method uses the wind tunnel N/rev (i.e., 4P) fixed system, balance-system hub loads to model the PVV. The analytical approach used in this method is the same as that used in the first method. In the second method, six different predictions of the PVV are obtained using, separately, each of the six components of the wind tunnel N/rev balance-system hub forces and moments. In addition to the above six predictions, two more predictions are obtained using the N/rev in-plane force (square root of the sum of the squares of the N/rev axial and side forces) and the N/rev hub moment (square root of the sum of the squares of the N/rev rolling and pitching moments).

An example of the prediction of the pilot vibration using the wind tunnel fixed system balance hub loads is given as follows. Using the measured wind tunnel N/rev in-plane force (defined above and presently denoted as IF4), the estimate for the pilot vertical vibration with IBC is as follows:

$$PVV_{IBC} = PVV_0 + [(\partial PVV_0 / \partial IF_4) (\partial IF_4 / \partial u_{IBC})] u_{IBC} \quad (12)$$

V. Results

The results in this paper are given for the following operating condition: $\mu = 0.10$ and $C_W/\sigma = 0.0725$. Also, for the results presented here, linear interpolation is used to numerically calculate the derivatives in equations such as Eqs. (11) and (12).

C. Pilot vibration from wind tunnel rotating system hub accelerations

Figure 1 below shows a sample variation of the wind tunnel 3P tangential hub acceleration $T3_{IBC}$ with a single 3P IBC input (Ref. 5). The amplitude and phase of the 3P IBC input were varied.

