MODELLING AND SIMULATION OF TWIN ENGINE FIGHTER AIRCRAFT REFUELLING SYSTEM AND SEQUENCE OPTIMISATION

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Abstract: Aircraft fuel system is one of the largest and complex fluid system in any aircraft, so the aircraft fuel system needs special attention in its design and modelling with precise control over the system. In the subsystem of aircraft fuel system lies the aircraft refuelling system. This paper aims for the appropriate model for the aircraft refuelling system with the proper sequence of filling of aircraft in order to minimise the centre of gravity variation due to incoming fuel in an aircraft. Before modelling of aircraft refuelling system the volumetric design and shape for the aircraft fuel tanks is finalised. The components used in the aircraft refuelling system and their parametric information are also mentioned in this paper. The software used for the component modelling and for complete system design is LMS AMESIM.
This paper aims in finalizing the complete model for aircraft refuelling system after carrying out number of iterations. This involves sequence optimization by finalizing the sequence of filling of aircraft fuel tanks. Simultaneously among these iterations the best model will be chosen based on the minimum variation of the centre of gravity due to addition of fuel inside the fuel tank.

Index Terms: Aircraft fuel system, LMS AMESIM, aircraft fuel tank, sequence optimization, centre of gravity.

I. INTRODUCTION

An aircraft fuel system enables fuel to be loaded, stored, managed and delivered to the propulsion system that is to the engine of an aircraft. The purpose of the fuel system is to deliver the correct amount of clean fuel from the fuel tanks to the engines with an adequate positive reliable pressure and flow rates through all phases of flights [1]. Phases of flights indicates aircraft during take-off, cruising and while landing of aircraft. The fighter aircraft is capable of carrying out sudden changes such violent manoeuvres, sudden acceleration and deceleration. There are wide ranges of aircraft fuel systems, in other words Fuel systems differ greatly from aircraft to aircraft due to the relative size and complexity of the aircraft in which they are installed.

A fuel system generally consists of fuel tanks, fuel pipelines and other units which are responsible for transfer of fuel and are installed in the fuel tanks. The fuel can be stored in fuselage section as well as wing for the purpose of achieving space efficiency. Thus the fuel will be stored in an aircraft wherever it is possible and at the same time we need to make sure that the changes in the aircraft's centre of gravity should be as minimum as possible.

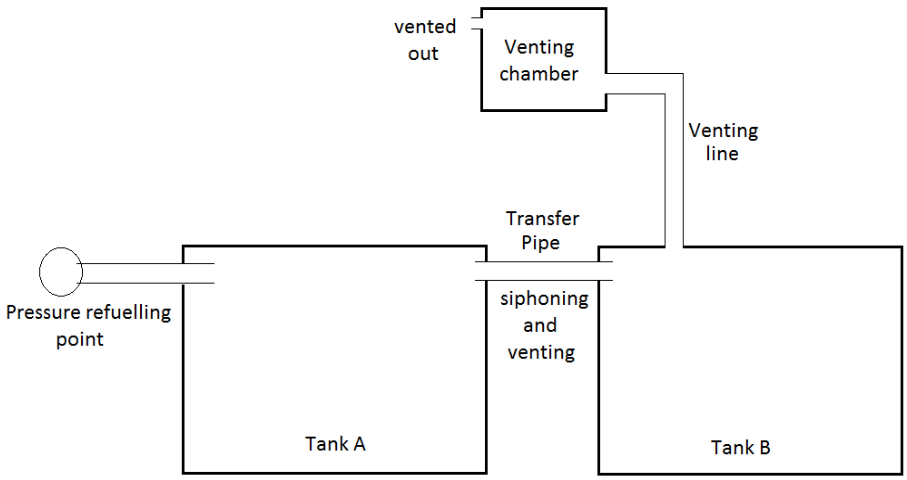

Fig-1: Basic refuelling system.

The figure shows general refuelling system in which the refuelling browser is attached to the single point pressure refuelling point. Single point pressure refuelling is a system in which the entire aircraft is refuelled through one point and it is advantageous rather than filling individual tanks. In the given figure an example for basic refuelling of two tanks is considered which shows filling of tank A followed by tank B and the transfer pipe in between them responsible for venting and siphoning. At first when the tank A is getting filled the air present inside has to be escaped outside the tank and is vented out via transfer pipe and thus filling of tank A is completed and then transfer pipe transfers fuel from tank A to tank B is transferred, meanwhile the venting chamber located above the tanks collects the vented air and then releases into the atmosphere. In order to have lesser time for filling it is requirement for high refuelling flow rates. However there is a risk of high pressure in fuel tanks in case of overshoot. Venting system is the one which ensures the limiting pressure in case of this refuelling overshoot.

