Technical Memorandum 33-604

A Method for Calculating Transient Thrust and Flow-Rate Levels for Mariner Type Attitude Control Nitrogen Gas Jets

John D. Ferrera

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JET PROPULSION LABORATORY
CALIFORNIA INSTITUTE OF TECHNOLOGY
PASADENA, CALIFORNIA

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PREFACE

The work described in this report was performed by the Guidance and Control Division of the Jet Propulsion Laboratory.
CONTENTS

I. Introduction ................................................................. 1
II. Flow Analysis ............................................................... 2
III. Digital Computer Solutions ............................................. 7
IV. Conclusions ................................................................... 8
References .......................................................................... 10

TABLES

1. Summary of computer equations .......................................... 11
2. Jet valve characteristics (computer input cards) ................... 12
3. MM'71 jet valve parameters (fixed) ...................................... 13
4. Computer program results .................................................. 14

FIGURES

1. MM'71 jet valve model ....................................................... 15
2. Typical valve chamber pressure profile ................................ 15
3. Typical valve electrical and pneumatic characteristics: (a) voltage to valve, (b) valve coil current, (c) valve chamber pressure, (d) valve orifice area ................................................. 15
4. Computer program flow chart .............................................. 16
5. Computer list printout of steady-state and transient thrust prediction program ....................................................... 17
6. Steady-state printout: (a) MM'71 pitch/yaw, (b) MM'71 roll, (c) MM'64 pitch/yaw, (d) MM'64 roll ..................... 22
7. MM'71 pitch/yaw valve parameters as a function of time: (a) chamber pressure, (b) total mass, nozzle, (c) total mass, chamber, (d) total mass, valve, (e) nozzle flow rate, (f) chamber flow rate, (g) valve flow rate, (h) total impulse, (i) chamber pressure derivative ......................................................... 23
8. MM'71 roll valve parameters as a function of time: (a) chamber pressure, (b) total mass, nozzle, (c) total mass, chamber, (d) total mass, valve, (e) nozzle flow rate, (f) chamber flow rate, (g) valve flow rate, (h) total impulse, (i) chamber pressure derivative ......................................................... 32

JPL Technical Memorandum 33-604
FIGURES (contd)

9. MM'64 pitch/yaw valve parameters as a function of time: (a) chamber pressure, (b) total mass, nozzle, (c) total mass, chamber, (d) total mass, valve, (e) nozzle flow rate, (f) chamber flow rate, (g) valve flow rate, (h) total impulse, (i) chamber pressure derivative................................. 41

10. MM'64 roll valve parameters as a function of time: (a) chamber pressure, (b) total mass, nozzle, (c) total mass, chamber, (d) total mass, valve, (e) nozzle flow rate, (f) chamber flow rate, (g) valve flow rate, (h) total impulse, (i) chamber pressure derivative................................. 50
ABSTRACT

The purpose of this report is to define and program the transient pneumatic flow equations necessary to determine, for a given set of conditions (geometry, pressures, temperatures, valve on time, etc.), the total nitrogen impulse and mass flow per pulse for the single pulsing of a Mariner type reaction control assembly valve. The rates of opening and closing of the valves are modeled, and electrical pulse durations of from 20 to 100 ms are investigated. In developing the transient flow analysis, maximum use was made of the steady-state analysis undertaken in Ref. 1. The impulse results are also compared to an equivalent "square-wave" impulse for both the Mariner Mars 1971 (MM'71) and Mariner Mars 1964 (MM'64) systems. It is demonstrated that, whereas in the MM'64 system, the actual impulse was as much as 56% higher than an assumed impulse (which is the product of the steady-state thrust and valve on time -- i.e., the square wave), in the MM'71 system, these two values were in error in the same direction by only approximately 4% because of the larger nozzle areas and shorter valve stroke used.
I. INTRODUCTION

