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INLET GUIDE VANE FAILURE: AERO-MECHANICAL and SYSTEM CONTROL INTERACTION EFFECT

Loc Q. Duong
Charlene X. Hu
Nagamany Thayalakhandan

Hamilton Sundstrand Power Systems
San Diego, CA 92186

ABSTRACT

The APU, a gas turbine engine is designed to provide the aircraft with electrical power and pneumatic air both on the ground and in-flight conditions. The variable inlet guide vane (VIGV) system is used to regulate the air flow to the load compressor. The vane motions are controlled by an actuator and associated linkage. Common failure mechanisms of the VIGV such as cracking, corrosion of vanes, have been reported. This paper discusses a particular mode of failure which involves the aero-mechanical and control feedback interaction. The failure phenomenon is characterized by sector and ring gear tooth non-uniform wear, jamming of sector gears, actuator resonance, actuator fluid contamination and subsequent engine shutdown. Solution to failure mode is also discussed.

INTRODUCTION

In a typical gas turbine engine operation, ambient air entering the engine through an intake is pressurized by a compressor for delivery to the combustor. Combustion of the aviation fuel with compressed air in the combustor yields high temperature, high pressure gas. This gas enters the turbine section where fluid energy is extracted and converted into mechanical work. The APU, a gas turbine engine is designed to provide the aircraft with electrical power and pneumatic air both on the ground and in-flight conditions. To satisfy these requirements, the APU commonly consists of two centrifugal compressors, the gas generator and the load compressors, as shown in Figure 1. The load compressor, typically a single stage centrifugal compressor, driven directly by the power section either though one spool or two spools shaft system is used to deliver required pneumatic air to the aircraft. Air is drawn into both compressors through a common inlet plenum. The variable inlet guide vane assembly is used to regulate air flow to the load compressor. In general, the VIGV system consists of a number of vanes supported by bushing distributed circumferentially on the inlet housing of the load compressor. The vane shaft is connected to a sector gear which in turn meshes with a ring gear. The gear mesh can be of external or internal type. The vane and gear motions are controlled by an actuator and associated planar linkage, which through servo-control system provides the mechanical force to close or open the VIGVs. There is very little information in open literature regarding the IGV failure modes. Reference [1] described some common failure mechanisms of the VIGV such as vane cracking, vane corrosion, fatigue and wear of bushing supporting vane rotation. One particular VIGV system failure mode is presented in this paper. The failure mechanism is of instable nature. It is a combination of the aero-mechanical interaction coupled with the control feedback loop. The failure phenomenon is characterized by a number of phenomena such as sector and ring gear tooth non-uniform wear, sector gear jammed, actuator vibration, actuator operating fluid line contamination due to actuator sealing system deterioration under unsteady feedback control action and possible engine shutdown. This paper begins with the functional description of the IGV system followed by failure

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characteristics, failure mechanism, and ends with a short discussion of some potential solutions.

LIST OF ACRONYMS

APUC	Auxiliary power unit control
ECS	Environmental control system
ECU	Electrical control unit
FCU	Fuel control unit
IGV	Inlet guide vane
IGVA	Inlet guide vane actuator
LVDT	Linear variable differential transformer
VIGV	Variable inlet guide vane

