Backward Whirl in Asymmetrically Supported Turbofan Engine Structure during High Rotor Unbalance Test

ISABE-2015-20134

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Abstract

One of the tests performed during development of turbofan engine is the high rotor unbalance test. Lissajous plot of response at various engine locations showed backward whirl of engine at multiple speed points. Lissajous orbit were generally elliptical and forward whirl in nature but at some speeds, the orbit gets collapsed into a line and then turns into backward whirl. Backward whirl continues to be there for some time and then again, gets collapsed into a line and then resumes back the forward whirl nature. Different engine locations showed this characteristic at different speed points. This characteristic at low speed is attributed to asymmetric mounting support stiffness of the engine; while at high speed, it is attributed to asymmetric bending stiffness of engine along lateral and vertical direction. This asymmetric property leads to different natural freq of the engine along lateral and vertical direction which causes the phase lag of the response to be different in lateral and vertical direction at a particular engine speed. At speeds, between these two natural frequencies, the difference in phase lag of the response between lateral and vertical directions exceeds 90 degrees and makes the orbit whirl in backward direction.

Nomenclature

M	Mass
C	Viscous damping coefficient
K	Stiffness
F	Applied force
Ω	Spin speed of rotor
φ	Phase angle
ς	Damping ratio
t	Time

Introduction

Turbofan engine is most commonly used gas turbine engine in aviation industry. Engine is mounted to the airframe structure through some static structure. Mounting support stiffness is generally asymmetric in nature.

During the development phase of turbofan engine, a system dynamics model is built to predict response at various locations of the engine under various loading conditions. The system dynamics model is validated by various tests. One of the tests used for model validation is High Rotor Unbalance Test, also commonly referred to as High Unbalance Test. In High Unbalance Test, engine is mounted on test stand. Test stand represents the airframe structure. Test stand is designed to match the dynamic behavior of airframe structure at engine mount location. During High Unbalance Test, unbalance is created at fan blade axial location, and engine is spooled up slowly till the max rated speed. Engine response during spool up phase is measured at various locations of the engine and this data is used to validate the system dynamics model.

Test data measured from High Unbalance Test shows presence of backward whirl at various locations of engine structure. Backward whirl is a phenomenon when the structure whirls in opposite direction with respect to whirl direction of rotor unbalance or the spin speed direction of rotor. In this paper, relation between backward whirl and asymmetric engine mounting support is studied.

Mathematical Formulation

In this section, mathematical background of forward and backward whirl of structure under rotating unbalance is presented. Rotating unbalance represents the unbalance due to rotor eccentricity.

Figure 1 shows the two degree of freedom representation of engine mounted to test stand.

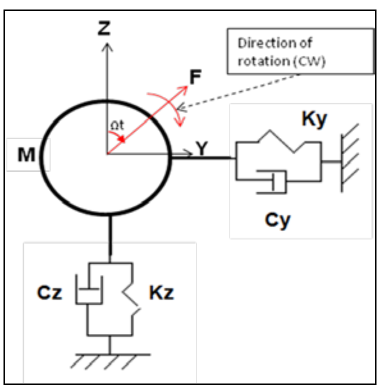

Figure 1: Two degree of freedom representation of Test stand mounted engine.

'M' represents the total mass of engine. 'Ky', and 'Kz' represents the mounting stiffness in lateral (Y) and vertical (Z) direction. 'Cy' and 'Cz' represents the idealized viscous damping in lateral and vertical direction. 'F' represents the rotor unbalance force. 'Ω' represents the spin speed of rotor. Spin direction of rotor is clockwise. Equation (1) and (2) represents the equation of motion in 'Y' and 'Z' direction.

Equation (1) and (2):

$$M*\ddot{Y}+Cy*\dot{Y}+Ky*Y=F*Sin(\Omega*t)$$

$$M*\ddot{Z}+Cz*\dot{Z}+Kz*Z=F*Cos(\Omega*t)$$

Equation (3) and (4) represents the steady state solution of equation (1) and (2).

