Transient Flow Analysis of an Aircraft Refueling System

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Transient pressures and flows in an aircraft aerial refueling system are presented for a sudden disconnect between a tanker aircraft and a receiver aircraft. Transient conditions are simulated in the tanker refueling system during and after the sudden closure of the poppet valve at the refueling nozzle of the tanker aircraft. The simulations are obtained using a transient flow analysis computer program originally developed for hydraulic systems. Transient pressure simulations are compared with pressure transients obtained experimentally during ground tests. Agreement between the simulations and experiment is obtained. Surge arrestors are shown to limit the surge pressure.

Introduction

REFUELING of aircraft in flight has become common practice. Since it is necessary to limit fuel surge pressures during aerial refueling operations, it is of interest to be able to predict the surge pressures through computer simulations. These predictions are particularly useful in designing new systems or in determining the effects of malfunctions or design changes in existing systems. For example, increasing the refueling flow rate has the advantage of reducing the time required to refuel receiver aircraft; however, a higher flow rate may generate transient pressures that exceed the design limits of the aerial refueling system of the tanker aircraft when a sudden disconnect occurs between the tanker and the receiver. Malfunctions during a disconnect, such as failure of the refueling pumps to shut off or failure of a bypass valve to open also may cause abnormally large transient pressures.

The U.S. Air Force has employed the KC-135 as a tanker aircraft for aerial refueling for a number of years. This study is undertaken to develop a means to obtain simulations of the transient pressures and flows in a modified KC-135 aerial refueling system for a sudden disconnect without the refueling boom retracting while the pumps continue to operate and the bypass valve fails to open. The simulations are to be compared with experimental data obtained during ground tests under similar conditions.

Transient Analysis

The transient response of fluid systems has been studied in considerable detail. Wylie and Streeter[1] provide many of the details regarding fluid transients, while Goodson and Leonard[2] summarize the development of models for fluid line applications. Numerical methods are available for determining the pressure and flow-time histories. These methods relate to or extend the classical waterhammer problem. Interest in the dynamic response of hydraulic systems led to the studies of Zielke[3] and McDonnell Douglas Corporation.[4,5] These studies modeled complex aircraft hydraulic systems, consisting of reservoirs, pumps, lines, valves, etc., and obtained simulations of the transient flows and pressures with good results on a digital computer.

Although the dynamic simulation methods developed by Zielke and McDonnell Douglas were for hydraulic systems, much that was reported is applicable to the dynamics of fluid systems in general. Thus, the results are applicable to fuel systems by making the appropriate changes to account for fluid properties, fuel system components, pressure conditions, etc. Therefore, HYTRAN, a transient flow analysis program developed for hydraulic systems by McDonnell Douglas Corporation,[4] under contract to the Aero-Propulsion Laboratory of the Air Force Wright Aeronautical Laboratories, was modified and used in this study to obtain the transient flow results in an aerial refueling system.

HYTRAN

HYTRAN, a computer program designed to predict transient pressures and flow rates in fluid systems, is divided into four parts: input; steady-state calculations; transient calculations, including line and component simulations; and output. The program calculates steady-state pressures and flow rates by requiring the net flow at selected points in the system (nodes) to be zero and solves a set of simultaneous linear equations for steady-state nodal pressures. Transients are computed using the method of characteristics. The basic equations that describe the unsteady flow in fluid systems are derived from the principles of conservation of mass and momentum. Two partial differential equations result that become ordinary differential equations along certain lines called characteristics. The ordinary differential equations are solved using a finite difference formulation to yield the transient pressures and flow rates. The characteristics method divides all system lines into reaches equal to $a\Delta t$, where a is the local wave speed and Δt the desired time step. Calculations proceed in a stepwise manner with pressure and flow rate at time t determined from the characteristics equations and known conditions at $t-\Delta t$. When a boundary such as a constant pressure reservoir is met, the characteristics equations are solved simultaneously with the prescribed conditions at that boundary.

The working fluid in HYTRAN was changed from hydraulic oil to a JP-4 type of fuel by simply using the kinematic viscosity, density, and bulk modulus for JP-4 fuel. The following values at 60°F were used: $\nu = 0.00136$ in.^{2}/s, $\rho = 0.000077$ lbf·s^2/in.^{4}, and $\kappa = 160{,}000$ lbf/in.^{2}. The line material modulus of elasticity was assumed to be 10^7 psi. A computational step time of 0.0005 s was used. Under these

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conditions, HYTRAN requires a core memory of 150,000 and a run time of approximately 80 s on the CDC 6600 computer.