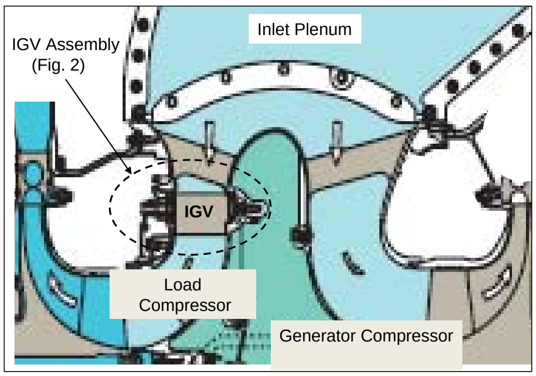

Figure 1: Typical APU Dual-compressor Module

SYSTEM DESCRIPTION

Figure 2 illustrates a typical VIGV assembly with external gear mesh. The IGV assembly includes three modules, the IGV mechanism, the control rod and the actuator. The inlet guide vanes are part of the IGV mechanism. Each inlet guide vane is connected to a sector gear which in turns meshes with a common ring gear. The control rod is placed between the ring gear and the actuator. By means of this control rod the rotational motion is converted into translational motion. The linkage motion is controlled by an actuator. The actuator consists of a piston, called actuator rod, whose position is controlled by fuel pressure metered by an electrical signal from the electronic control unit (ECU). The constant fuel pressure delivered to the IGVA is controlled by the fuel control unit (FCU) valve system. The actuator provides the mechanical force to close or to open the VIGVs. Mechanical seals are used for actuator rod sealing. The IGV position is sensed by a LVDT connected to the actuator rod. The IGV actuator rod moves at a rate and in the direction determined by the auxiliary power unit control (APUC). The APUC positions the vane in response to the demand from the aircraft. A feedback control loop is used to correct the IGV position. The IGV actuator rod stops moving when the error between the ECS demand signal and the IGV position signal is zero. Figure 3 depicts an IGV mechanism with internal gear meshing system. Figure 11 shows a pictorial external sector and ring gear mesh design at two extreme conditions, fully close and fully open corresponding to the fully extension and fully contraction of the control rod.

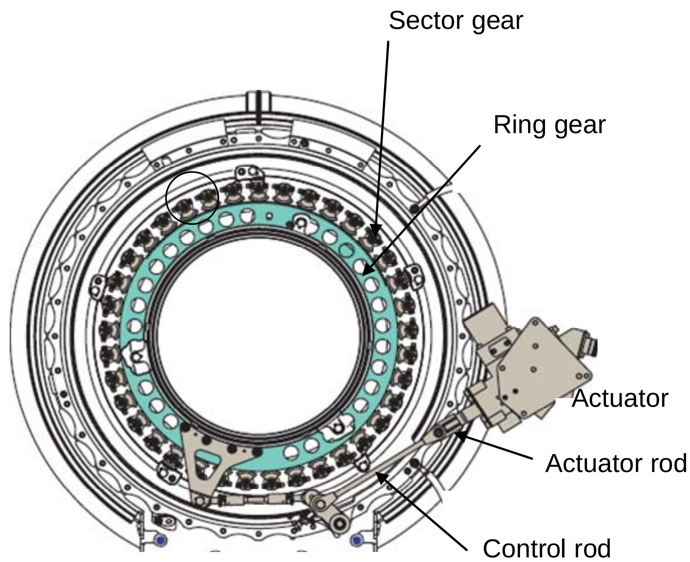

Figure 2: IGV System
(External Gear Mesh)

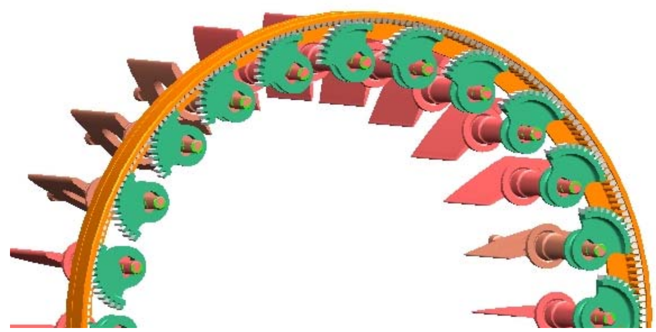

Figure 3: IGV Assembly
(Internal Gear Mesh)

FAILURE CHARACTERISTICS

Depending on the total engine running time, the failure of the IGV system bears more or less the following characteristics with tooth wear being the most prominent one:

a) Wear
- Sector and ring gear tooth wear in a non-uniform distribution along the ring gear circumference
- IGV shaft support bushing wear
- Control rod joints wear
- Actuator mechanical seal system wear

b) High cycle fatigue failure as subjected to resonance of IGV actuator components

c) Jamming and failure of sector gear

d) Fuel contamination

e) Generation of engine fault codes leads to engine shutdown, such as fuel filter clogging and IGV mechanical failure

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Since tooth wear is the most dominant symptom, the failure analysis begins with the investigation on the tooth wear characteristics.