There are two types of pressure refuelling methods:-

- Basic variant
- Full variant

In basic variant of refuelling service Tank and wing tank are refuelled to their respective capacity. This type of mode is very helpful when a short range flight is been planned and so other tanks (other than service and wing) are kept empty in order to minimise the weight of the aircraft and thus ensuring safe landing of the aircraft and no damage to the landing gear. In full variant the fuel is completely filled in all the tanks and this type of operation is generally performed for long distant flights.

Once the desired fuelling mode is selected then the refuelling hose, which acts as a connector between aircraft fuel inlet point and the fuel carrying pipe, is connected. The inlet point is generally located near the landing gear compartment. The next step in this method is to start the fuel supply by pressing ON switch, this starts the pump responsible for transferring the fuel from where it is stored to the aircraft. The presence of fuel shut off valve makes it possible for various mode selection and ensuring the fuel is been filled in the desired tank only. In this paper the full variant mode is applied and then the tanks are refuelled at a common pressure to all the models.

Aircraft Fuel Tanks :- The fuel tank used for fuel storage must be capable to withstand the vibrations, inertia forces generated in aircraft and it may cause deterioration, leakage and fuel may expand as a result of temperature change, along with it should be able to handle its structural load by considering both cases while in operation and not in operation. Fuel tanks can have different shapes and can be located at different locations as per convenience. The fuel tanks volume is known based on the type of application and the flight range and the tank shape is chosen considering the aerodynamic drag forces acting over it. The aerofoil shape of the wing is an example of the tank shape due to aerodynamic drag force acting over it.

The shape of the fuel tanks adopted for this simulation is different and each has variable volume. While designing the tanks symmetry is taken into consideration for Centre of gravity to hold constant in that respective direction. Gauging system in incorporated in the given model to calculate the amount of fuel at any instant. Various aircraft parameters such as location of engine, accumulator (recuperator), size and shape of landing gear and its compartment where it will be accommodated after its take-off has been taken into consideration for the tank design. Along with this the shape of the canopy plays important role in designing of front tank.

The fuel feed system has been considered before modelling of refuelling system and on this basis main tank has been designed for the highest volume and CG consideration as it will be possessing highest fuel mass in it. As the pump serves the purpose of providing fuel flow at pressure and flow rate established by aircraft requirements during aircraft operation, fuel availability to pump is made sure by the tapered bottom shape of aircraft fuel tanks.

II. MODELLING OF AIRCRAFT FUEL SYSTEM

Before the modelling the full system has to be studied with its requirements in terms of position of tanks and their respective capacities. The basic aircraft tank positions with required units attached to the tanks are given below. The figure shows various tanks such as front tank, main service tank, rear tanks and fuel is also stored in wing tank to increase the flight hour by increasing the fuel capacity.

Detailed sequencing (Basic model explained)

i. The refuelling hose is connected.
ii. Desired refuelling pressure with which the fuel is transferred into the tank is selected.
iii. The fuel is monitored through the fuelling meter that is fuel flow transmitter.
iv. Pipe junction is provided to bifurcate the pipe line into two parts, where the one line goes to front section of main tank and the other line is been sent for refuelling of rear tanks (rear tank 1 and rear tank 2).
v. Flow control valve is added into the line and then the fuel is ejected into the service front portion
vi. Service front portion is connected via flap valve (tank hole with non-return valve) to the tank sections Front left and Front right, hence the fuel level in this two (front left and front right) sections will be rising same as the level in front portion of service section of main tank.
vii. The second pipe which emerged from the junction is brought forward and is responsible for fuelling 4 tanks and those are wing left, wing right, rear tank 1 and rear tank 2. This pipe is junctioned in three directions among which one pipe goes to left wing, the second one goes to the right wing and last one leaves for rear tanks.
viii. Line towards wing is equipped with the ejector pump which is fitted inside the rear left and rear right portion for the right and left wing respectively, the ejector makes it sure to transfer the fuel first in wings and when the wing reaches its predefined quantity then the fuel outlet is closed and the fuel starts getting ejected into the rear right and rear left section.