This memorandum is a supplement to Technical Report 32-1353 (Ref. 1) and is intended to be used in conjunction with it. The work presented in that report is limited to steady-state thrust and flow-rate determinations vs. varying design parameters for the Mariner type ball valve/nozzle configuration, in which a subsonic orifice is in series with a sonic nozzle throat separated by a chamber volume of approximately 0.2 cm³. Design variables investigated include inlet pressures of $6.9 \times 10^4$ to $2.1 \times 10^5$ N/m² (10 to 30 psi), ambient pressure of $1 \times 10^{-4}$ N/m² ($1 \times 10^{-6}$ torr), inlet temperatures of -100 to 150°C, valve orifice areas of $0.32$ to $2.6 \text{ mm}^2$ ($5 \times 10^{-4}$ to $40 \times 10^{-4}$ in.²), nozzle throat diameters of $0.13$ to $1.3 \text{ mm}$ ($5 \times 10^{-3}$ to $50 \times 10^{-3}$ in.), nozzle geometric area ratios of 25 to 275, and nozzle cone half-angles of 15 to 40 deg. The thrust levels considered are in the millinewton range, and the propellant is cold nitrogen gas. The equations used to determine nozzle losses are based on flat-plate analogies.

The work described here extends the analysis and computer program presented in Ref. 1 (using the same ranges of parameters) to include an investigation of the transient thrust and flow-rate effects for both the Mariner Mars 1964 and 1971 cases. Of particular concern was the total quantity of gas consumed in the firing of each axis of the MM'71 reaction control assembly. The results were used in the Mariner Mars 1971 program to aid in the flight analysis of total gas consumption, and tended to correlate with in-flight data. The resulting Univac 1108 program can easily be modified to investigate other valve geometries and conditions.

*The dimensions in the equations are in English units to correspond to the computer program on which they are based.
II. FLOW ANALYSIS

The model used to represent the MM'71 RCA jet valve is shown in Fig. 1, where the subscripts 0, c, and N refer to conditions at the jet valve orifice, in the plenum chamber between the jet valve orifice and nozzle, and in the nozzle throat, respectively.

For this model, the weight of gas in the thrust chamber \( W_c \) at any time \( t \) is assumed to be given by the perfect gas law,

\[
W_c = \rho_c V_c = \frac{V_c}{RT} P_c
\]

where \( \rho \) is the gas density, \( V_c \) is the chamber volume, \( R \) is the gas constant, \( T \) is the gas temperature, and \( P_c \) is the chamber pressure. For an adiabatic process, the change in weight is proportional to the change in pressure, or

\[
\frac{\partial W_c}{\partial t} = \frac{V_c}{RT} \frac{\partial P_c}{\partial t}
\]

For the case to be considered in this report, at \( t = 0 \) (i.e., immediately prior to the initiation of valve opening), \( P_0 \) equals the supply pressure of \( 1.0 \times 10^5 \) N/m\(^2\) (15.0 psia), and the chamber pressure \( P_c \) and ambient pressure \( P_a \) equal zero (i.e., vacuum condition). Between the time the valve starts to open and the time that the chamber pressure reaches a steady-state level (see Fig. 2), there is a difference in flow rates between the solenoid valve orifice \( W_0 \) and the nozzle \( W_N \). This flow-rate difference causes an accumulation of gas in the chamber, thereby building up the chamber pressure. The differential equation of the rate of gas accumulation is

\[
\frac{dW_c}{dt} = W_0 - W_N
\]
Because the local ambient is vacuum, the flow rate through the nozzle is always sonic and is given by

$$W_N = C_{DN} A_N P_c \left[ \frac{g_0 \gamma}{RT} \left( \frac{2}{\gamma + 1} \right)^{\frac{\gamma + 1}{\gamma - 1}} \right]^{\frac{1}{2}}$$

(4)

where $C_{DN}$ is the nozzle discharge coefficient, and $A_N$ is the nozzle cross-sectional area.