Tooth Non-uniform Wear

Figures 4 and 5 illustrate the sector gear tooth wear and its corresponding ring gear at about nine o'clock looking downstream from the engine front (Figure 8). Tooth wear can also be observed at other locations but with reduced wear levels.

The tooth wear has the following characteristics:

- No original metallurgical abnormalities were found.
- Hardness measurements were taken and the results indicated compliance with requirements.
- The micro-structure of both gears is in compliance with the drawing specifications (Figure 6).
- Spectrographic analysis indicated that the materials of the gears were consistent with the compositional requirements (Figure 7).
- Gear measurements indicated all errors are within tolerance (involute profile, spacing, lead, etc…)

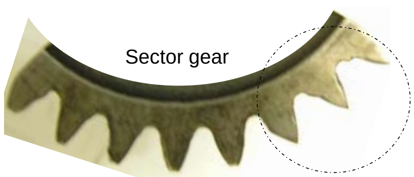

Figure 4: Sector Gear Tooth Wear

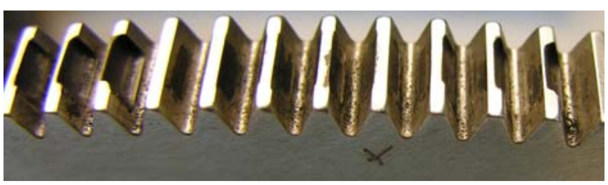

Figure 5: Ring gear Tooth Wear

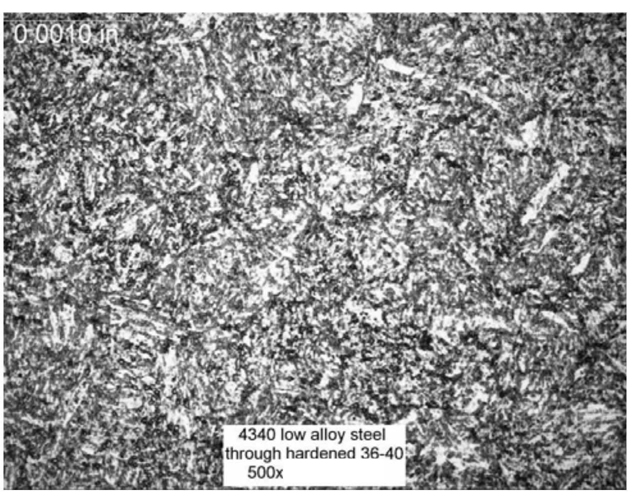

Figure 6: Ring Gear Tooth Micro-Structures (AMS4340)

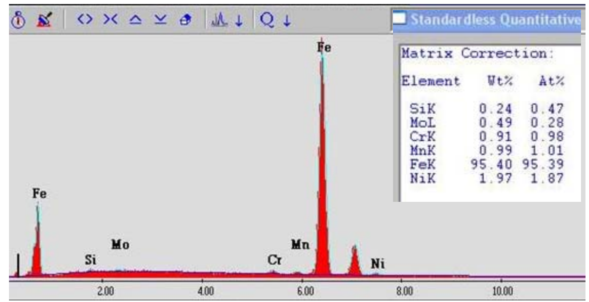

Figure 7: Gear Tooth Spectrograph

FAILURE MECHANISM

1) Aeromechanical Interaction

The full CFD transient analysis is beyond the scope of this paper. Only the resilient points are presented.

Ambient air enters the inlet duct through the inlet plenum before reaching the IGVs as shown in Figure 8. The flow field in the plenum is characterized by Figure 9. The flow field at the plenum core is illustrated in Figure 10.