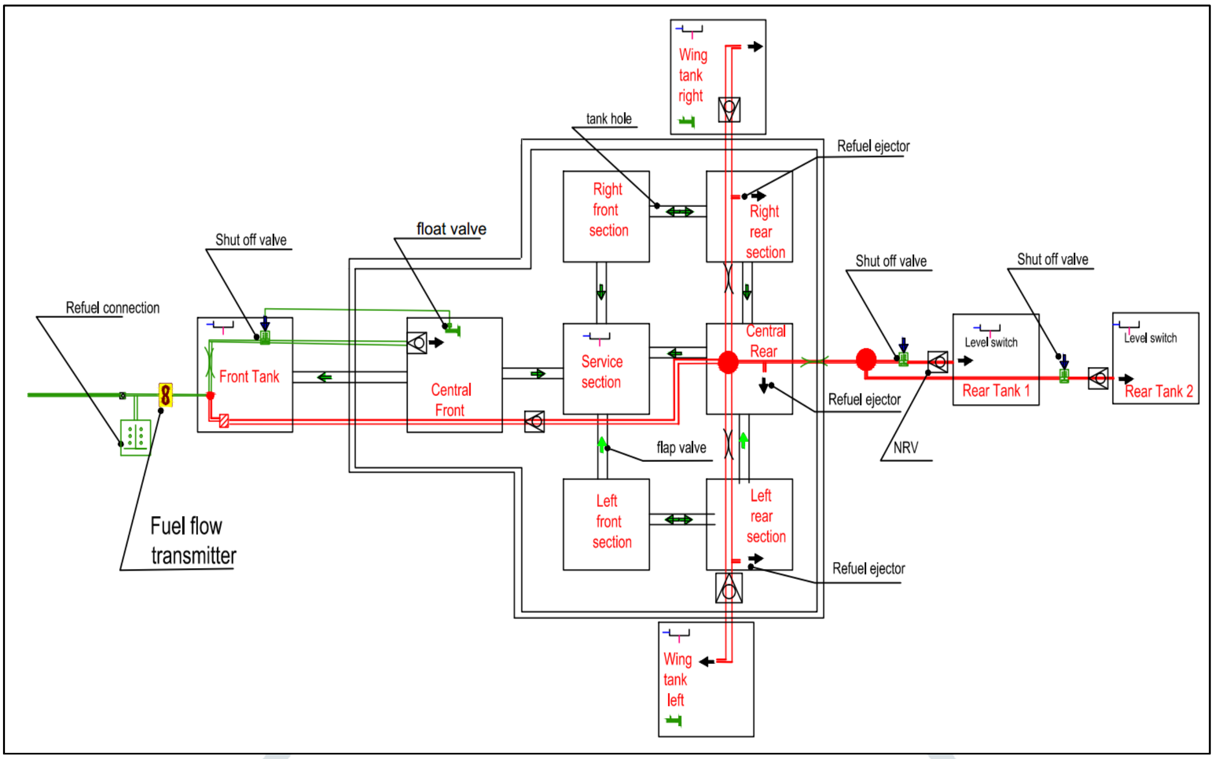

Fig-2 : Ray model for refuelling system

ix. The line which leaves for rear tanks 1 and 2 is also equipped with the ejector and this is also done to make sure that the fuel will come in main tank only when the rear tanks are filled to their desired capacity.

x. Rear tank 1 and rear tank 2 are smaller in capacity so they will be filled first to their desired capacity. Presence of fuel shut off valve and float valves makes sure that the refuelling of that tank is stopped once a certain height is reached.

xi. Now the fuel is incoming in main tank from 4 lines and they are two wings, from rear tanks and from the front section of service tank.