Equation (3):

$$Y=Yo*Sin(\Omega*t-\phi y)$$

Where,

$$Yo=\frac{F/Ky}{\sqrt{(1-(\Omega/\omega y)^2)^2+(2*\varsigma y*\Omega/\omega y)^2}}$$

$$\varphi y=a\tan\left(\frac{2*\varsigma y*(\Omega/\omega y)}{(1-(\Omega/\omega y)^2)}\right)$$

Equation (4):

$$Z=Zo*Cos(\Omega*t-\phi z)$$

Where,

$$Zo=\frac{F/Kz}{\sqrt{(1-(\Omega/\omega z)^2)^2+(2*\varsigma z*\Omega/\omega z)^2}}$$

$$\varphi z=a\tan\left(\frac{(1-(\Omega/\omega z)^2)}{-2*\varsigma z*(\Omega/\omega z)}\right)$$

The phase lag angle ('φy' & 'φz') is not same in 'Y' and 'Z' direction. When difference in phase lag angle (φz- φy) exceeds 90 degrees, the whirl orbit of mass point 'M' becomes backward whirl.

Figure 2 shows the plot of variation of (φz- φy) with respect to frequency for two values of damping ratios (0.1 and 0.3). The model used for this plot has natural freq in 'Z' direction as (ωz=15Hz), and natural freq in 'Y' direction as (ωy=25Hz).

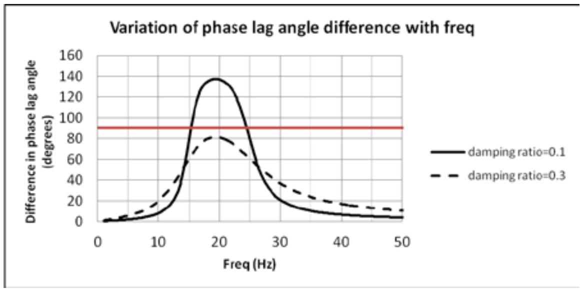

Figure 2: Variation of phase lag angle difference with frequency.

For damping ratio as 0.1 (ς_y= ς_z =0.1), difference is phase angle below ~15 (ω_z) Hz and above ~25 Hz (ω_y), is lower than 90 degrees. This implies that whirl direction of rotor is forward whirl in the freq range of below ~15 Hz and above ~25 Hz. In the freq range between 15-25 Hz, difference in phase angle is greater than 90 degrees and backward whirl exists in this range. For higher damping ratio (ς_y= ς_z =0.3), backward whirl doesn't exist.

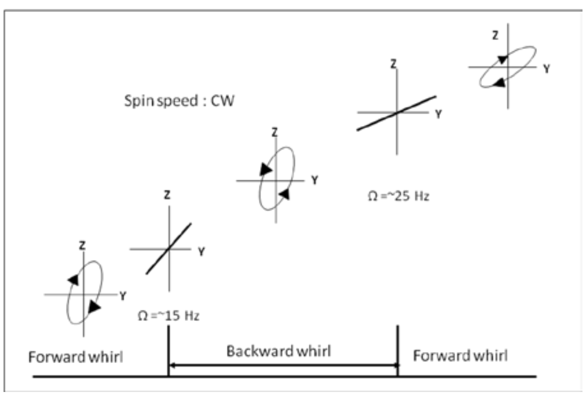

Figure 3: Forward and Backward whirl orbits at different speed points.

Figure 3 shows the graphical representation of lissajous plot at various frequency points. For clockwise spin speed, forward whirl and backward whirl orbits are shown. Whirl orbits are elliptical because of different natural frequency in lateral and vertical direction. Also, the elliptical orbit is not purely aligned along either 'Y' or 'Z' direction but is slightly inclined. Inclination in elliptical orbit is due to damping in the system. Frequency range of forward and backward whirl is consistent with explanation given in Figure 2.