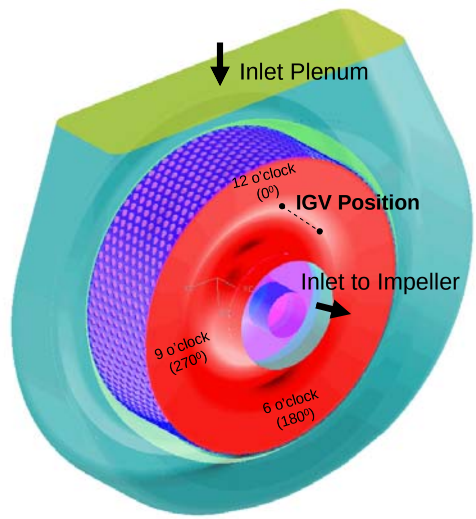

Figure 8: APU Plenum

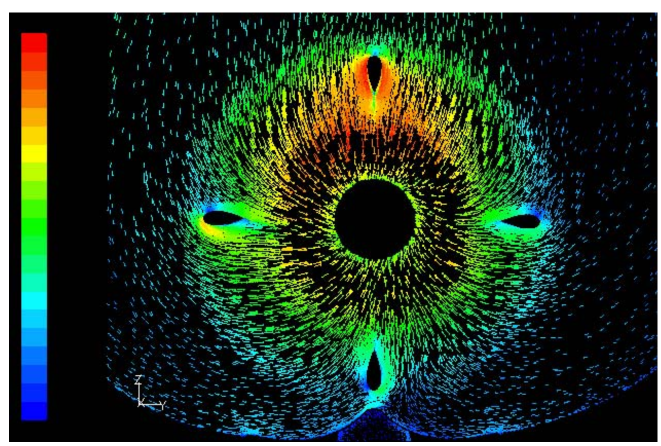

Figure 9: Flow Field in the Plenum

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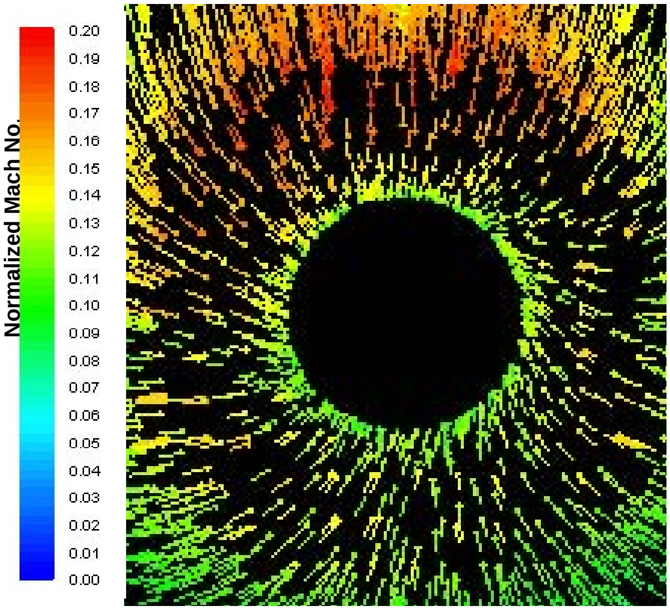


Figure 10: Flow Field at the Plenum Core

By varying the position of the IGVs, the air flow rate to the load compressor is regulated. From the plenum inlet to the impeller entrance, the flow field can be divided into two distinct zones:

(a) Radial inflow at the inlet to the engine &

(b) Axial flow into the impeller face

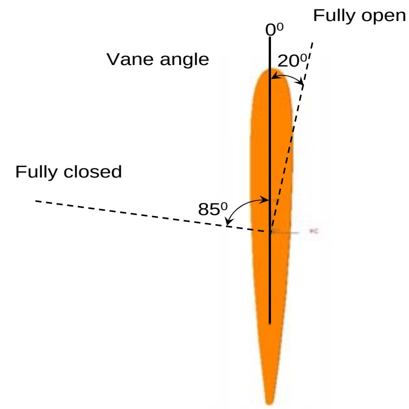
Vortices are generated in both flow fields, namely vortex whistle and vortex shedding.

