Cyclic Pressure Test of Vapour Core Pump of Reheat Fuel Control System Of an Aero-Engine

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Abstract

Airborne accessories and systems are required to successfully undergo a number of qualification tests as per airworthiness certification procedures before these can be fitted on the platform (aircraft/helicopter). Qualification tests and their severity level are governed by the mission /usage criticality, safety and their operating flight envelope. Cyclic pressure test is one of the very important test performed during qualification for evaluating the fatigue life of pressure vessels, which, in turn, is helpful in arriving at the useful life of the accessories/system.

For evaluating the design of the vapour core pump for cyclic pressure test, there are three cyclic pressure levels i.e. low pressure, intermediate pressure and high pressure are to be applied. But the design of the pump is such that three physically distinct zone cannot be created. Hence by an innovative approach i.e. "Equivalent Pressure" is calculated and applied to simulate the load arising on the pumps due to three cyclic pressure levels. For calculating the equivalent pressure, the whole pumps is theoretically divided in three pressure zone i.e. low pressure zone , intermediate pressure zone and high pressure zone. The addition of forces acting on three pressure zones gives the total force acting on pump casing. Equivalent Pressure is obtained by the total force divided by total area.

For creating the Equivalent Pressure in pump during testing the orifice size to be fitted at outlet of pump is calculated with the help of flow number at inlet and outlet of the pump.

Keywords: Cyclic Pressure, Equivalent Pressure, Vapour Core Pump and Flow Number

1. Introduction

Fuel system LRUs are exposed to pressure pulsation during service life. Cyclic pressure test is carried out during qualification to emulate these pressure pulsations seen by the LRUs during service life (Cyclic Pressure test qualifies the product design). Added benefit of cyclic pressure testing is to determine weak link in the design.

Crack initiation and propagation [1] are two important factors towards testing for fatigue. Crack initiation is not expected to take place before the end of useful life. Inherently, Fuel LRUs do have multiple stress raisers. It is the designer's expertise and experience which governs the importance of a given stress raiser and design is concluded accordingly.

To arrive at appropriate cyclic pressure test plan, cycle rate is decided based on usage of LRU and duration of cyclic pressure test is decided from S-N curve of the material [2].

It is rather simpler to carry out cyclic pressure test on bodies of LRU having constant pressure along the line of flow like cylindrical bodies. But it becomes tedious when a body with varying geometry is to undergo cyclic pressure test as pressure is varying along the flow line. For example, in case of centrifugal pump, pressure will follow parabolic variations along the impeller blade due to its geometry. An approach for carrying out cyclic pressure test on vapour core pump is being explained below.

2. Vapour Core Pump

Vapour Core Pump is one of the major sub-assemblies in a Reheat Fuel Control system. Reheat Fuel Control System[3] supplies fuel for augmenting the basic thrust of the engine during acceleration and take-off. This is achieved by providing metered fuel flow through reheat system in response to electrical signals from Digital Engine Control Unit (DECU) of the engine. Fuel flow from Filter passes through a plug in hole type flow meter and reaches Inlet Throttle Valve of the pump. Operation of Inlet Throttle Valve is, in turn, controlled by the DECU to set the desired pump outlet flow. Outlet of pump goes to the engine manifolds via a Transient Pressure Regulator (TPR). When Reheat is off, Inlet Throttle Valve [4] allows

cooling flow through a hole in it and when reheat is selected it allows full flow through the pump.
There are three pressure zones in a Vapour Core Pump i.e.

- Low pressure zone at the eye of the pump.
- Variable pressure zone across the impeller.
- High pressure zone in the volute.

Typical pressure variation across the pump [5] is shown in Fig 1.

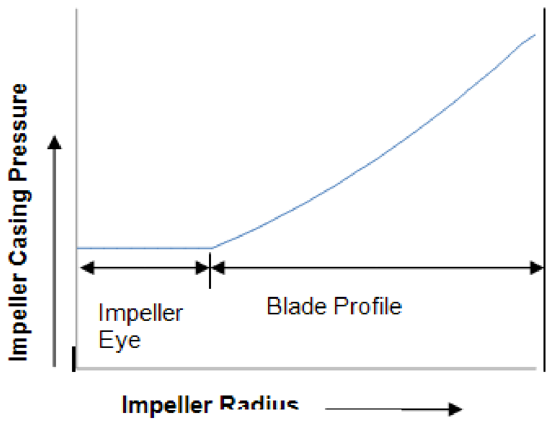

Figure1 Pressure Vs Radius

3. Cyclic Pressure Level

Cyclic Pressure level for LRUs of fuel systems for military aircraft, is determined by using the following expression in line with British Standard IAE 2000 [6].