Results

High Unbalance Test (HUT) Set-up

In High Unbalance Test, engine is mounted on test stand. Engine mounting stiffness is asymmetric. Figure 4 shows the rough sketch of engine mounted on test stand. Unbalance is created by adding weights at washer end of bolted flange near to fan location.

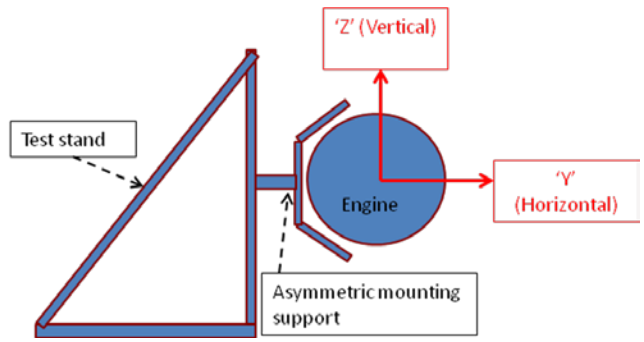

Figure 4: Sketch of engine mounted on test stand.

Accelerometers are mounted at different locations of engine. Figure 5 shows the accelerometer position on one of the component of the engine. Accelerometers shown in Figure 5 are used to draw a lissajous plot in this section.

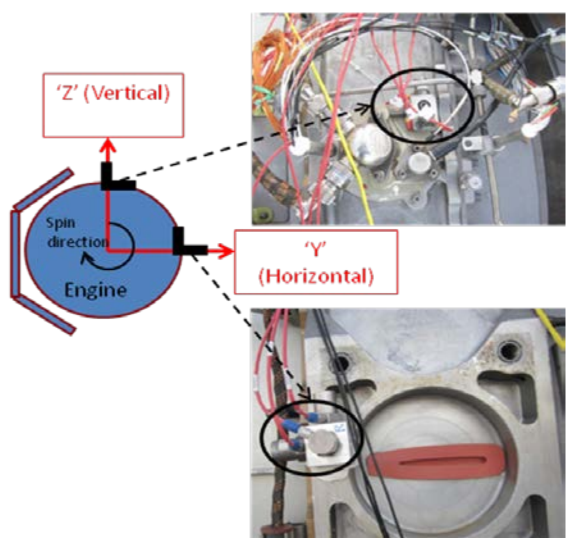

Figure 5: Accelerometer location on engine.

Engine is spooled up in quasi-static manner to avoid transient vibration response. Figure 6 shows the variation of engine speed with respect to time.

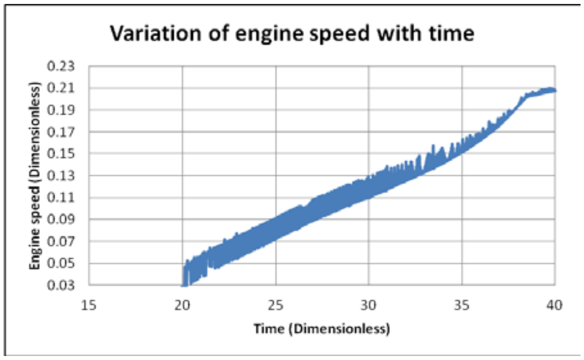

Figure 6: Engine speed with respect to time.

All the data in this section is dimensionless to protect the IP.

HUT test data interpretation

Accelerometer data's were analyzed to identify modes of the engine. First few modes are identified as rigid body mode of the engine followed by flexural mode of engine static structure. Rigid body mode of engine has engine moving as rigid body on mounting support. Most of strain energy for rigid body modes is in mounting structure. Since the mounting support is asymmetric, engine rigid body mode is different in lateral ('Y') and vertical ('Z) direction. Figure 7 shows the mode shape (looking from side) of rigid body mode in vertical direction. This is actually a pitch mode of the engine.