The flow rate through the valve orifice $W_0$ is sonic initially, since $P_c/P_0 < 0.528$. During this period ($0 < P_c/P_0 \leq 0.528$, $0 < t < t_{r1}$, from Fig. 2), the sonic orifice flow rate is given by

$$W_0 = C_{DV} A_0(t) P_0 \left[ \frac{g_0 \gamma}{RT} \left( \frac{2}{\gamma + 1} \right)^{\frac{\gamma + 1}{\gamma - 1}} \right]^{\frac{1}{2}}$$

(5)

where $A_0(t)$ is the valve orifice area as a function of time, and $C_{DV}$ is the valve discharge coefficient. During the subsequent period, when the pressure ratio $P_c/P_0$ is greater than 0.528 ($t_{r1} < t < t_{r2}$), the flow rate through the orifice is subsonic and is given by the following equation:

$$W_0 = \frac{P_0 A_0(t) a^*}{RT} \left( \frac{P_c}{P_0} \right)^{\frac{1}{\gamma}} \left\{ \frac{2}{\gamma - 1} \left[ 1 - \left( \frac{P_c}{P_0} \right)^{\frac{\gamma - 1}{\gamma - 1}} \right] \right\}^{\frac{1}{2}}$$

(6)

where $a^*$ is the characteristic sonic velocity (equal to $\sqrt{g_0 \gamma RT}$). At a time $t = t_{r2}$, the rate of pressure buildup in the chamber becomes zero (i.e., chamber pressure is constant), and the flow through the orifice equals the flow out of the nozzle until such time $t_2$ as the valve starts to close.

This is the steady-state thrust case and is described in detail, along with performance losses, in Ref. 1, where

$$W_N = W_0, \quad \frac{dP_c}{dt} = 0$$
From the time \( t_2 \) the valve starts to close until the time \( t_3 \) when it is fully closed, the flow through the valve orifice is subsonic and is given by Eq. (6). For \( t \geq t_3 \), the valve is fully closed \( (W_0 = 0) \), and the gas accumulated in the chamber is discharged by an isentropic process through the nozzle \( (W_N = -W_0) \). The density ratio for isentropic expansion is

\[
\frac{\rho}{\rho_3} = \left( \frac{P_c}{P_{c3}} \right)^{\frac{1}{\gamma}}
\]

where the subscript 3 refers to conditions at \( t = t_3 \) and \( \rho \) is the gas density. Using Eq. (1) for the initial weight of gas trapped in the chamber, Eq. (7) becomes

\[
W_N = \frac{V_c P_{c3}}{RT_{c3}} \left( \frac{P_c}{P_{c3}} \right)^{\frac{1}{\gamma}}
\]

Differentiating \( P_c \) with respect to time, and substituting Eq. (4) and the equation

\[
\frac{T_c}{T_{c3}} = \left( \frac{P_c}{P_{c3}} \right)^{\frac{\gamma-1}{\gamma}}
\]

into the results and then integrating from \( t_3 \) to any time \( t > t_3 \) gives the following equation for decay pressure as a function of time:

\[
P_c(t) = P_{c3} \left[ 1 - \frac{(1 - \gamma) A_2(t - t_3)}{2} \right]^{\frac{2\gamma}{1-\gamma}}
\]

where \( A_2 \) is defined in Table 1.
Equations (5) and (6) require that the valve area as a function of time, \( A_0(t) \), be known. Appendix A of Ref. 1 details the derivation of the steady-state (valve full open) valve orifice effective area (\( A_{0,ss} \)). This value as a function of valve ball travel \( T_B \) and for a ball radius of 0.24 cm (0.094 in.) and a seat radius of 0.17 cm (0.066 in.) (MM'71 data) is (Eq. A-11 of Ref. 1)

\[
A_0 = \frac{(0.2073)(T_B)(0.134 + T_B)}{\left[0.008836 + T_B(0.134 + T_B)\right]^{1/2}}
\]