Cyclic pressure= $P_W \times F_{MF} x F_F$

Where P_W = Normal working pressure
F_{MF} = Fatigue multiplying factor
F_F = Fatigue cycling temperature factor [7]

4. Approach for Cyclic Pressure Test

One way of doing the cyclic pressure test on the pump is to divide the pump in three zones i.e. low, variable and high pressure zones and apply the respective pressure level on each zone simultaneously. In present case, geometrical design of the pump casing is such that it is not feasible to make physically distinctive three pressure zones in the pump. Hence this method can not be used for doing the test.

Alternative to this could be an approach to apply equivalent pressure to simulate the force arising on casing due to three pressure zones. This approach is practically feasible. The same is explained below.

4.1 Parameters

Parameters which are utilized in cyclic pressure test of the Vapour Core Pump are as follows:

- Inlet (P_i) and outlet (P_o) pressures are provided by designer.
- Geometrical dimensions of the impeller.
- Cross sectional area of volute.
- Type of impeller used.

Last three parameters are available from design of the pump.

4.2 Methodology for Calculating the Equivalent Pressure

As stated above, it is not feasible to apply different pressure level in three pressure zones of the pump. Hence innovative approach has been evolved to calculate the total load on the pump casing and based on total load an *'Equivalent Pressure'* is determined. Term 'Equivalent Pressure' is defined as the pressure level that would exert the same thrust on the impeller casing as would be experienced when the pump is running. Total force and equivalent force are calculated as follows.

4.2.1 Force due to Low Pressure Zone

The force exerted by low pressure zone is calculated by multiplying pump eye area and inlet pressure.

Say, $F_1 = P_i \text{ x } a_1$

'$P_{i,}$ inlet pressure and 'a_1' cross section area of eye of impeller.

4.2.2 Force due to Variable Pressure Zone

The force exerted by variable pressure zone of impeller is calculated by following approach.
Total head developed by a centrifugal pump [8] is expressed by following equation.

$$H = \frac{V2^2 - V1^2}{2g} + \frac{(w.r2)^2 - (w.r1)^2}{2g} + \frac{Vr1^2 - Vr2^2}{2g}$$

Above equation indicates that pressure variation across the impeller follows square law. Therefore, a parabolic equation in terms of pressure and radius is expressed as follows.

$$P = Ar^2 + B \quad .... \quad (1)$$

Where P is pressure and r is radius of impeller.
Following steps described the use of equation (1) for calculation of force arising on casing due to variable pressure zone.

i) Value of constants A & B of equation (1) is calculated by substituting the following two known boundary conditions from pump specification.

- Inlet pressure at inlet radius of impeller.
- Outlet pressure at outlet radius of impeller.

ii) By substituting the value of A & B in equation (1), a general equation in terms of P & r is achieved. This equation is used for calculating pressure at any point in variable pressure zone.

iii) Divide the impeller in concentric rings having a thickness of δr starting from radius r, r+δr, r+2δr, r+3δr …….r+nδr. where r is the radius of eye of impeller. Division of impeller in concentric circle is shown in figure-2.

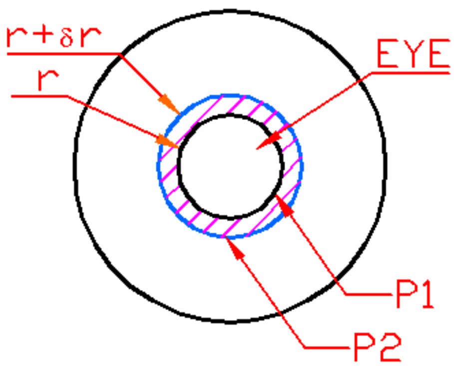

Figure 2 Impeller cross section

iv) By application of equation achieved in point (ii), pressure level P_1, P_2, P_3…P_n at radius r, r+δr, r+2δr r+3δr …….r+nδr respectively are computed.

v) Subsequent to above, the mean pressure i.e $(P_1+P_2)/2$, $(P_2+P_3)/2$ …..and $(P_{n-1}+P_n)/2$ acting on rings of thickness {(r+δr)-r}, {(r+2δr)-(r+δr)}…. .{(r+(n-1)δr)-(r+nδr)} respectively are determined.

vi) Having computed the mean Pressure, Force f1, f2, f3…..fn exerted by each rings are calculated by multiplying average pressure and area of respective ring i.e.$\{(P_1+P_2)/2\}X[\pi\{(r+\delta r)^2-(r)^2\}]$, $\{(P2+P3)/2\}X[\pi\{(r+2\delta r)^2-(r+\delta r)^2\}]$,….. $[\{(Pn-1+Pn)/2\}X[\pi\{(r+n\delta r)^2-(r+(n-1)\delta r)^2\}]$.

vii) Adding the force exerted by each ring gives the total variable force acting on the pump. Hence total variable force
F2 = f1+f2+f3 ….fn.

4.2.3 Force due to High Pressure Zone

Force exerted by high pressure zones (volute) is calculated by multiply the volute area and outlet pressure.

