Assessing Fan Flutter Stability in Presence of Inlet Distortion Using One-way and Two-way Coupled Methods

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Background: Boundary Layer Ingestion


- Boundary Layer Ingestion (BLI) Propulsion has potential for significant reduction (5%-10%) in aircraft fuel burn.

- BLI may present significant flow distortion to fan. Aeromechanical response of fan in presence of distorted flow must be understood, and applied design must be aeromechanically robust.
CFD & Aeromechanics Code: TURBO-AE

- Unsteady Reynolds-Averaged Navier Stokes equations
- Characteristics-based finite-volume solver
- Newton-iterative, implicit, time-accurate
- Structured multi-block code
- Decoupled $k - \epsilon$ turbulence model
- Sliding interfaces where applicable
- Inlet distortion boundary condition
- Throttle exit boundary condition
- Dynamic grid deformation for blade vibration
  - One-way prescribed harmonic blade vibration (previously validated in aeromechanics analyses in clean flow and applied herein)
  - Two-way coupled blade motion (implemented and applied herein)
## Computational Research Fan

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tip Diameter</td>
<td>22 in.</td>
</tr>
<tr>
<td>Blade Count</td>
<td>22</td>
</tr>
<tr>
<td>Rotor Speed(^2)</td>
<td>10800 rpm</td>
</tr>
<tr>
<td>Blade Natural Frequency</td>
<td>220 Hz</td>
</tr>
<tr>
<td>Rotational Frequency</td>
<td>180 Hz</td>
</tr>
<tr>
<td>Time Steps/Passage</td>
<td>15</td>
</tr>
<tr>
<td>Time Steps/Revolution</td>
<td>330</td>
</tr>
<tr>
<td>Time Steps/Oscillation</td>
<td>270</td>
</tr>
<tr>
<td>Subiterations, Clean</td>
<td>6</td>
</tr>
<tr>
<td>Subiterations, Distorted</td>
<td>9</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Mesh Specifications</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Passage Mesh</td>
<td>214/76/58</td>
</tr>
<tr>
<td>Blade Mesh</td>
<td>81/70/58</td>
</tr>
<tr>
<td>Inlet Duct Length(^1)</td>
<td>1.387</td>
</tr>
<tr>
<td>Exit Duct Length(^1)</td>
<td>2.365</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Time Specifications</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clock per step, Clean</td>
<td>1m:16s</td>
</tr>
<tr>
<td>Clock per step, Distorted</td>
<td>1m:53s</td>
</tr>
<tr>
<td>Clock per rev, Clean</td>
<td>6h:58m</td>
</tr>
<tr>
<td>Clock per rev, Distorted</td>
<td>10h:21.5m</td>
</tr>
</tbody>
</table>

\(^1\) axial chords at tip radius  
\(^2\) Part-speed condition studied here
Inlet Total Pressure

- **Clean Inlet**
- **Sinusoidal Inlet Distortion (4% mean-to-peak)**

Azimuthal orientation: $0^\circ$ at 12 o’clock, increasing clockwise. Fan rotates counterclockwise.
- Speedlines for clean and distorted inlets.
  - Averaged over one revolution.
  - Distorted flow yields slight degradation in mass flow and pressure recovery.
One-way Coupling: Mathematics

Blade vibrations are prescribed in a selected mode ($\Phi$), frequency ($f$), and nodal diameter pattern (ND) or inter-blade phase angle ($\sigma$). The work done on the vibrating blade is calculated as follows:

$$ W = - \int_{\text{surface}} \int p d\vec{A} \cdot \frac{\partial \vec{X}}{\partial t} dt $$  

(1)

where $p$ is the aerodynamic pressure, $\vec{A}$ is the blade surface area vector, $\vec{X}$ is the displacement vector on the blade surface, and $t$ denotes time. The aerodynamic damping ratio ($\zeta$) can be approximately related to the work-per-cycle ($W$) and the average kinetic energy ($K_E$) of the blade over one cycle of vibration through the following expression:

$$ \zeta \approx - \frac{W}{8K_E} $$  

(2)
One-way Coupling: Time Marching Scheme

Calculate unsteady flow field on new mesh

Calculate new aerodynamic work acting on blade

Generate new mesh in accordance with blade position

Calculate new blade position and velocity from prescribed harmonic motion

Aerodynamic damping is calculated from the aerodynamic work quantity. Positive aerodynamic work signifies negative aerodynamic damping and indicates the possibility of flutter.
One-way Coupling: Clean Inlet, Near Op-Line

Convergence of Aerodynamic Work for All 22 Blades

\[ \sigma = 0^\circ \text{ for } 0 \text{ ND, and } \sigma = 180^\circ \text{ for } 11 \text{ ND} \]

- May require a few cycles to converge (11 ND here)
- Consistent about annulus (clean inlet)
One-way Coupling: Distorted Inlet, Near Op-Line

Convergence of Aerodynamic Work for All 22 Blades

\[ \sigma = 0^\circ \text{ for 0 ND, and } \sigma = 180^\circ \text{ for 11 ND} \]

- May require a few cycles to converge (11 ND here)
- Work is a function of azimuthal position:
  - Unique for each subset of blades within each ND pattern
  - May exhibit mixed stability/instability (0 ND here)
One-way Coupling: Aerodynamic Work Versus Azimuthal Position

\[
\begin{array}{|c|c|c|}
\hline
\sigma & \text{1 ND} & \text{2 ND} \\
\hline
\text{avg blade, clean} & -0.068\% & +0.49\% \\
\text{all blades, clean} & \text{mixed} & \text{mixed} \\
\text{avg blade, distorted} & -0.072\% & +0.09\% \\
\text{all blades, distorted} & \text{mixed} & \text{mixed} \\
\hline
\end{array}
\]
Aerodynamic damping versus nodal diameter using average-blade aerodynamic work from one-way coupled method.
Two-way Coupling: Mathematics