Since it can be demonstrated (Ref. 2) that the particular solenoid valve will open \((t_1)\) and close \((t_3 - t_2)\) in both cases in less than 1 ms, and since the total on time \( t_2 \) is 20 ms or greater, it is a reasonable approximation that the ball opening and closing is a linear function of time. Figures 3a-c demonstrate the typical electrical and pneumatic properties of the valve under study as a function of time. Figure 3d is, therefore, the mathematical representation of the valve orifice area as a function of time as developed from Fig. 3c. With reference to Fig. 3d, the following equations for \( A_0(t) \) can be developed:

\[
A_0(t) = \frac{(A_0)(t)}{(t_1)} \quad 0 < t < t_1 \tag{11a}
\]

\[
A_0(t) = A_0 \quad t_1 < t < t_2 \tag{11b}
\]

\[
A_0(t) = \frac{(A_0)(t_3 - t)}{(t_3 - t_2)} \quad t_2 < t < t_3 \tag{11c}
\]

\[
A_0(t) = 0 \quad t > t_3 \tag{11d}
\]

For this study, the values of \( t_1, t_2, t_3 \) which represent the MM'71 flight data are taken from Ref. 2 and tabulated in Table 2. In this table, the appropriate values for the MM'64 valves are also tabulated such that the computer program results for the two flight programs can be compared.
With the value for \( A_0(t) \) thus determined, the chamber pressure \( P_c(t) \) and the flow rates \( W_N(t), W_0(t), \) and \( W_c(t) \) can be calculated using the appropriate equations previously defined. With the flow rates known, the accumulated mass \( (m_0, m_N, \) or \( m_c) \) is determined by solving the integral

\[
m = \int_t W \, dt
\]

with the appropriate flow rate equation over the appropriate time interval. The total effective impulse \( I \) is given by the integral

\[
I = \int_{t=0}^{t=\infty} F_{\text{net}}(t) \, dt
\]

where, from Ref. 1,

\[
F_{\text{net}} = (1 - \text{losses}) P_c A_t C_{DN} \left[ \frac{2\gamma^2}{\gamma - 1} \left( \frac{2}{\gamma + 1} \right)^{\gamma - 1} \right]^{\frac{1}{2}}
\]

and thus,

\[
I = K \int_{t=0}^{t=\infty} P_c(t) \, dt
\]

where

\[
K = A_t C_{DN} (1 - \text{losses}) \left[ \frac{2\gamma^2}{\gamma - 1} \left( \frac{2}{\gamma + 1} \right)^{\gamma - 1} \right]^{\frac{1}{2}}
\]

The thrust losses are taken into account in Eq. (14). These losses, derived and explained in Ref. 1, are assumed here to be a constant as a function of
time. It is also assumed that both the inlet pressure $P_0$ and the inlet temperature $T_0$ stay constant as a function of time. The actual specific impulse $I_{sp}$ for nitrogen at ambient temperature $T_0$ is

$$I_{sp}(at\ T_0) = \frac{I}{m_0} \tag{15}$$

Reference 3 gives an estimated temperature profile for the entire MM$^171$ mission, including Mars occultation. If the specific impulse at any other temperature $T$ is desired, the following equation can be used:

$$I_{sp}(at\ T) = I_{sp}(at\ T_0) \left(\frac{T}{T_0}\right)^{\frac{1}{2}} \tag{16}$$

However, it should be remembered that the total impulse $I$ does not change, since $I_{sp} \propto \sqrt{T}$ and $m_0 \propto 1/\sqrt{T}$ (see Eq. 15).

For the purposes of this report, an "effective" valve on time will be defined as

$$\Delta t_e = \frac{I}{\text{steady-state thrust}} \tag{17}$$

Furthermore, an equivalent "tailoff" on time, $t_{t0}$, will be defined as

$$t_{t0} = \Delta t_e - (\text{actual valve on time})$$

$$t_{t0} = \Delta t_e - t_2 \tag{17}$$

The use of the two time values, $\Delta t_e$ and $t_{t0}$, in the sizing of a gas system for attitude control system application is explained in Ref. 2.