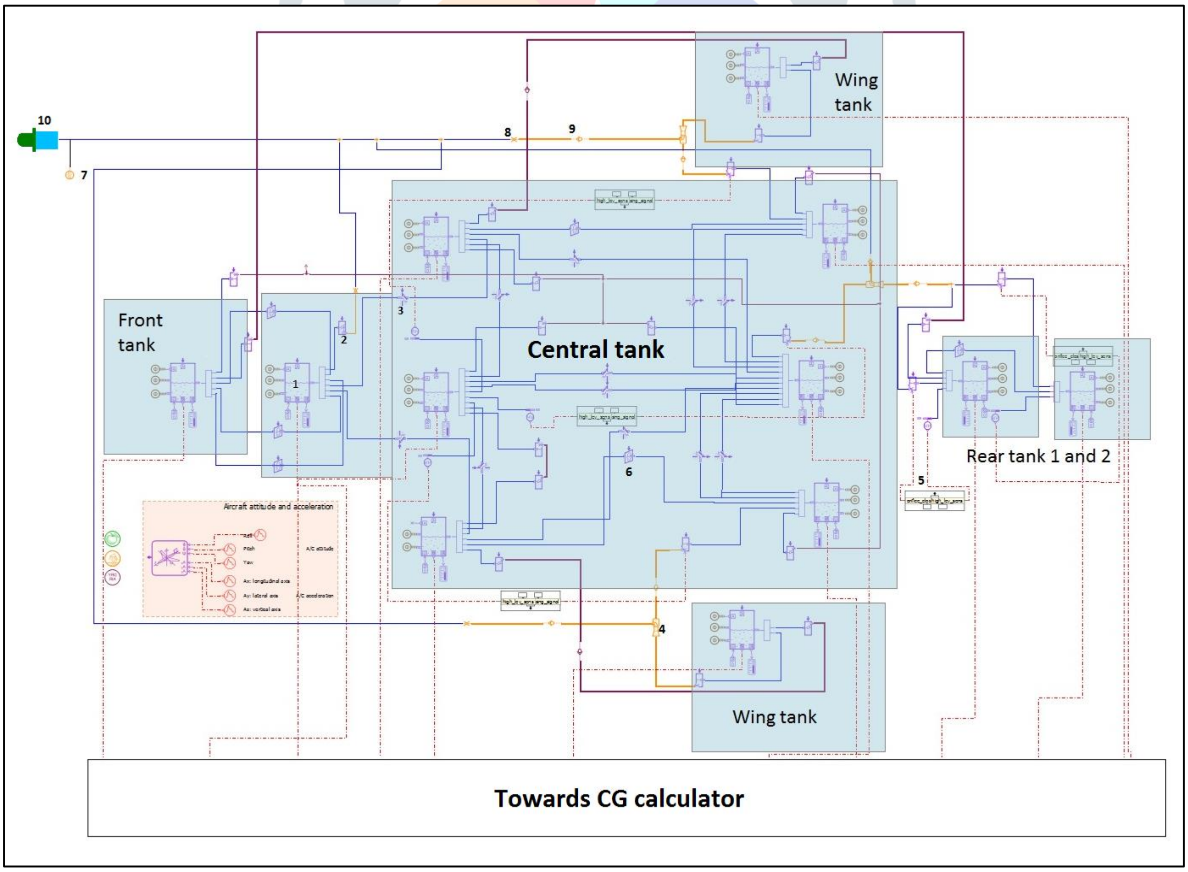

Fig-3: Refuelling system model with its main components

xii. Thus the entire main tank is filled and the tank hole in front tank fills the entire tanks in the fighter aircraft.

xiii. Thus the sequence of refuelling in full mode is rear tank 2-rear tank 1- wing tank (left and right together)-main central tank-front tank.

xiv. Then the fuel shut off valve operates and refuelling is stopped and the hose is now removed and the fuel which is remaining in the line is drained out through fuel drain valve.

Table-1: Part number and name of the component

Part number	Name of the component
1	Aircraft fuel tank
2	Float valve for filling
3	Flap valve between tank compartments
4	Ejector
5	Shut off valve
6	Tank hole
7	Pressure source
8	Orifice
9	Non return valve
10	Refuelling boom

The detailed software model is shown in figure above. In which the aircraft fuel tanks (labeled as 1). Main service tank is a combination of multiple sections and is divided into service tank and central front tank for calculation purpose. The model has pressure input of 4 bar and this is supplied at the hose via single point pressure refuelling. The table below shows major components used in the model.

The detailed sequence for the refuelling operation is explained in earlier section. Various combinations are made in order to come to arrive to an optimum CG variation. Various model made in order to arrive to the optimum conclusion are

Model 1:- The design for this model is made in such a way so that the resulting sequence is achieved **- wing tanks - rear tank 2 - rear tank 1 – main tank – central front tank – front tank**. The unit responsible for achieving this sequence is ejector, which satisfies the purpose of refuelling of wing tanks along with rear tanks at first place then the fuel us transferred to main tank once the shut off valve is operated. Thus from the sequencing it is clear that the wing and rear sections are the first one to be getting filled and further the fuel is received by main tank. Main tank and central front portion are attached to each other so filling of central front and main tank is executed simultaneously.