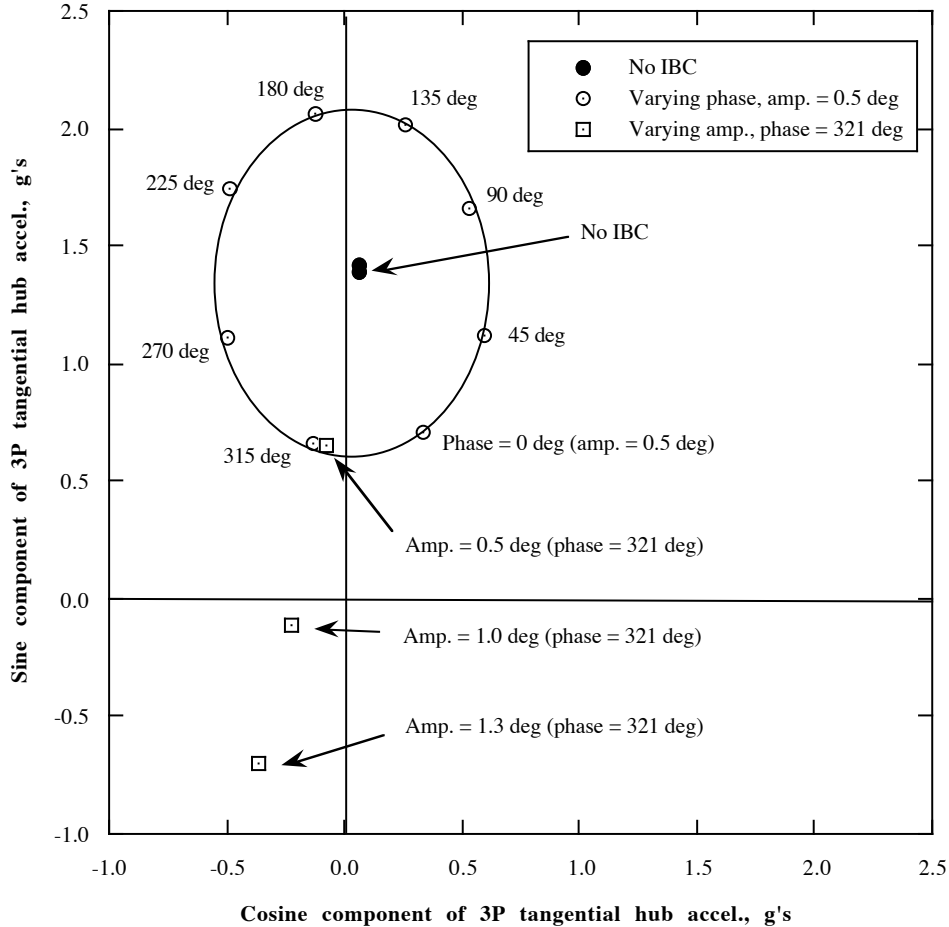


Figure 1. Variation of measured UH-60A 3P wind tunnel hub acceleration ($T3_{IBC}$) with single 3P IBC input (Ref. 5), $\mu = 0.10$, $C_W/\sigma = 0.0725$.

At the above operating condition of interest, the following equation is obtained from Eq. (11):

$$PVV_{IBC} = 0.09 + 0.0662(T3_{IBC} - T3_0) + 0.0874(T5_{IBC} - T5_0) \quad (13)$$

First, the 3P input amplitude was kept constant (0.5 deg) and the 3P input phase was varied (Ref. 5). Using Eq. (13) above, Fig. 2 below shows the predicted pilot vertical vibration PVV_{IBC} variation with the phase of the 3P input. The maximum value of the PVV_{IBC} occurs at a 3P input phase of 180 deg and the minimum value occurs in the neighborhood of 315 deg. Figures 1 and 2 show that at the above optimum phase value, the 3P tangential hub acceleration was reduced by 50% whereas the pilot vertical vibration is predicted to be reduced by 70% (compared to their respective baseline values).