a) Vortex whistle

IGVs impart a tangential component to the radial inlet flow, as a function of IGV position. Hence downstream of the IGVs the flow field consists of both radial and tangential components. Flow circulation is generated due to the presence of this tangential flow component. The strongest circulation occurs when the IGVs position is about half close. The circulation is stretched as it moves towards the impeller entrance. Since the gas flow path cross section is reduced towards the impeller entrance the vortex intensity increases due to conservation of momentum. This could lead to the generation of an undesirable audible tone noise, vortex whistle. Whether vortex whistle is generated or not the failure of the IGV system is independent of this phenomenon.

b) Vortex shedding

In APU application, the inlet guide vane profile usually is of low or zero cambered profile. Figure 11a shows an IGV with zero camber profile. The setting angle is typically ranged from -20 degrees (fully open) to +85 degrees (fully closed) as illustrated in Figures 11a and 11b. At full power, the maximum flow to the impeller corresponds to the vane setting of 0 degree. At this angle setting, the vanes are radially aligned. Without the inlet duct and plenum structure, air is drawn radially into the intake with incidence angle of zero degree. With no lift resulting from a typical vane of zero cambered profile, the net torque acting on the ring gear is virtually zero. This would correspond to a zero actuator force to maintain equilibrium. With the presence of the duct and the plenum system, the flow incidence angle varies from vane to vane, as can be visualized in Figures 9 and 10. With an inlet plenum opening at twelve o'clock as shown in Figure 8, the IGVs experience high incidence angle are located at 90, 180, and 270 degrees. As incidence angle differs from zero, vane force is developed. At larger incidence angles such as those mentioned above, boundary layer separation would occur on the suction surface of the vane leading to vortex shedding. Figures 12a and 12b illustrate how separated flow changes from laminar to turbulent flow. As a consequence the vane force fluctuates at the vortex shedding frequency. This frequency was measured though engine test.



a) Vane with Zero Camber profile

ACTUATOR FULLY EXTENDED

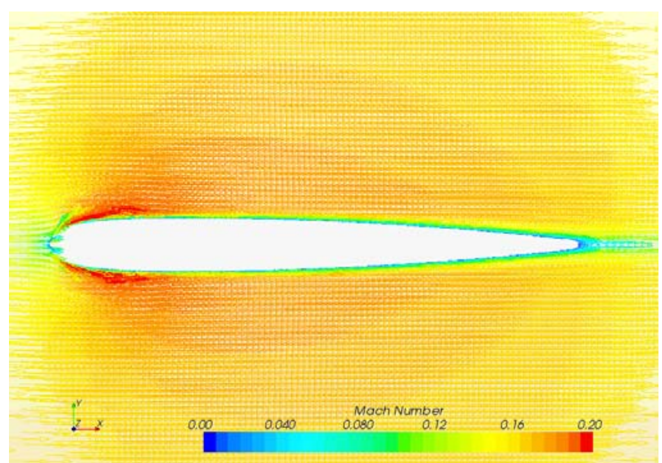
IGV CLOSED

ACTUATOR FULLY RETRACTED

IGV OPEN

b) Setting Angle

Figure 11: Inlet GuideVane



a) Incidence Angle = 0°

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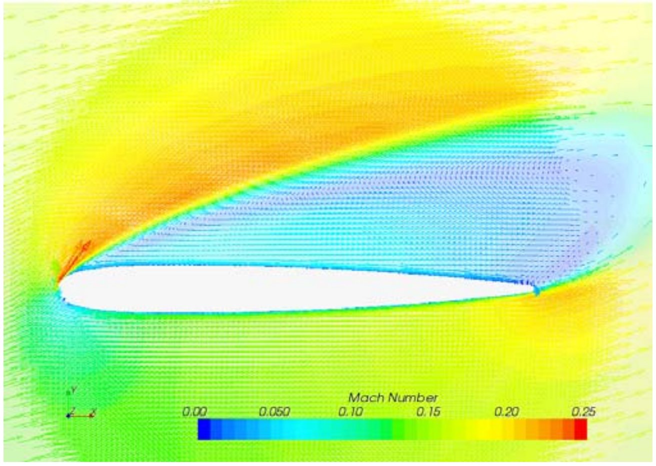