From the original equation of motion,

\[
[M]\{\ddot{X}\} + [C]\{\dot{X}\} + [K]\{X\} = \{F\} - \{f_s\}
\]  \hspace{1cm} (3)

where

\[
\{F\} = - \int_{surface} p \, d\tilde{A}
\]  \hspace{1cm} (4)

Pre-multiply by the mode shape \([\Phi]^T\), establish the generalized displacement coordinate \(\eta\), and normalize to unit modal mass:

\[
[\Phi]^T[M][\Phi] = 1
\]  \hspace{1cm} (5)

\[
\{X\} = [\Phi]\{\eta\}
\]  \hspace{1cm} (6)

Applying the conservative simplification of neglecting material and structural damping (i.e., assuming \(C = 0\)) yields independent second order ordinary differential equations for each mode \(i\):

\[
\ddot{\eta}_i + \omega_i^2 \eta_i = [\Phi_i]^T \{F_i - f_{s,i}\}
\]  \hspace{1cm} (7)
Two-way Coupling: “Static Modal Force”

- Static modal force: Modal force on rigid blades due to unsteady pressure loading of clean and distorted flows. One blade shown.

$$\begin{align*}
\{\Phi_i\}^T \{f_{s,i}\} &= - \int_{\text{surface}} \Phi_i^T \cdot p \, d\bar{A} \\
\end{align*}$$  \hspace{1cm} (8)
Two-way Coupling: Time Marching Scheme

Calculate unsteady flow field on new mesh

Calculate new aerodynamic forces acting on blade

Generate new mesh in accordance with blade position

Calculate new blade position and velocity from aeroelastic equation of motion

Aerodynamic damping is quantified by logarithmic-decrement analysis of blade modal displacements. **Increasing magnitudes of displacements signify negative aerodynamic damping and indicate possibility of flutter.**
Two-way Coupling: Near op-line, 0 Nodal Diameter

All 22 Blades, $\sigma = 0^\circ$

- Clean inlet
- Distorted inlet

Decreasing magnitudes of oscillation indicate flutter stability.
Damping: One-way = +1.64%; Two-way = +1.60% to +1.80%.
Clean and distorted inlets nearly-identically stable.
Two-way Coupling: Near stall, 1 ND FTW

All 22 Blades, $\sigma = 16.36^\circ$

- Clean Inlet
- Distorted Inlet

<table>
<thead>
<tr>
<th></th>
<th>One-way avg blade</th>
<th>One-way all blades</th>
<th>Two-way coupled</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clean Inlet</td>
<td>-0.068%</td>
<td>mixed</td>
<td>$\approx$ -0.038%</td>
</tr>
<tr>
<td>Distorted Inlet</td>
<td>-0.070%</td>
<td>mixed</td>
<td>$\approx$ -0.20%</td>
</tr>
</tbody>
</table>
Two-way Coupling: Near stall, 2 ND FTW

All 22 Blades, $\sigma = 32.73^\circ$

- Clean Inlet
- Distorted Inlet

<table>
<thead>
<tr>
<th>Condition</th>
<th>One-way avg blade</th>
<th>One-way all blades</th>
<th>Two-way coupled</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clean Inlet</td>
<td>+0.049%</td>
<td>mixed</td>
<td>$\approx +0.014%$</td>
</tr>
<tr>
<td>Distorted Inlet</td>
<td>$\approx +0.09%$</td>
<td>mixed</td>
<td>$\approx +0.16%$</td>
</tr>
</tbody>
</table>
Summary

- A two-way coupled flutter analysis method has been implemented in TURBO-AE.
- One-way and two-way coupled flutter analysis methods have been applied to study fan flutter in presence of inlet distortion (total pressure).
- Distortion defined as single, once-per-revolution distribution about annulus with a 4% (mean-to-peak) variation about clean inlet’s radially-varying total pressure profile.
- Fan run at part-speed with artificial mode shape and natural frequency.
Conclusions

- Distorted flow conditions consistently yield slight degradations in mass flow, pressure recovery, and flutter stability versus the clean flow conditions of identical circumferential-mean total pressure distribution.

- Flow nonuniformity and nodal diameter pattern determine each blade's aerodynamic work response. Individual blade aerodynamic work response will vary consistently about the annulus from cycle to cycle due to interplay of blade natural frequency and rotor rotational frequency.
Conclusions – Continued

- Two-way coupled method corroborated one-way coupled method’s average-blade flutter assessment when:
  - all blades showed stability about the whole annulus using one-way coupled method;
  - OR
  - “average” blade showed instability.

- For 2 ND FTW near stall:
  - One-way coupled method’s average-blade showed stability in both clean and distorted flows.
  - Two-way couple method showed stability in clean flow but instability in distorted flow.
Future Work

- Refined time-stepping, longer simulation times, refined gridding:
  - More clearly establish existence and magnitude of instabilities;
  - Interrogate higher-fidelity results to better understand fundamental aeromechanics. (incidence angle, shock position, e.g.)

- Improved fluid-structure time-coupling

- More realistic, more complete inlet distortion definition (swirl, e.g.)

- Physical experiment