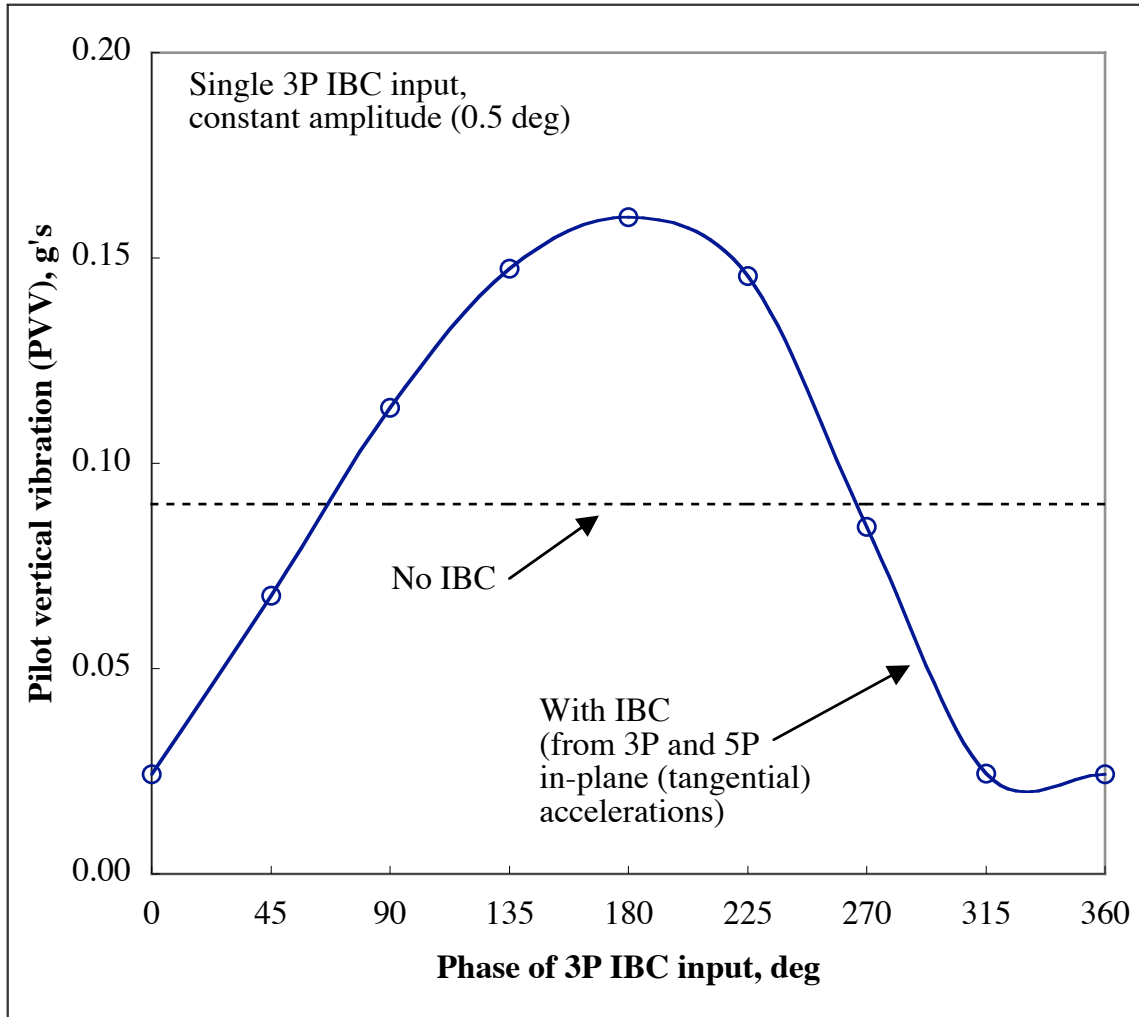


Figure 2. Predicted UH-60A pilot vibration with IBC (PVV_{IBC}) using “no IBC” flight test pilot vibration (Refs. 2 and 3) and “with IBC” measured wind tunnel in-plane (tangential) hub accelerations (Ref. 5), $\mu = 0.10$, $C_w/\sigma = 0.0725$.

Second, the 3P input phase was kept constant (321 deg) and the 3P input amplitude was varied (Ref. 5). Using Eq. (13) above, Table 1 below shows the predicted pilot vertical vibration PVV_{IBC} variation with the amplitude of the 3P input. Despite the fact that the wind tunnel hub accelerations are an order of magnitude greater than the pilot vibration values, for the operating condition under consideration, an input amplitude of approximately 1 deg (3P IBC input) may be sufficient to eliminate the pilot floor vertical vibration. This may not be the case for other wind tunnel or flight test operating conditions.

D. Pilot vibration from wind tunnel fixed system balance hub loads

First, the 3P IBC input amplitude was kept constant (0.5 deg) and the 3P input phase was varied (Ref. 5). Figure 3 below shows the three PVV variations obtained by using, separately, the three wind tunnel fixed system balance N/rev (4P) hub forces.

3P IBC Input Amp. deg	Predicted PVV_{IBC} Using In-plane Hub Accelerations g's
0.5	0.02
1.0	0.00
1.5	0.04

Table 1. Sample PVV_{IBC} variation with 3P IBC input amplitude (phase = 321 deg) using wind tunnel in-plane hub accelerations, $\mu = 0.10$, $C_W/\sigma = 0.0725$ (wind tunnel test data from Ref. 5).