III. DIGITAL COMPUTER SOLUTIONS

With all the relevant equations available, a number of methods may be used to obtain the sought after solutions. Reference 4, from which much
of the above discussion is abstracted, details a solution assuming a constant flow density. Reference 5 describes a solution that can readily be implemented on an analog computer. The solution method used in this study involves numerical differentiation and integration programmed for a Univac 1108 computer using in part the existing program for the steady-state analysis discussed in Ref. 1. The computer flowchart for the steady-state portion of this analysis is given in Ref. 1, along with a list of nomenclature. For the transient analysis, which is the principal concern here, the equations previously derived must be written in the appropriate computer format for numerical differentiation and integration. This has been done for all the equations and is summarized in Table 1. The computer flow diagram for the transient analysis is given in Fig. 4. The transient analysis is added onto the end of the steady-state analysis program and is called up at statement number 600 in the main program, as can be seen by the list-print (Fig. 5). The input to the entire program is via a single read card (the variable NZ controls the number of possible read cards) which uses a 7F10.5 format to read in the seven variables on a single horizontal line in Table 2. All other data, including those in Table 3, are fixed and already in the program for this study.

In addition to the steady-state printout shown in Fig. 6, the program is also set up to print out in tabular form, in 0.1-ms intervals, the values of the following variables: t, A0(t), MC(t), M0(t), MN, PC(t), ΔP/ΔT, I(t), WC(t), W0(t), and WN(t). The program also plots out the last nine of these variables as a function of time (see Figs. 7-10).

IV. CONCLUSIONS

Figures 7-10 show the plots for the four cases (defined in Table 2) studied for this report. Table 4 summarizes these plots. From the table, a number of conclusions can be drawn.

(1) On the MM'64 pitch and yaw valves, the area ratio (ratio of valve seat area to nozzle throat area) was 24.5:1. As a result, the transient flow rate for a short period of time is greater than 15 times the steady-state flow, with a 56% increase in impulse per pulse for a nominal 20-ms valve on time.
The equivalent area ratios for the MM'71 pitch/yaw and roll valves are 6.24 and 2.38, respectively. With these much lower ratios, the resulting increase in impulse per pulse is only 4 and 3%, respectively, for a nominal 79.5- and 27.3-ms value on time. Note that the 4% figure would have increased only slightly had the nominal on time been closer to 20 ms.

From these test points, it is concluded that for area ratios of less than 10:1, the impulse per pulse (and gas consumed per pulse) calculated by the much simpler steady-state approach would be in error on the low side by less than 10%.

(2) As expected, the gas vacuum specific impulse is the same (within 4%) when calculated by either the transient or steady-state approach.

(3) All computer runs were made assuming a local ambient temperature of 25°C. No attempt was made to determine an in-flight ambient or gas temperature, although this could be done.

(4) The shortest electrical valve on time assumed was 20 ms. Since pressure and flow rate build up to their steady-state value in a short period of time (usually less than 2.0 ms), steady-state approximations for value times of somewhat less than 20 ms should be valid.

(5) For this study, it was assumed that the discharge coefficients (losses) stay constant over the relatively short transient flow periods.
REFERENCES


Table 1. Summary of computer equations\textsuperscript{a}

<table>
<thead>
<tr>
<th></th>
<th>(a)</th>
<th>(b)</th>
<th>(c)</th>
<th>(d)</th>
<th>(e)</th>
<th>(f)</th>
<th>(g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_0$</td>
<td>$0 &lt; P &lt; 0.5 \overline{P}$</td>
<td>$0.5 \overline{P} &lt; P &lt; P_{\text{case}}$</td>
<td>$P + P_{\text{case}}$</td>
<td>$0 &lt; P &lt; 0.5 \overline{P}$</td>
<td>$0.5 \overline{P} &lt; P &lt; P_{\text{case}}$</td>
<td>$P + P_{\text{case}}$</td>
<td>$0 &lt; P &lt; 0.5 \overline{P}$</td>
</tr>
<tr>
<td>$\phi$</td>
<td>$t &lt; t_1$</td>
<td>$t_1 \leq t \leq t_2$</td>
<td>$t_2 &lt; t &lt; t_3$</td>
<td>$t \geq t_3$</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