Model 2: - This model is prepared in order to execute the mentioned sequence **- main tank - wing tank (both left and right) - rear tank2 – rear tank 1 –central front – front tank.** The unit which is responsible for the change of sequence as compared to model 1 is ejector pump. The position of ejector pump is inverted and is placed in such way that the incoming fuel is delivered to main tank at first place. Hence the main tank is the first one getting filled in the obtained sequence and thus centre of gravity position of filling also changes. Receiving a signal from shutoff valve changes the flow direction after filling of the main tank and now the fuel is delivered to the wing and rear section so they will be getting filled after the main tank. As stated above central front and front tank will be filled subsequently.

Model 3: - This model is organized in such a way to accomplish the sequence specified**- main tank - wing tank (both left and right) - rear tank2 – rear tank 1 –central front – front tank**, which is same as the previous one but there is variation in center of gravity position as compared to the model 2. The same arrangement of reverse jet pump is used in this model. The actual difference between both the model is with the flap valve been replaced by a tank hole. This is responsible for the filling of front portion along with the main tank, as the tank hole is a unit when connected between two tanks the level of liquid rises constantly and equally. Thus the time required for filling will be reduced in this case as all the three jet pumps will be in operation for longer duration thus more discharge will be received, reducing the time required for refueling.

Model 4: - The model has its units rearranged and this is done in order to get the sequencing as mentioned **wing tank - rear tank 2 - rear tank1 – service tank – central front – front tank.** In this model ejector is replaced with a pipe T joint. This model refuels wing tank and central tank simultaneously unlike the previous model which refuels wing tank first and then the service section. In this model, as the fuel is flowing simultaneously therefore the filling sequence depends upon the capacity of the fuel tanks. Wings and rear tanks will be filled in the first place along with main tank and then the further filling of front portion of the aircraft is fulfilled.

Model 5:- This model is designed in a way to achieve the sequence stated **- wing tank - rear tank 2 - rear tank1 – service tank – front tank - central front.** Change of position of refuelling orifice is responsible for the sequence change as compared to the preceding models. In general case the model refuels the aircraft through central front portion, wing tanks and rear tanks nut in this model the refuelling is done through font tank instead of central front tank. This is done in order to check for the center of gravity variation.

Among this given models which are modelled are to be simulated and then the cg variation for each and every model has to be computed. Lesser the centre of gravity variation more stable the aircraft will be and hence the model with lesser center of gravity variation will be finalised

III. SIMULATION AND RESULTS OF AIRCRAFT REFUELLING SYSTEM

The simulation for the complete refuel system is done in order to know the exact time taken for the refuelling operation of all the tanks located in an aircraft and not only the time taken is known but along with that the variation of Centre of gravity from its reference position is also known. Some other parameters such as the fuel temperature changes can also be known. The individual tank's fuel filling time can be known and hence the time required for last tank to be filled will be the total time required for filling up of entire aircraft fuel tanks in aircraft fuel system. The input parameters for the refuelling system's aircraft fuel tank shape and size for the aircraft fuel tanks which includes its exact volume, total height of the tank, exact position of the tank with respect to the reference frame of the aircraft and the information about the height is to volume ratio is provided. These parameters are to separately evaluated for each and every fuel tank separately as each and every tank has different shape and size and has different location.

The graph below shows time required for filling up of the fuel tanks volume versus the time required its operation the inclined line indicates about the tank getting filled and the slope of this line indicates its flow rate in (m3/sec). Similarly it can be seen that the sequence of its filling operation can be determined from this graph. Once the line becomes horizontal then the tank is said to be full and hence the fuel flow is stopped either by float valve or by shutoff valve or even both are used for achieving the redundancy and ensuring that the fuel is stopped as soon as the desired fuel height is reached.

The filling time of each tank can be determined from the graph. Rear tanks are filled once the wings are filled. The capacity of the rear tank 2 is around 335 kg which is lowest among all the tanks and is kept low considering the limited space and the weight of the engine which is accumulated at rear end of the aircraft. The flow rate with which the rear tank 2 is fuelled is around 7 kg/sec. Shut off valve stops the supply of fluid in rear tank 2 once a level of 0.5 m is reached. The time required for filling is 50 sec. hence the line for rear tank 2 (green coloured) is horizontal after 50 seconds. Rear tank 1 is also refuelled at the same flow rate of 7 kg/sec till 50 sec but once the refuelling of rear tank 2 is stopped the entire flow rate is diverted towards the rear tank 1 and thus slope of filling curve for rear tank 1 (pink colour) after 50 seconds increases indication rise in the flow rate of filling. Wing tanks (both right and left) are refuelled with flow rate of about 5 kg/sec in both tanks simultaneously. The time for filling is 147 seconds.