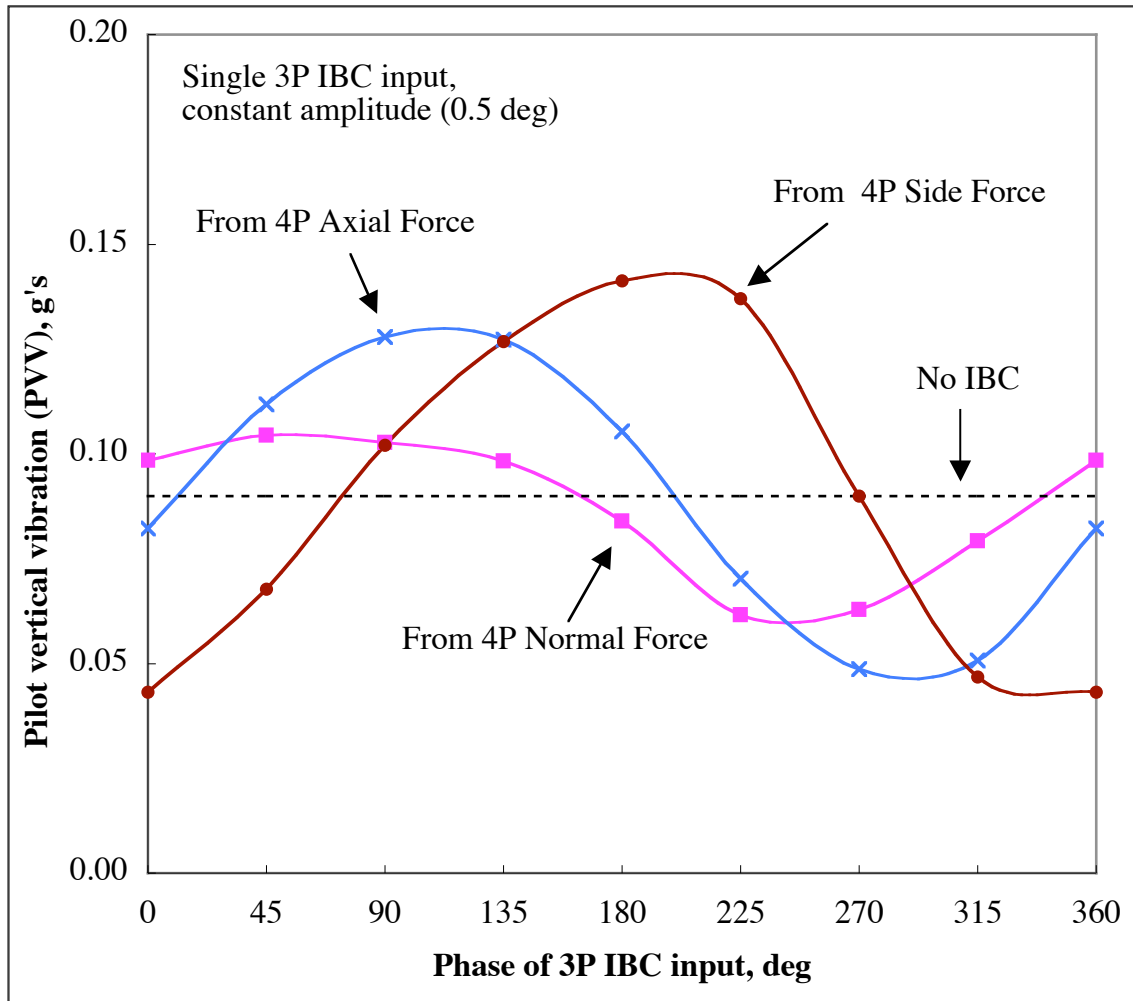


Figure 3. Predicted UH-60A pilot vibration with IBC (PVV_{IBC}) using “no IBC” flight test pilot vibration (Refs. 2 and 3) and “with IBC” measured wind tunnel hub forces (Ref. 5), $\mu = 0.10$, $C_W/\sigma = 0.0725$.

Figure 4 below shows the three PVV variations obtained by using, separately, the three wind tunnel fixed system balance N/rev (4P) hub moments. Figure 5 below shows the PVV variations using the above defined wind tunnel fixed system N/rev (4P) in-plane force and the wind tunnel N/rev hub moment. The PVV variation from Fig. 2 (using the wind tunnel rotating system in-plane hub accelerations) is also shown in Fig. 5. Figure 5 shows that the

PVV variations that are based on the wind tunnel in-plane hub measurements (the rotating system in-plane hub accelerations and the fixed system in-plane hub force) show similar trends.