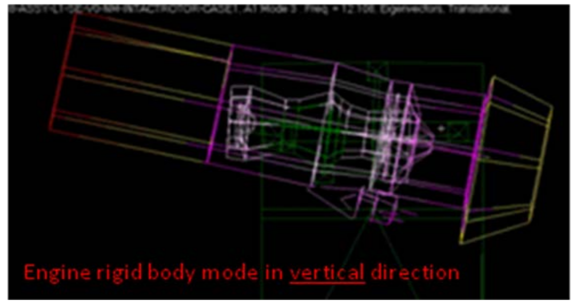

Figure 7: Engine rigid body mode in vertical direction.

Figure 8 shows the mode shape (looking from top) of engine rigid body mode in horizontal direction. This is actually a bounce mode in horizontal direction.

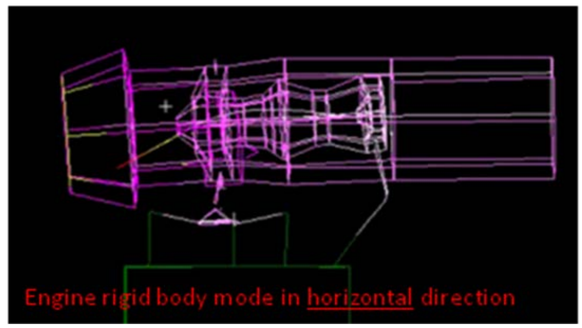

Figure 8: Engine rigid body mode in horizontal direction.

Mode in vertical direction occurs lower in freq compared to horizontal direction because the mounting support is stiffer in horizontal direction. Mode shape shown in Figure 7 and Figure 8 are basically obtained from analytical simulation but it is similar mode observed in the test.

Figure 9 shows the synchronous response of accelerometer in vertical and horizontal direction. It clearly shows the presence of two distinct vertical and horizontal rigid body mode of the engine. Both engine speed and response is made dimensionless to protect the IP.

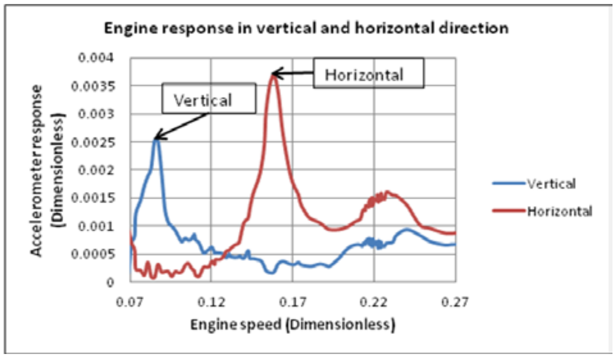

Figure 9: Frequency response of engine in vertical and lateral direction.

Lissajous plots

To plot the lissajous plot of response, the time history data collected from accelerometer is filtered to remove any noise or sub and super synchronous response content in the data. Figure 10 shows the lissajous plot of accelerometer at TDC (Top Dead Center) and 3 o'clock location at speed between vertical and horizontal rigid body mode. Spin speed of rotor is in clockwise direction. Lissajous plot shows that the point on structure at accelerometer location is orbiting in counter clockwise direction which is backward whirl. This observation is consistent with explanation given in 'mathematical formulation' section for two degree of freedom system (See Figure 3).

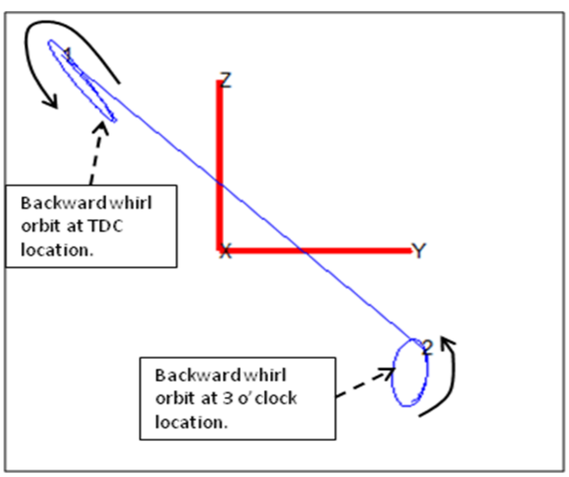

Figure 1: Lissajous plot at speed between vertical and horizontal rigid body mode frequency.