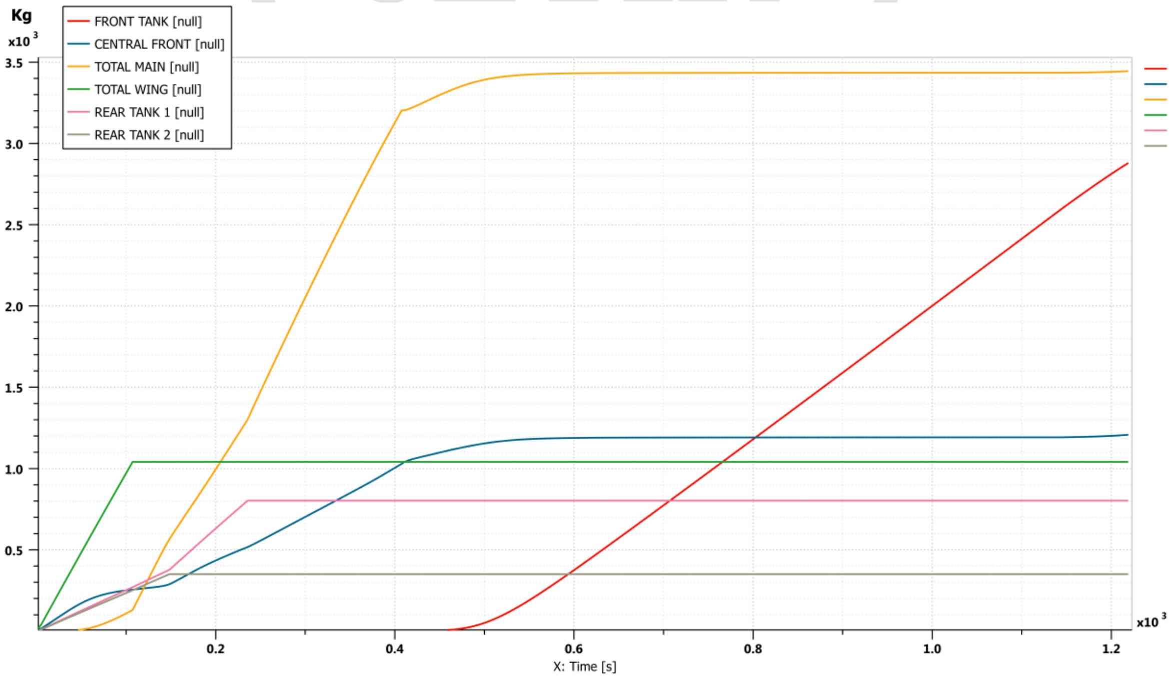

Fig-4: Graph for Volume filling vs. time for model 1

Central tank is initially refuelled through central front portion at a constant flow rate of 5.5 kg/sec and this filling orifice is supplying fuel to all the 7 compartments of central tank and then to the front tank. When the wing tank and rear tanks are completely refuelled the refuelling is directed towards the central tank thus two sudden rises are present in the plot of central tank refuelling. Further the refuelling through all point is stopped and only refuelling through central front portion is continued till entire aircraft is refuelled. Refuelling of front tank is carried out via tank hole present in between front tank and central tank, the height of the hole can be varied and thus the time at which fuel enters in the front tank can be adjusted. The time required for refuelling of all tank is 1110 seconds. Total fuel inside the aircraft at any instant is the sum of individual fuel volume in all fuel tanks at that instant. Hence the graph shows the fuel quantity in m3. Hence the graph shows the total volume of fuel present inside the aircraft.

For a given aircraft, weight and center of gravity position have a significant impact on performance and handling, specifically stall speed, take-off and landing distance, climb performance and cruise performance. Incorrect Weight and Balance (W&B) management may also result in severe safety issues [2].

Note that the centre of gravity variation takes place due to the change in fuel volume during refuelling process. It is made sure that the fuel cannot be added into the single tank located at extreme position of the fuel tank, to compensate it we should counter balance the weight by adding fuel into the other end of the aircraft and thus the movement of the centre of gravity will be minimum and the risk of aircraft getting topple down can be avoided.

When the aircraft is been refuelled on ground, its advantageous that its resting on landing gear and wheels thus the aircraft is at low risk in case of CG variation is considered, but in case of aerial refuelling is considered which is a critical case as far as the change of centre of gravity and aircraft stability is considered. As the fuel is supplied to the engine and simultaneously the aircraft is refuelled via refuelling boom by air to air refuelling (also known as aerial refuelling).