Second, the 3P input phase was kept constant (321 deg) and the 3P input amplitude was varied (Ref. 5). Table 2 below shows the resulting, predicted pilot vertical vibration PVV_{IBC} variation obtained by using the N/rev in-plane force. Tables 1 and 2 show that that the PVV predictions based on the in-plane wind tunnel hub measurements show similar trends.

3P IBC Input Amp. deg	Predicted PVV_{IBC} Using In-plane Hub Force g's
0.5	0.04
1.0	0.00
1.5	0.03

Table 2. Sample PVV_{IBC} variation with 3P IBC input amplitude (phase = 321 deg) using wind tunnel balance in-plane hub force, $\mu = 0.10$, $C_W/\sigma = 0.0725$ (wind tunnel test data from Ref. 5).

VI. Concluding Remarks

In the absence of actual individual blade control (IBC) flight test data for the UH-60A helicopter, an approximate, first order perturbation type of model that analytically estimates the effects of IBC on the UH-60A pilot vertical vibration (PVV) has been derived in this initial study. The present results are based on the available full-scale flight test pilot vibration data that do not contain IBC effects and the full-scale low speed wind tunnel data that contain IBC effects. The measured wind tunnel parameters include both the rotating system parameters (hub accelerations) and the fixed system parameters (N/rev hub loads from the dynamic rotor balance system).

The low speed, level flight PVV with a single IBC input has been considered using two methods. The first method uses the wind tunnel rotating system tangential (in-plane) hub accelerations. The second method uses the wind tunnel fixed system balance hub loads. Using each of the six components of the balance hub forces and moments separately, six different estimates of the PVV have been obtained. In addition, two more estimates have been obtained using the in-plane hub force (obtained from the axial and side forces) and the hub moment (obtained from the rolling and pitching moments). The PVV variations that are based on the wind tunnel in-plane hub measurements (the rotating system in-plane hub accelerations and the fixed system in-plane hub force) show similar trends.

References

- ¹Kottapalli, S., "Neural Network Modeling of UH-60A Pilot Vibration," Proceedings of the 4th Decennial Specialists' Conference on Aeromechanics, American Helicopter Society, San Francisco, California, January 21-23, 2004.
- ²Kufeld, R.M. and Bousman, W.G., "UH-60A Helicopter Rotor Airloads Measured in Flight," *The Aeronautical Journal of the Royal Aeronautical Society*, May 1997.
- ³Kottapalli, S., "Neural Network Based Representation of UH-60A Pilot and Hub Accelerations," *Journal of the American Helicopter Society*, Vol. 47, No. 1, January 2002, pp. 33-41.
- ⁴Norman, T. R., Shinoda, P. M., Jacklin, S. A., and Sheikman, A., "Low-Speed Wind Tunnel Investigation of a Full-Scale UH-60 Rotor System," Proceedings of the 58th Annual Forum of the American Helicopter Society, Montreal, Canada, June 11-13, 2002.
- ⁵Jacklin, S. A., Hater, A., de Simone, G., Norman, T. R., Kitaplioglu, C., and Shinoda, P. M., "Full-Scale Wind Tunnel Test of an Individual Blade Control System for a UH-60 Helicopter," Proceedings of the 58th Annual Forum of the American Helicopter Society, Montreal, Canada, June 11-13, 2002.
- ⁶Shinoda, P.M., Yeo, H., and Norman, T.R., "Rotor Performance of a UH-60 Rotor System in the NASA Ames 80- by 120-Foot Wind Tunnel," *Journal of the American Helicopter Society*, Vol. 49, No. 4, October 2004, pp. 401-413.