Figure 12 shows the lissajous plot at speed closer to mode in horizontal direction. Whirl orbit at TDC has turned into a line which is also consistent with explanation given in 'mathematical formulation' section.

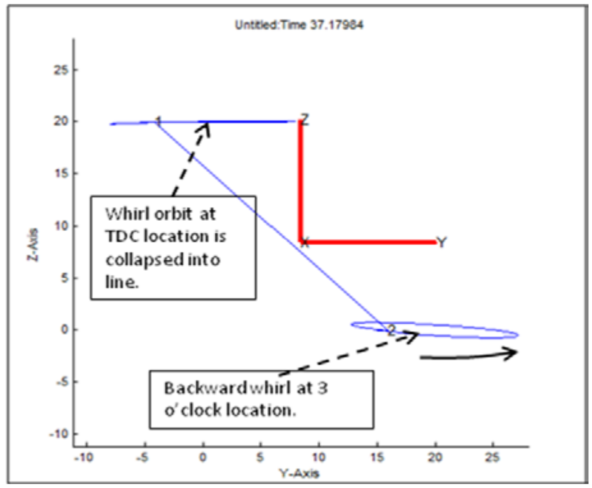

Figure 2: Lissajous plot at speed closer to horizontal rigid body mode frequency.

Whirl orbit at 3 o'clock location is still backward whirl which also gets collapsed into a line after slight increment of frequency (~2 Hz) than TDC point as shown in Figure 12.

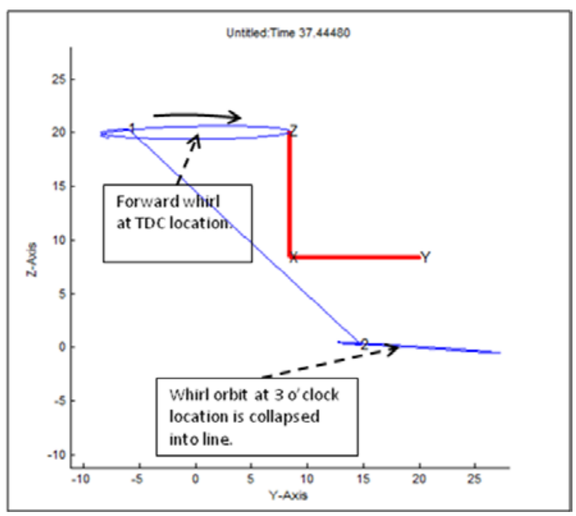

Figure 3: Lissajous plot at speed slightly higher than the horizontal rigid body mode frequency.

The reason for small difference in frequency, at which elliptical orbit gets collapsed into a line, between 'TDC' point and 3 o'clock point is because that engine doesn't behave exactly as a rigid body. Different points on engine has different modal participation factor.

Figure 13 shows the lissajous plot at frequency above the mode at horizontal direction.

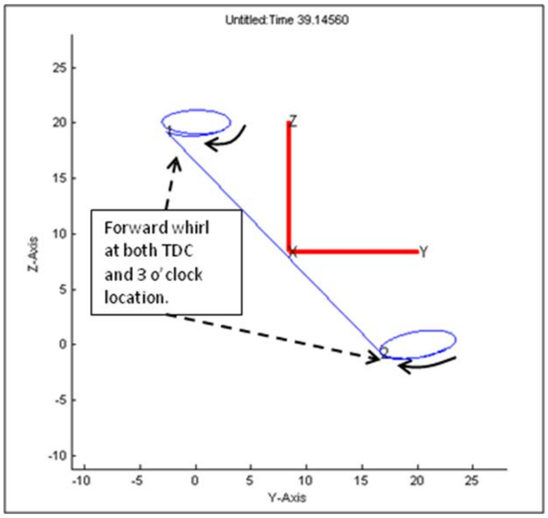

Figure 43: Lissajous plot at speed greater than the horizontal rigid body mode frequency.