The fuel centre of gravity can be calculated by the formula

$$center\ of\ gravity = \frac{\sum_{i=1}^{i=n} mi\ \ xi}{\sum_{i=1}^{i=n} mi}$$

The centre of gravity calculation needs the input value for the individual mass of the fuel inside the fuel tank and the x coordinates of the tanks centre of gravity from the aircraft reference position. In this way all the tanks individual mass are to be considered along with their CG coordinate for the CG calculation of the entire aircraft.

The above formula can be expanded as below

$$\frac{m_1x_{1+}\ m_2x_{2+}m_3x_{3+}m_4x_{4+}m_5x_{5+}m_6x_{6+}m_7x_7 + m_8x_8}{m_{1+}m_{2+}m_{3+}m_{4+}m_{5+}m_{6+}m_7 + m_8}$$

Where,

m_1 and x_1 are mass of fuel in kg for front tank and x position of CG for front tank in metres respectively.

m_2 and x_2 are mass of fuel in kg for central front tank and x position of CG for central front tank in metres respectively.

m_3 and x_3 are mass of fuel in kg for main service tank and x position of CG for main service tank in metres respectively.

m_4 and x_4 are mass of fuel in kg for wing tank left and x position of CG for wing tank left in metres respectively.

m_5 and x_5 are mass of fuel in kg for wing tank right and x position of CG for wing tank right in metres respectively.

m_6 and x_6 are mass of fuel in kg for rear tank 1 and x position of CG for rear tank 1 in metres respectively.

m_7 and x_7 are mass of fuel in kg for rear tank 2 and x position of CG for rear tank 2 in metres respectively.

m_8 and x_8 are the mass of empty (without fuel) aircraft in kg and the x position of CG in an empty aircraft

Sample calculation for CG at a specific time t= 500 sec for Model 1.

Service tank consists up of multiple compartments. Mass for the service tank is the summation of individual masses of all the sections which consists of service section. For calculating x coordinate of CG the formula used is same as that of entire CG but only this is been applied for 6 compartments only.

$$center\ of\ gravity = \frac{\sum_{i=1}^{i=n} msi\ xsi}{\sum_{i=1}^{i=n} mi}$$

X coordinate for the individual compartment is known

There are six service sections and their masses addition are as below.

$= m_{s1} + m_{s2} + m_{s3} + m_{s4} + m_{s5} + m_{s6}$

= 476.08+932.81+476.08+368.62+770.09+368.62

= 3388.3 kg

Put the all the values in given formula

$$= \frac{(476.08\times11.70)+(932.81\times11.70)+(476.08\times11.70)+(368.62\times12.83)+(770.09\times12.83)+(368.62\times12.83)}{3388.3}$$

$$= \frac{41393.19}{3388.3}$$

= 12.21 m

Enlisting all the values for masses and CG coordinates which will be used for calculating the CG for entire aircraft.

Table-2: Masses and cg values of respective tanks

m_1 = 50.79 kg	x_1 = 9.03 m	m2 = 1154.84 kg	x_2 = 10.57 m
m_3 =3388.3 kg	x_3 =12.21 m	m_4 =520.62 kg	x_4 =12.85 m
m_5 = 520.62 kg	x_5 =12.85 m	m_6 = 645.30 kg	x_6 =15.97 m
m_7 =350.93 kg	x_7 =17.94 m	m_8 =19080 kg	x_8 =11.78 m

Put the above values in the formula for finding the CG of aircraft at time= 500 sec

$$= \frac{(50.79\times9.03)+(1154.84\times10.57)+(3388.3\times12.21)+(520.62\times12.85)+(520.62\times12.85)+(645.30\times15.97)+(350.93\times17.94)+(19080\times11.78)}{(50.79+1154.84+3388.3+520.62+520.62+645.30+350.93+19080)}$$

$$= \frac{308779.89}{25711.41}$$

= 12.00 m

This value gives the CG variation due to fuel addition during refuelling process for model 1 at time 500 sec after the start of refuelling process.

This value gives the CG variation due to fuel addition during refuelling process for model 1 at time 500 sec after the start of refuelling process.