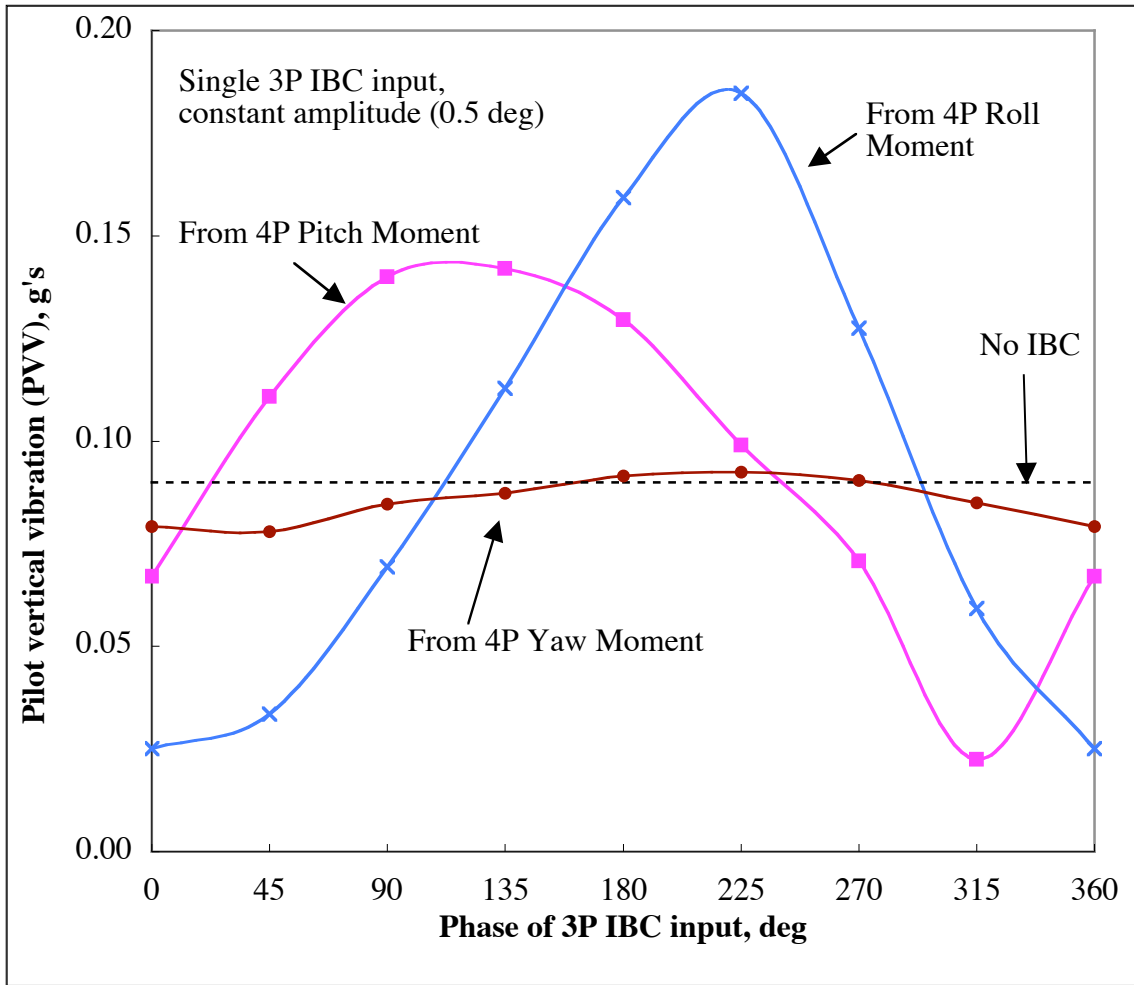


Figure 4. Predicted UH-60A pilot vibration with IBC (PVV_{IBC}) using “no IBC” flight test pilot vibration (Refs. 2 and 3) and “with IBC” measured wind tunnel hub moments (Ref. 5), $\mu = 0.10$, $C_w/\sigma = 0.0725$.