1. $A_2(0)$

2. $A_3 A_2(0) : A_3(2P + 1)$

3. $\frac{\phi}{2}$

4. $W_0(0)

5. $W_0(0)

6. $W_0(0)

7. $W_0(0)

8. $W_0(0)

9. $W_0(0)

10. $W_0(0)

11. $W_0(0)

\textsuperscript{a} A_n = \Pi - \Pi \eta \text{ for } \eta = \frac{t}{t_0}

\textsuperscript{b} \phi = \Pi - \Pi \eta \text{ for } \eta = \frac{t}{t_0}

\textsuperscript{c} P = \frac{P_0}{P_0} \text{ for } \frac{P_0}{P_0} \text{ steady-state, and } P_{\text{case}} = \phi \eta \text{ at } t_1 \leq t_2$.
Table 2. Jet valve characteristics (computer input cards)

<table>
<thead>
<tr>
<th>Mission</th>
<th>Axis</th>
<th>( P_0 ), N/m² (psi)</th>
<th>( T_0 ), °C</th>
<th>( D_t ) a</th>
<th>( T_B ) b</th>
<th>( t_1 ) b</th>
<th>( t_2 ) b</th>
<th>( t_3 ) b</th>
</tr>
</thead>
<tbody>
<tr>
<td>MM'71 Pitch/yaw</td>
<td>1.0 \times 10^5 (15)</td>
<td>25</td>
<td>0.513 (0.0202)</td>
<td>0.173 (0.0068)</td>
<td>0.001</td>
<td>0.0795</td>
<td>0.0805</td>
<td></td>
</tr>
<tr>
<td>MM'71 Roll</td>
<td>1.0 \times 10^5 (15)</td>
<td>25</td>
<td>0.831 (0.0327)</td>
<td>0.173 (0.0068)</td>
<td>0.001</td>
<td>0.0273</td>
<td>0.0283</td>
<td></td>
</tr>
<tr>
<td>MM'64 Pitch/yaw</td>
<td>1.0 \times 10^5 (15)</td>
<td>25</td>
<td>0.290 (0.0114)</td>
<td>0.216 (0.0085)</td>
<td>0.001</td>
<td>0.020 c</td>
<td>0.021 c</td>
<td></td>
</tr>
<tr>
<td>MM'64 Roll</td>
<td>1.0 \times 10^5 (15)</td>
<td>25</td>
<td>0.374 (0.0147)</td>
<td>0.216 (0.0085)</td>
<td>0.001</td>
<td>0.020 c</td>
<td>0.021 c</td>
<td></td>
</tr>
</tbody>
</table>

a Nozzle throat diameter.
b See Fig. 3 for definition.
c Estimate.

Nozzle throat diameter.

See Fig. 3 for definition.