b) Incidence Angle=15°

Figure 12: IGV Vortex Shedding

2) **Linkage Dynamics**

Assuming the line of action of the teeth in mesh remains at all times on the common tangent to the sector and ring gear base circles, the dynamics of the sector and ring gears can be represented by the general equation:

$$M x'' + Cx' + Kx = F + F_d e^{i\Omega t} , \qquad (1)$$

where x is the mesh displacement, K is the average mesh stiffness, M is the gear system mass, C is the gear system damping, dot denotes derivative with respect to time, F is the gear mesh force, F_d represents the mesh disturbance force, assuming to be sinusoidal with the same frequency as that of the vortex shedding, Ω. $F_d \neq 0$ for t>0.

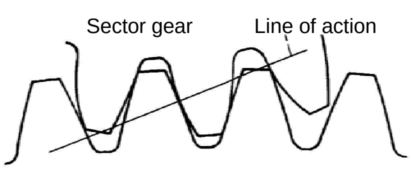

Figure 13: Gear Tooth Mesh

In response to the aircraft demand for pneumatic air, The APUC sends command to the FCU to provide the fuel pressure to control the actuator rod to a predetermined length corresponding to a vane setting angle. As the vane reaches the position, the gear mesh is in a state of equilibrium. Consider at time t = 0, the torque generated by the actuator rod to rotate the ring gear is balanced by the equivalent steady state aerodynamic torque acting on the vane (F_{net}=0). As vortex shedding is generated, the IGV is subjected to a disturbance torque oscillating at the vortex shedding frequency. An instantaneous change in IGV torque translates into the motion of the gear set. The rotation of the vane out of its equilibrium position is translated into axial motion through the control rod and is sensed by the actuator LVDT. An error signal is sent to the APUC.

3) **IGV Actuator and IGV Dynamics**

3.1) IGV Actuator Dynamics

The APUC processes the error signal and an updated command is sent to the FCU to generate the required fuel pressure to correct the angle setting error. However, a time delay exists in the feedback control loop which translates into a phase lag in the response. In other words, the mechanical force (F) provided by the IGVA to correct the disturbed motion is lagging the excitation source (F_d). Equation (1) becomes:

$$Mx'' + Cx' + Kx = Fe^{i(\Omega t + \Psi)} + F_d e^{i\Omega t} , \qquad (2)$$

where Ψ denotes phase lag between disturbance and response.

This implies system instability. As a consequence the sliding back and forth of the pair of teeth under mesh at the vortex shedding frequency results in tooth wear. Figure 14 illustrates the tooth wear condition at the early stage. As wear proceeds, phase lag increases due to the increase in backlash. This further increases the level of instability.

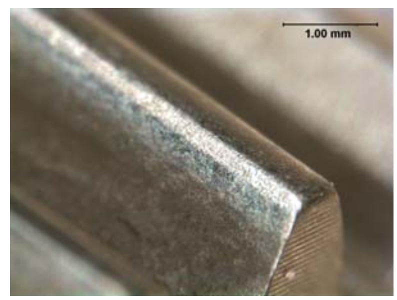

Figure 14: Ring Gear Tooth Wear at Early Stage

In addition, the actuator consists of mechanical components controlling the fuel flow and pressure. If the natural frequencies of these components coincide with the induced aero-excitation frequency, failure due to resonance would entail. For instance, if the actuator servo-valve natural frequency is in the vicinity of the excitation frequency, it would fail by fatigue. The authors have experienced this failure mode of the actuator by itself.