System Description and Modeling

The modified KC-135 refueling system[6] consists of four hydraulically driven fuel pumps that pump fuel from two body tanks through a 4 in. i.d. fuel line (refueling manifold) and out a flying boom. A simplified schematic diagram is shown in Fig. 1. The boom is an extension of the refueling manifold and can be aerodynamically positioned by the boom operator. The centrifugal fuel pumps, driven by constant displacement hydraulic motors, are each designed to operate in conjunction with pressure sensors and maintain an output pressure of 77-80 psig over a flow range of 0-300 gal/min. A flapper-type check valve, located downstream of each pump, prevents reverse flow of fuel to the pump.

The refueling pumps were modeled as constant pressure reservoirs due to their constant pressure output. Feedback response of the pump to transient pressure surges was assumed slow enough to have little effect on pressures downstream. The flapper check valves were modeled as spring-loaded valves with variable-orifice characteristics between fully opened and fully closed positions. The relatively slow closing rate of the flapper valves was accounted for by using a spring constant of 0.1 lbf/in. compared to a value of 10 lbf/in. for a typical check valve.

A pressure regulator, located upstream of the boom in the refueling manifold, is automatically adjusted to maintain 50 ± 5 psig at the boom nozzle (poppet valve). The regulator is a slider-type valve that is actuated in response to a pressure sensor. The poppet valve at the end of the boom is a spring-loaded valve that is open only when the receiver and tanker aircraft are in contact and closes upon disconnect. A poppet valve closure time of 0.05 s was used in this study to approximate the closure times used in the ground tests.[7] This 0.05 s closure time, however, may not be representative of all tanker systems, since closure times as fast as 0.014 s have been reported.

The pressure regulator was modeled as an orifice with a diameter that was established to obtain desired steady-state conditions. Dynamic response of the regulator to pressure surge was not accounted for in this simulation. The poppet valve was modeled as a simple two-way valve with a program input of the valve position vs time. A square-law, pressure-flow relationship with a constant discharge coefficient was used. Poppet valve closure time was input in five equally spaced time steps of 0.01 s each.

The refueling system contains surge arrestors and level control (relief) valves that serve to reduce the pressure surge. The surge arrestors consist of two pressurized rubber surge boots that surround a 200 in. section of the fuel tube in the flying boom. A schematic diagram of the fuel tube and a boot is shown in Fig. 2. During pressure surges, fuel flows from the perforated tube into the surge boots through 168 holes (14 holes in 12 equally spaced rings). The surge boots together have a maximum volume of 1250 in.^{3} and a preload pressure of 50 psig. The boots were modeled using a parallel arrangement of 12 piston accumulators. Each accumulator was identified with a ring of holes along the fuel tube. A line with a cross-sectional area equal to the area of the 14 holes was used to connect the main line to each accumulator. The total volume of the two surge boots was divided equally among the 12 accumulators. Isothermal expansion and compression were assumed and the frictional effects of the piston were neglected.

Two level control valves are located in lines leading from the refueling manifold to the forward and aft body tanks. The primary purpose of these valves is to control the flow of fuel to the body tanks when the aircraft is being ground refueled. In addition, the valves provide surge relief and have a cracking pressure of 85-115 psi, which allows fuel to flow to the body tanks during pressure surges in flight. These valves were modeled as check valves with the preload force calculated from the cracking pressure and line area.

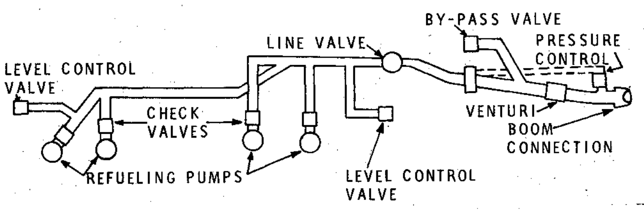

Fig. 1 Simplified schematic diagram of KC-135 refueling system.

Results

To initiate the simulation in the refueling system, the poppet valve was closed as previously described in 0.05 s. This caused the fuel flow rate at the boom nozzle to change from a steady-state value of 3900 in.^{3}/s to zero in 0.05 s and to remain zero for the duration of the simulation. The simulation was conducted for the case where the boom was not retracted automatically after disconnect. The transient pressures predicted at the boom nozzle and at the venturi (approximately 74 ft upstream of the boom nozzle) are shown in Figs. 3 and 4, respectively. Time is measured from the start of valve closure. The results of ground tests performed by the 4950th Test Wing[7] are also shown in Figs. 3 and 4. The simulation compares reasonably well with the experimental data, except at the peak pressure spikes where the simulation generally indicates higher peak pressures. The simulations also show more fluctuations than were found in the experiment. Closer agreement with experiment is obtained after 0.5 s. The discrepancies between the simulations and the experimental results could be due to a number of possibilities. Among these, the computer solutions may be rather sensitive to component modeling, particularly the modeling of the

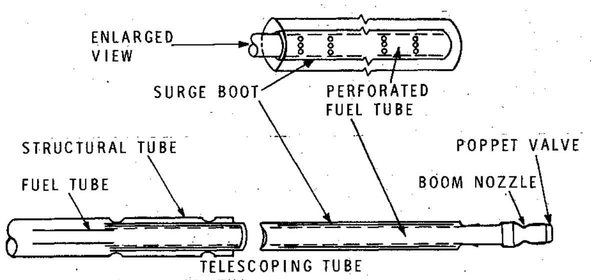

Fig. 2 Simplified schematic diagram of KC-135 boom and surge boot.