Say, F3 = Po × a2

Where, 'Po' outlet pressure and 'a_2' cross sectional area of volute at the outlet of volute.

4.2.4 Total Force due to all three Zones

Sum of the three forces computed in the preceding points gives the Total force (F) acting on the pump casing i.e.

F= F1 +F2 +F3

4.2.5 Calculation of Equivalent Pressure

The total force divided by total area give the equivalent pressure as below:

P= Total Force (F)/Total Area (A)

Where 'A' is the area from centre of the impeller to outer diameter of volute.
This is the pressure which is required to be developed, inside the pump during testing.

5. Methodology for applying Equivalent Pressure during Cyclic Pressure Test

Vapour Core pump is attached with Reheat Control System during cyclic pressure test. Therefore pressure at inlet of pump is also experienced by other sub-assemblies of the Reheat Fuel Control System. Hence magnitude of inlet pressure at the pump is not disturbed.

During cyclic pressure test Inlet Throttle Valve will remain closed and fuel in the pump is coming through a cooling hole provided in inlet Throttle Valve (ITV). Thus orifice dimension at inlet of the pump is known. Orifice dimension at outlet of the pump is required to be calculated to set the required Equivalent Pressure during testing.

5.1 Orifice Design for Outlet Port

The methodology explained below is required to find the dimension of orifice at outlet port to achieve the desired Equivalent Pressure in the pump. Path of fuel flow through Vapour Core Pump is analogous to flow through a pipe of varying cross section. The fuel flow through the pump is represented by line diagram in figure-3.

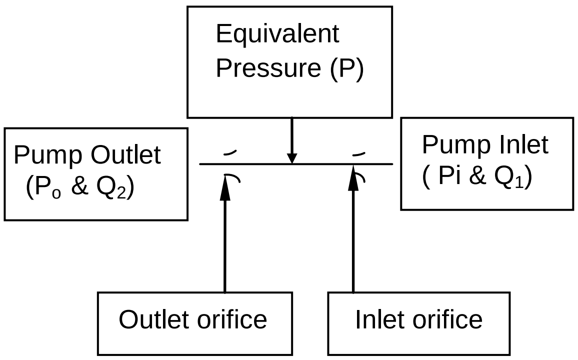

Figure-3 Representation of Fuel Flow

As per Continuity Equation [9] fuel flow between inlet and outlet orifice of the pump shown in figure-3, is expressed by following equation.

$$Q_1 \ = Q_2 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots. \ (2)$$

Q_1: Flow at inlet orifice
Q2: Flow at outlet orifice.
Flow through an opening [10] is also described by following equation.

Flow (Q) = Flow Number (FN) X square root of pressure drop. Hence from Fig 3.

$$Q_1 \ = \ FN_1 \times (P - P_i)^{1/2} \ldots\ldots\ldots (3)$$

$$Q_2 = FN_2 \times (P_o - P)^{1/2} \ldots\ldots\ldots. \ (4)$$

Where FN_1 and FN_2 are flow number of inlet and outlet orifice.
In equation (3) & (4) FN_1, P, Pi and P_0 are known variables and FN_2 is only unknown variable. From Eqn (3) & (4), value of FN_2 is calculated as below:

$$FN_2 \times (P_o - P)^{1/2} = FN_1 \times (P - P_i)^{1/2}$$

$$FN_2 = \frac{FN_1 \times (P - P_i)^{1/2}}{(P_o - P)^{1/2}} \ldots\ldots\ldots. (5)$$

Flow Number at outlet is also defined as follows

$$FN_2 = \mathrm{k} \times \ Area\ of\ Orifice \ \ldots\ldots\ldots\ldots\ldots (6)$$

Where k is constant and depends on geometry of hole and fluid properties. For circular orifice.

$$FN_2 = \ \mathrm{k} \times \frac{\pi}{4} \times D^2 \ldots\ldots\ldots\ldots\ldots\ldots\ldots. (7)$$

Substituting the value of FN_2 from equation (5) to equation(7) and arranging the terms following equation is achieved for determining the diameter of orifice at outlet port.

$$D = \left(\frac{4 \times FN_1 \times (P - P_i)^{1/2}}{\mathrm{k} \times \pi \times (P_o - P)^{1/2}} \right)^{1/2} \quad \ldots. (8)$$

Orifice dimension at outlet port is achieved by application of equation (8).
Orifice of this diameter is placed at the outlet of pump to achieve the required Equivalent Pressure for cyclic pressure test.

6. Conclusion

It is not possible to simultaneously apply the low pressure, variable pressure and high pressure in the pump for carrying the cyclic pressure test. By the methodology explained in this paper an equivalent pressure is calculated and applied to simulate force arising on the pump casing due to low pressure, variable pressure and high pressure zone. This approach has been successfully used for carrying out the cyclic pressure test on Vapour Core pump of an Aero-engine in India.

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