Extensive analysis of the IGVA control system and its associated electronics were conducted, but the results were not published outside Hamilton Sundstrand. Overall, they are acceptable. Experimentally, the close loop response of the IGV actuator from the command input to the output of the LVDT is measured from laboratory test. No deviation from design specification was observed.

3.2) IGV Dynamics

The fundamental mode shapes, bending and torsional, of the IGV are shown in Figure 15. Typically with metallic IGV these fundamental natural frequencies are well above the vortex shedding frequency. With accelerometers mounted on the control-rod and ring gear, IGV vortex shedding frequency was measured. Commonly, for this type of low cambered

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profile, it is in the range between 100 -200Hz, depending upon the flow mass. Figure 16 illustrates the frequency spectrum on the accelerometer mounted in the direction parallel to the control rod axis. In summary, the vanes are not in resonance under unsteady aero-loads at vortex shedding frequency of close to 160 Hertz.

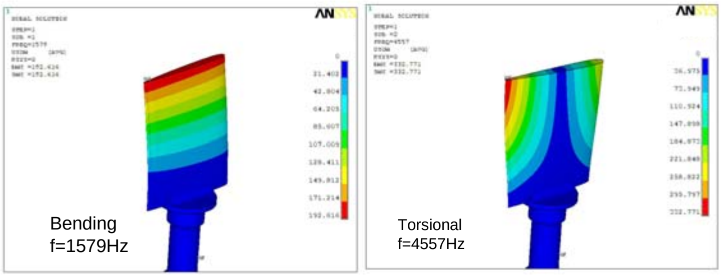

Figure 15: Fundamental Mode Shapes

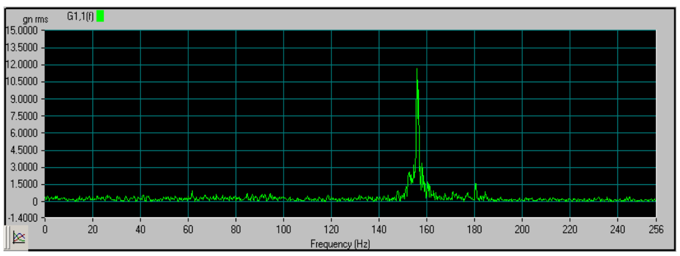

Figure 16: Frequency Spectrum
(Accelerometer mounted on control rod)

4) **Fuel Contamination**

Fuel contamination and seal wear are not the root cause of the IGV failure, but as it develops, it accelerates the failure rate. Figure 17 shows a schematic diagram of the actuator which uses fuel as the working fluid. Pressurized fuel from the FCU is regulated by a servo-valve before entering the actuator. The excess fuel is returned to the fuel system. O-ring is typically used on the actuator rod to prevent fuel leakage. The dithering of the actuator rod at the vortex shedding frequency wears off the seals. Through drainage the seal debris travels back to the FCU and contaminates the engine fuel system. This activates the engine fault codes leading to the eventual shutdown of the engine. Figure 18 illustrates the seal wear material marks on the actuator rod as a consequence of dithering.