The figure below shows the variation of cg with respect to time the figure also shows the coordinate at 500 seconds and its cg value as shown in above figure. We get the same value from calculations as described above. This value of the CG can be expressed in MAC (mean aerodynamic chord) as the position of centre of mass is determined relative to the beginning of the wing mean aerodynamic chord and is expressed in percentage of its length. The coordinates of centre of mass are determined in percentage MAC from the following equation

$$MAC = \frac{\bar{X} - X_b}{b_a} \times 100$$

The value of the distance between origin of coordinate to beginning of MAC is 10.240 m and for wing MAC is 4.646 m

$= \quad \frac{12-X_b}{b_a} \times 100$

$=$ 37.98 % MAC

IV. CONCLUSION

As discussed in the results section the minimum flow rate with which the aircraft is refuelled is 600 liter/min and it varies up to 1000 liter/min when the case of aerial refuelling is considered where time constrain is present during war situations the flow rate with which fighter aircraft is been refuelled is increased to about 2000 liter/min.

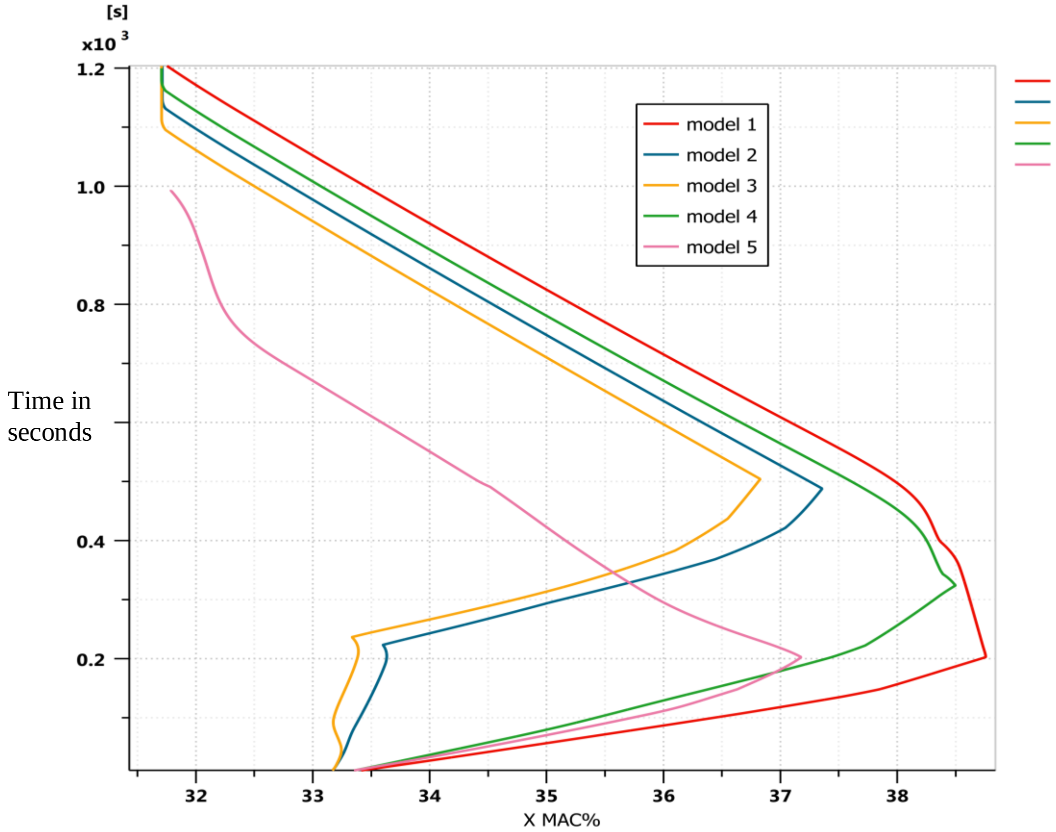

Fig-5: Graph for CG values vs. time

When it comes to gravity refuelling where the tanks are filled separately from the top through an opening, same flow rates can be used. Hence these conditions are validated by calculating the time required for refuelling and comparing it with the flow rate and its corresponding time which is desired for refuelling of fighter aircraft. From the various models which are prepared it is clear that the refuelling when done with the method of reversed jet pump and connecting main tank and central main tank with a hole the centre of gravity variation is minimum and optimum as compared to all the other models. The case in model 4, where the refuelling sequence is changed and front tank initiates refuelling also has a good impact on the CG variation, CG is considerably controlled in this case. But this model has its own drawback. During the basic refuelling only the wing tank, main tank and central front tank is refuelled but in case of model 4 this seems to be impossible due to the fact that the fuel is delivered to the front tank first and this tank has to be kept empty in basic refuelling scenario.

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