Estimate.
Table 3. MM'71 jet valve parameters (fixed)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nozzle discharge coefficient $C_{DN}$</td>
<td>1.0</td>
</tr>
<tr>
<td>Valve discharge coefficient $C_{DV}$</td>
<td>0.63</td>
</tr>
<tr>
<td>Ambient temperature $T_0$, °C</td>
<td>25</td>
</tr>
<tr>
<td>Valve ball diameter, cm (in.)</td>
<td>0.478 (0.188)</td>
</tr>
<tr>
<td>Valve seat diameter, cm (in.)</td>
<td>0.335 (0.132)</td>
</tr>
<tr>
<td>Nozzle geometric area ratio</td>
<td>250:1</td>
</tr>
<tr>
<td>Nozzle exit geometry half-angle, deg</td>
<td>25</td>
</tr>
<tr>
<td>Ratio of specific heats (nitrogen)</td>
<td>1.4</td>
</tr>
<tr>
<td>Nitrogen gas constant, N-m/kg K (ft-lbf/lbm °R)</td>
<td>$2.967 \times 10^2$ (55.16)</td>
</tr>
<tr>
<td>Ambient pressure, N/m$^2$ (psi)</td>
<td>0</td>
</tr>
<tr>
<td>Valve inlet pressure $P_0$, N/m$^2$ (psi)</td>
<td>$1.0 \times 10^5$ (15.0)</td>
</tr>
<tr>
<td>Valve chamber volume $V_C$, cm$^2$ (in.$^2$)</td>
<td>$7.48 \times 10^2$ (0.0116)</td>
</tr>
<tr>
<td>Time differential, s (DELT)</td>
<td>0.0001</td>
</tr>
</tbody>
</table>
### Table 4. Computer program results

<table>
<thead>
<tr>
<th>Mission</th>
<th>Throat diameter, cm (in.)</th>
<th>Chamber pressure (steady-state), N/m² (psi)</th>
<th>Thrust (steady-state), N x 10⁻³ (mib)</th>
<th>Flow rate (steady-state), g/s (lb/s)</th>
<th>Flow rate (transient), max, g/s (lb/s)</th>
<th>Flow rate max Flow rate, s⁻¹</th>
<th>Mass Pulse g (lb)</th>
<th>Impulse, N·s (lb·s)</th>
<th>Iₑₑ = I / Mₐₐ s</th>
<th>Iₑₑ / Wₛₛ ₐₐb</th>
<th>Δt, ms</th>
<th>tₑₑ (valve on time), ms</th>
<th>Δt, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>MM71 pitch/yaw</td>
<td>0.0513 (0.0202)</td>
<td>10.20 × 10⁻⁴ (14.8)</td>
<td>33.85 (7.61)</td>
<td>4.85 × 10⁻⁴ (0.107 × 10⁻³)</td>
<td>1.94 × 10⁻¹ (0.428 × 10⁻³)</td>
<td>4.0</td>
<td>4.03 × 10⁻³ (0.889 × 10⁻⁵)</td>
<td>2.80 × 10⁻³ (0.629 × 10⁻⁵)</td>
<td>70.8</td>
<td>71.2</td>
<td>82.7</td>
<td>79.5</td>
<td>3.2 104</td>
</tr>
<tr>
<td>MM71 roll</td>
<td>0.0831 (0.0327)</td>
<td>9.37 × 10⁻⁴ (13.6)</td>
<td>82.82 (18.62)</td>
<td>11.70 × 10⁻² (0.258 × 10⁻³)</td>
<td>1.94 × 10⁻¹ (0.428 × 10⁻³)</td>
<td>1.7</td>
<td>3.29 × 10⁻³ (0.726 × 10⁻⁵)</td>
<td>2.32 × 10⁻³ (0.522 × 10⁻⁵)</td>
<td>71.9</td>
<td>72.3</td>
<td>28.0</td>
<td>27.3</td>
<td>0.7 103</td>
</tr>
<tr>
<td>MM64 pitch/yaw</td>
<td>0.0290 (0.0114)</td>
<td>10.33 × 10⁻⁴ (14.98)</td>
<td>10.59 (2.36)</td>
<td>1.56 × 10⁻² (0.345 × 10⁻⁴)</td>
<td>2.42 × 10⁻¹ (0.534 × 10⁻³)</td>
<td>15.1</td>
<td>5.16 × 10⁻² (0.113 × 10⁻⁵)</td>
<td>0.331 × 10⁻³ (0.744 × 10⁻⁵)</td>
<td>66.1</td>
<td>68.9</td>
<td>31.3</td>
<td>20</td>
<td>11.3 156</td>
</tr>
<tr>
<td>MM64 roll</td>
<td>0.0374 (0.0147)</td>
<td>10.31 × 10⁻⁴ (14.96)</td>
<td>17.88 (4.02)</td>
<td>2.60 × 10⁻² (0.573 × 10⁻⁴)</td>
<td>2.42 × 10⁻¹ (0.534 × 10⁻³)</td>
<td>9.3</td>
<td>7.12 × 10⁻² (0.157 × 10⁻⁵)</td>
<td>0.476 × 10⁻² (0.107 × 10⁻⁵)</td>
<td>68.2</td>
<td>70.0</td>
<td>26.7</td>
<td>20</td>
<td>6.7 133</td>
</tr>
</tbody>
</table>