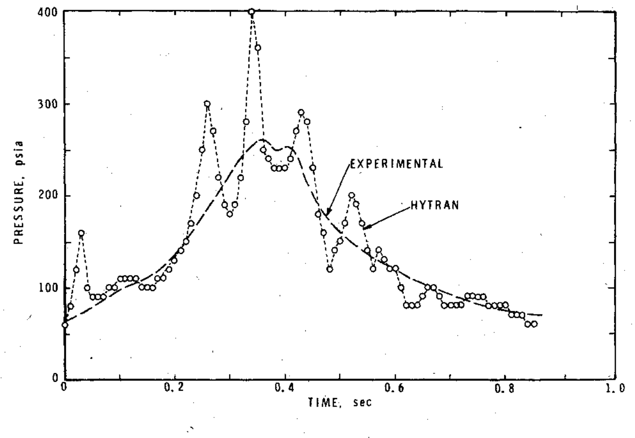

Fig. 3 Transient pressure at boom nozzle.

surge boots as parallel accumulators along the boom. Also, the test instrumentation may have been less sensitive to the pressure fluctuations than the computations.

The peak pressure, shown by the HYTRAN simulation in Fig. 3, that occurs at approximately the time of poppet valve closure would be expected to increase in magnitude for faster closure times. Thus, valve closure time influences the magnitude of the transient pressure that occurs at the boom poppet valve. Since the results of this study were limited to a closure time of 0.05 s, further studies of the effect of valve closure time on transient pressures are believed warranted.

The use of a surge arrestor is especially important in the system. Simulations (not shown) were obtained under the same test conditions as for those shown in Figs. 3 and 4; however, the surge boots and level control valves were not included in the model. The transient pressures obtained without the surge-arresting equipment had some initial peak pressures as high as 900 psig. These results do not compare well with the experimental results and are thus not representative of the transient pressures.

While the fuel flow rate at the boom nozzle goes to zero because of poppet valve closure, the fuel flow in the refueling manifold at the venturi decreased and then reversed direction. The flow simulation is shown in Fig. 5. The fuel flow rate at this location does not change significantly until after the poppet valve has been completely closed for over 0.1 s due to the fuel flow into the surge boots. The simulation of the fuel flow into one of the accumulators at the upstream end of the surge arrestor is shown in Fig. 6. The gas pressure or, equivalently, the fuel pressure for the same accumulator is shown in Fig. 7. This particular accumulator begins to fill after 0.05 s and reaches its peak fuel volume between ap-

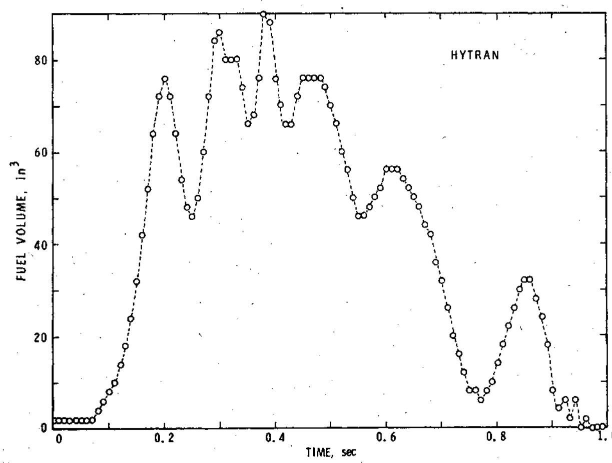

Fig. 6 Single accumulator fuel volume at upstream end of surge boot.

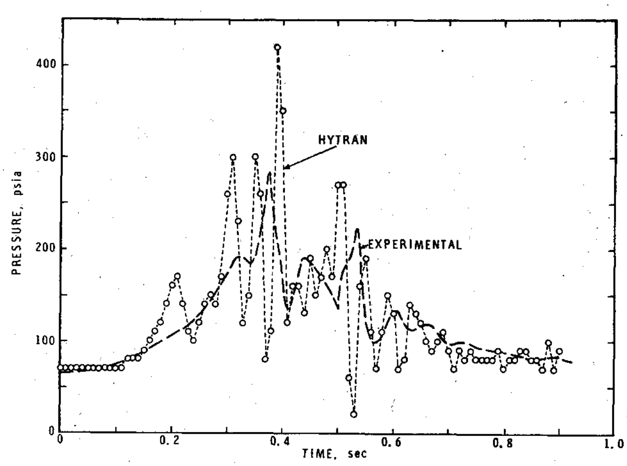

Fig. 4 Transient pressure at venturi.