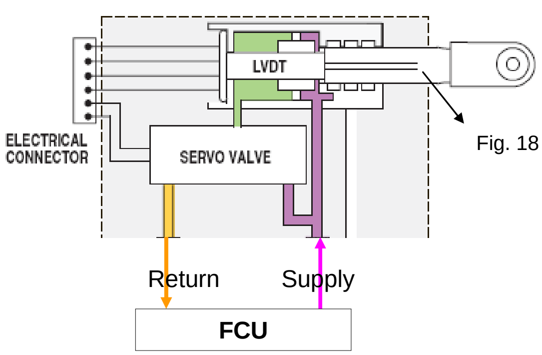

Figure 17: Fuel Contamination Due to Seal Deterioration Under Dithering Effect

Figure 18: Seal Wear

DISCUSSION

IGV vortex shedding frequency was measured. Strong level of vibration occurred at the IGV positions where inlet flow was at high incidence angles. As the incidence angle increases, flow separates on the suction surface and larges wakes are formed at the trailing edge of the IGVs. Since the flow field is restricted by the plenum, IGV vortex shedding is generated. The intensity of the vortex is amplified as the flow approaches the impeller leading edge. This implies that the ideal option is to eliminate the disturbance at its source. The source can be eliminated by individually tailoring the IGV leading edge metal angles around the circumference to minimize the incidence angle. In practical terms, this option is less desirable since it increases the number of component parts, along with a tight control in manufacturing tolerance. It also requires control in assembly to prevent faulty installation.

The second option is of mechanical nature. Tooth wear is a consequence of oscillatory sliding of the pair of teeth in mesh at very small amplitude under load. This implies that in order to prevent tooth wear, it is necessary to apply spring preload, either of torsional or translational type (Ref. 2). In general, the preload spring increases the system dynamic stiffness or impedance to resist disturbances. The location of the torsional spring is illustrated in Figure 19.

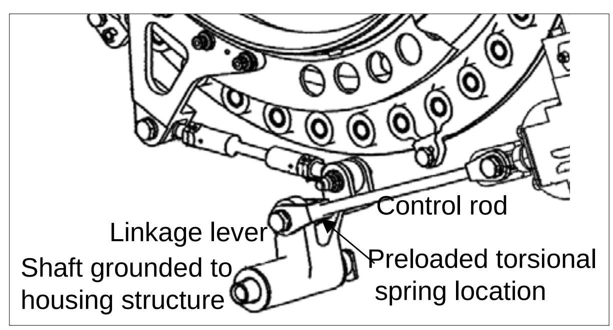

Figure 19: Torsional Spring Preload (Ref. 2)

Some other potential alternatives are:
- Reducing LVDT gain
- Increasing actuator dampening
- Shaping inlet plenum contour
- Asymmetric tooth profile
- Different linkage assemblies

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Reducing LVDT gain and increasing actuator dampening would reduce the effectiveness of a quick response to overcome sudden system changes. Shaping the inlet plenum contour is limited by manufacturing complexity, the increased risk of localized ice formation. Asymmetric tooth profile improves tooth bending strength but it cannot prevent oscillatory sliding. Different linkage assemblies would require modifications to the existing interfaces.

In essence, the selected choice is a compromise of different factors such as cost, complexity, durability, producibility, weight, and especially no change to the existing design configuration. Among these options, the spring preload emerges as the most preferable one.

CONCLUSIONS

The failure mechanism of the IGV assembly is of instable nature. It involves the aero-mechanical interaction coupled with the delay effect of the control feedback loop.

1) The inlet plenum induces flow field distortion leading to vortex shedding due to large incidence angle on certain IGVs, resulting in ring gear torque oscillating at the vortex shedding frequency.
2) From IGV fully open to fully close, both gear tooth flanks are active. But wear is only strongly associated on one side of the tooth flank corresponding to the setting angle resulting in high incidence flow angle in which boundary layer separation occurs with vortex shedding.
3) A phase lag exits between the excitation source and the control feedback response. Reducing tooth backlash would improve phase lag. However, it is constrained by mesh interference under cold operational conditions.
4) The IGV is not under resonance, since its natural frequencies are much higher than the vortex shedding frequency.
5) Tooth wear results from the oscillatory sliding of the pair of teeth under mesh at the vortex shedding frequency.
6) One option to prevent tooth wear is to increase the system dynamic stiffness or impedance by preloading the gearing system.

ACKNOWLEDGEMENTS

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REFERENCES

1) R.L. McAlpin, P.T. Talley, H.L. Bernstein, “Failure Analysis of Inlet Guide Vanes”, Transactions of the ASME, Journal of Engineering, vol. 125(1), January 2003.
2) Patent docket no. PA-10891-US; 67036-256.

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