a Valve inlet pressure = 1.0 × 10⁵ N/m² (15.0 psi); valve inlet temperature = 25°C.
b Fₛₛ = steady-state thrust (see column 3); Wₛₛ = steady-state flow rate (see column 4).
Fig. 1. MM'71 jet valve model

Fig. 2. Typical valve chamber pressure profile

\[ \frac{P_c}{P_0} = \frac{CHAMBER \ PRESSURE}{VALVE \ INLET \ PRESSURE} \]

SEE FIG. 3 FOR \( t_2 \)

Fig. 3. Typical valve electrical and pneumatic characteristics:
(a) voltage to valve, (b) valve coil current, (c) valve chamber pressure, (d) valve orifice area
Fig. 4. Computer program flow chart
Fig. 5. Computer list printout of steady-state and transient thrust prediction program
Fig. 5 (contd)
Fig. 5 (contd)
Fig. 6. Steady-state printout: (a) MM'71 pitch/yaw, (b) MM'71 roll, (c) MM'64 pitch/yaw, (d) MM'64 roll
Fig. 7. MM'71 pitch/yaw valve parameters as a function of time: (a) chamber pressure, (b) total mass, nozzle, (c) total mass, chamber, (d) total mass, valve, (e) nozzle flow rate, (f) chamber flow rate, (g) valve flow rate, (h) total impulse, (i) chamber pressure derivative
Fig. 7 (contd)
Fig. 7 (contd)
Fig. 7 (contd)
Fig. 7 (contd)
Fig. 7 (contd)
Fig. 7 (contd)
Fig. 7 (contd)
Fig. 7 (contd)
Fig. 8. MM'71 roll valve parameters as a function of time: (a) chamber pressure, (b) total mass, nozzle, (c) total mass, chamber, (d) total mass, valve, (e) nozzle flow rate, (f) chamber flow rate, (g) valve flow rate, (h) total impulse, (i) chamber pressure derivative
Fig. 8 (contd)
Fig. 8 (contd)
Figure 8 (contd)
Fig. 8 (contd)
Fig. 8 (contd)
Fig. 8 (contd)
Fig. 8 (contd)
Fig. 9. MM'64 pitch/yaw valve parameters as a function of time: (a) chamber pressure, (b) total mass, nozzle, (c) total mass, chamber, (d) total mass, valve, (e) nozzle flow rate, (f) chamber flow rate, (g) valve flow rate, (h) total impulse, (i) chamber pressure derivative
Fig. 9 (contd)
Fig. 9 (contd)
Fig. 9 (contd)
Fig. 9 (contd)
Fig. 9 (contd)
Fig. 9 (contd)
Fig. 9 (contd)
Fig. 9 (contd)
Fig. 10. MM'64 roll valve parameters as a function of time: (a) chamber pressure, (b) total mass, nozzle, (c) total mass, chamber, (d) total mass, valve, (e) nozzle flow rate, (f) chamber flow rate, (g) valve flow rate, (h) total impulse, (i) chamber pressure derivative.
Fig. 10 (contd)
Fig. 10 (contd)
Fig. 10 (contd)
Fig. 10 (contd)
Fig. 10 (contd)
Fig. 10 (contd)
Fig. 10 (contd)