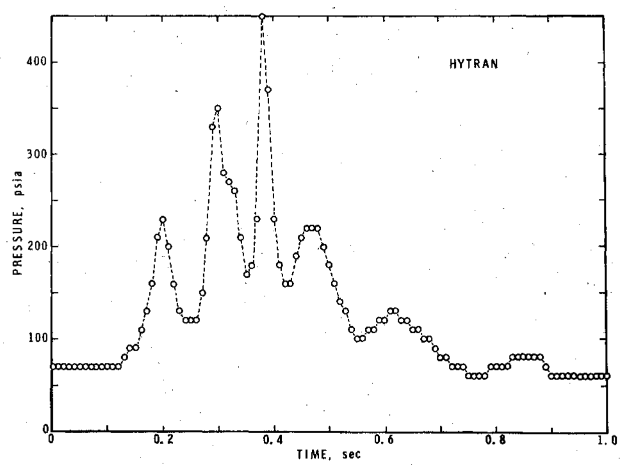

Fig. 7 Single accumulator gas pressure at upstream end of surge boot.

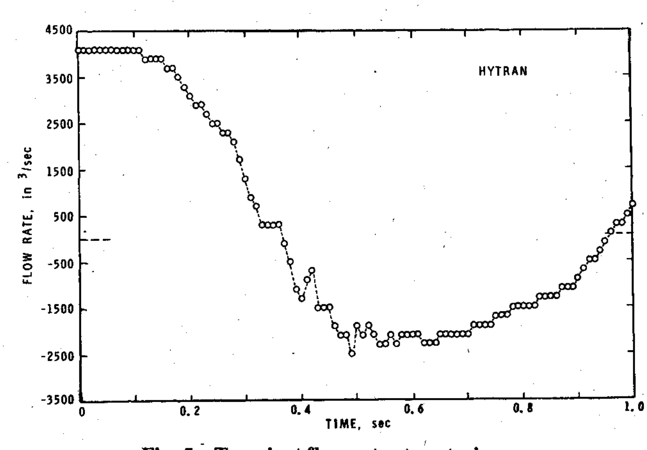

Fig. 5 Transient flow rate at venturi.

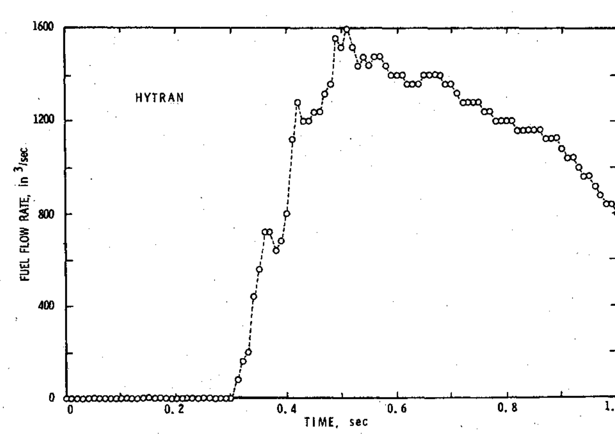

Fig. 8 Flow rate through the aft tank fuel level control valve.

proximately 0.3 and 0.4 s after disconnect. Fuel then begins to flow out of the accumulator and back into the line. Some of the flow reversal occurs because the aft tank relief valve (level control valve) starts to open around 0.3 s after disconnect. Fuel flow through the relief valve is shown in Fig. 8. The forward tank valve also opens shortly after the aft tank valve opens. The addition of a relief valve in the bypass line between the venturi and the pressure regulator that had a relief setting of 85 psi was found by simulation to decrease maximum transient pressure by approximately 30% at the boom nozzle and approximately 60% at the venturi.

Conclusions

1) Transient pressures predicted by HYTRAN compare reasonably well with those measured experimentally, except that the simulations appear more sensitive and have larger fluctuations in pressure than found in the experiment. During the first 0.2 s and after about 0.5 s, the agreement between the simulations and the experimental pressure measurements is quite good.

2) The sensitivity of the simulation does not appear to limit the use of HYTRAN in predicting surge pressure trends. The modeling of components and the effects of boom poppet valve closure time need to be studied further.

3) The use of surge-arresting equipment (surge boot and level control valves) is essential to limiting surge pressures in the refueling system during disconnect without automatic boom retraction.

4) The addition of a relief valve in a bypass line between the venturi and the regulator further reduces surge pressure during disconnect without automatic boom retraction.

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