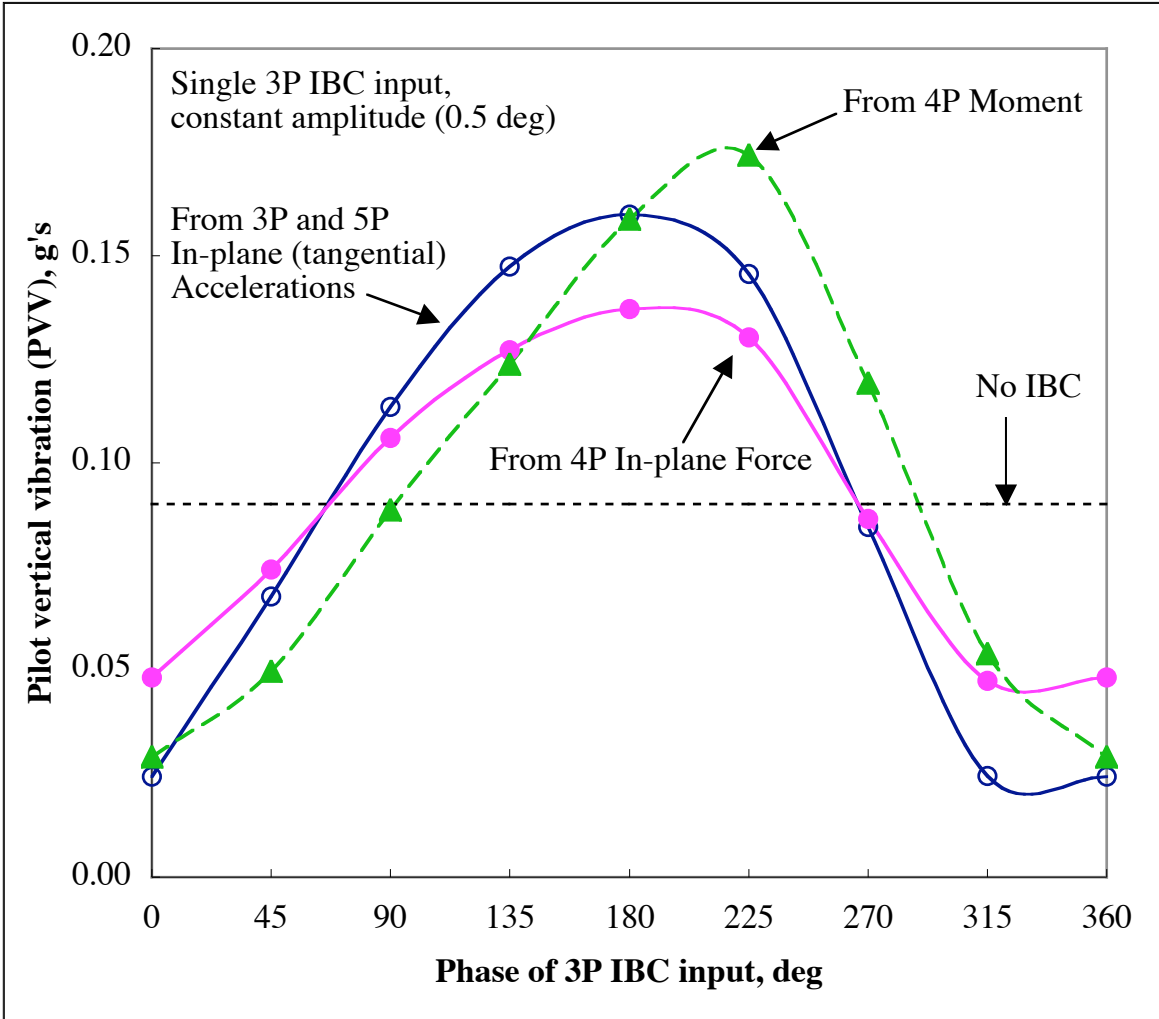


Figure 5. Predicted UH-60A pilot vertical vibration with IBC (PVV_{IBC}) using "no IBC" flight test pilot vibration (Refs. 2 and 3) and "with IBC" measured wind tunnel fixed system balance loads (Ref. 5), $\mu = 0.10$, $C_w/\sigma = 0.0725$.