Lissajous plot at both 'TDC' and 3 o'clock location shows forward whirl orbit. This is also consistent with explanation given in 'mathematical formulation' section.

Relation between Whirl orbit and phase difference

In 'Mathematical Formulation' section, it was stated that, backward whirl occurs when difference in phase lag angle between 'Z' and 'Y' direction (φz-φy) exceeds 90 degrees. Though (φz-φy) is not directly measured from the test data, but its evidence can be seen in the time history plot. Figure 14 shows the time history plot at two different time points. Time history response of accelerometer at TDC (Top Dead Center) is plotted in 'Y' and 'Z' direction.

As the spin direction of rotor is clockwise, we should expect 'Z' direction response should lead the 'Y' direction response by 90 degrees, if there is no phase lag due to mode or damping.

In Figure 14, there are two plots. Plot 'A' is time history at time point, when forward whirl orbit is observed. Plot 'A' shows that 'Z' direction response is leading the 'Y' direction response by approximately 90 degrees. This means that both 'Y' and 'Z' has approximately same phase lag (φz-φy≈0) angle.
Plot 'B' is time history at time point, when the backward whirl orbit is observed. Plot 'B' shows that, phase difference between 'Z' and 'Y' direction is ~260 degrees, which means that difference in phase lag angle difference between 'Z' and 'Y' (φz-φy) is ~170 degrees (260-90=170). Plot 'B' also shows that 'Y' is leading 'Z' which is an indication of backward whirl.

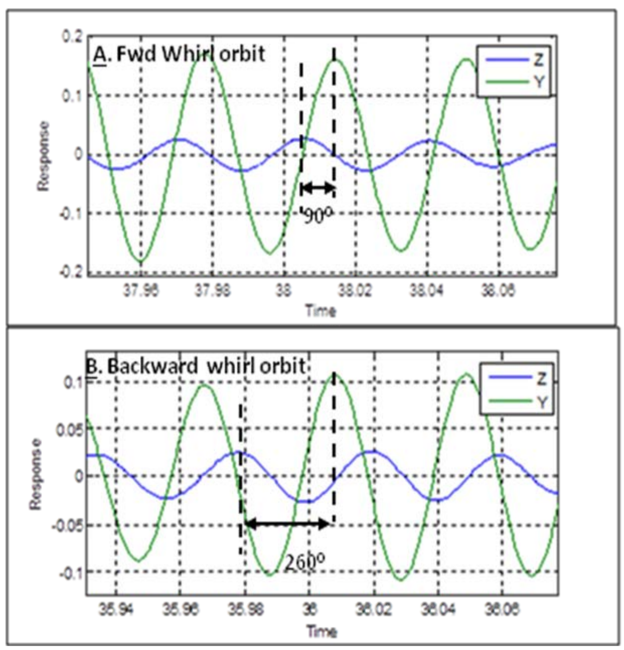

Figure 54: Time history plot of response at TDC location at two different time points.

General Comments

Backward whirl in rotor is in general an un-desirable phenomenon. However, the present study refers to observance of backward whirl in static structure of engine in certain frequency range. This has not yet been found to be of concern primarily because of two reasons. First reason is that- it occurs only for certain narrow frequency range during engine spool up. This phenomenon is not observed at normal operating speed of engine. Second reason is- it is found to be observed only when there is high unbalance at the fan blade location. For nominal unbalance condition, this phenomenon is not found to be observed.

Conclusion

Backward whirl is observed in the engine structure response in the freq range between modes in vertical and horizontal direction. This kind of change in whirl orbit direction at various speeds indicates a presence of mode in engine structure.

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