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TRANSIENT RESPONSE CHARACTERISTICS OF TEST CHAMBER MACH NUMBER

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By

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1. <u>Establishment of linear relationship between the Mach number and pressures.</u>

The test chamber Mach number is computed from the following equation:

$$M = \sqrt{5\left[\left(\frac{p_t}{p_s}\right)^{2/7} - 1\right]} \tag{1}$$

where

M = test chamber Mach number

p_t = test chamber stagnation, psf

p_s = test chamber static pressure, psf

Equation (1) is derived quasi-statically and is applicable only to the equilibrium states of the wind tunnel. Assuming that the tunnel is initially in equilibrium state 1, a second equilibrium state will eventually be reached after a stepped disturbance is initiated in the test chamber. The Mach number change between the two equilibrium states could be computed by equation (2).

$$\Delta M = \frac{5\left(p_{t_1}/p_{s_1}\right)^{2/7}}{7M_1}\left[\frac{\Delta p_t}{p_{t_1}} - \frac{\Delta p_s}{p_{s_1}}\right] \tag{2}$$

where

$\Delta M = M_2 - M_1$ = Mach number change

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$\Delta p_t = p_{t_2} - p_{t_1}$ = stagnation pressure change, psf

$\Delta p_s = p_{s_2} - p_{s_1}$ = static pressure change, psf

Equation (2) is the linear approximation of equation (1) and is valid for small changes of pressures only. The validity of equation (2) is established by a comparison in Table 1 of the Mach number changes computed from equation (1) with those computed from equation (2). Small variations between these two changes are seen. Note that SEL data of p_t and p_s were used for the calculation. In other words, for one ambient pressure (latm) and elevated temperature (120°F) flap-model test, a linear relationship between Mach number change and pressure changes exists for Mach number change up to ±.070. The block diagram in Figure 1 illustrates this cause-effect relationship. Note that the gain values in the three blocks of Figure 1 are different for different equilibrium conditions of the tunnel.

2. Relative contributions of the two pressure changes on the Mach number change.

The two terms inside the brackets of equation (2) are percentage changes of stagnation and static pressures. Experimental results of these two percentage changes are listed in Table 2. The last column shows the ratio of percentage change of static pressure over the percentage change of stagnation pressure. The average ratio found is -6.4. If a new variable, λ defined as the ratio of these two percentage changes is introduced, then equation (2) can be rewritten as:

$$\Delta M = -\frac{5\left(p_{t_1}/p_{s_1}\right)^{2/7}}{7M_1}\frac{\Delta p_s}{p_{s_1}}\left(1 - \frac{1}{\lambda}\right) \tag{3}$$

where

$$\lambda \equiv \left(\frac{\Delta p_s}{p_{s_1}}\right)\bigg/\left(\frac{\Delta p_t}{p_{t_1}}\right) = \left(\frac{p_{t_1}}{p_{s_1}}\right)\left(\frac{\Delta p_s}{\Delta p_t}\right) \tag{4}$$

The negative sign of λ indicates that the two pressure changes are opposite in signs, i.e., when one increases then the other decreases and vice-versa. The magnitude of λ shows that the test chamber Mach number change is dominated by the test chamber static pressure change. Therefore, equation (3) can be approximated as

$$\Delta M \approx -\frac{5\left(p_{t_1}/p_{s_1}\right)^{2/7}}{7M_1}\left(\frac{\Delta p_s}{p_{s_1}}\right) \qquad (5)$$

3. Mach number response speed.

A set of experimental data of test chamber pressure changes (from FM recordings) as shown in Figure 2 illustrated that these changes are almost instantaneous at subsonic speeds and are completed within three seconds at $M = 1.20$. Thus, according to equation (5), fast response speed on Mach number is implied. Since the approximation given by equation (5) is only good for $\frac{\lambda}{\lambda - 1}$ or 86% of the total Mach number change, it means that once the test section is disturbed, the test chamber Mach number will be changed almost instantaneously to within 86% of its total change. The final 14% change of test chamber Mach number then will be dictated by the large time constant (6 or 8 seconds) of the stagnation pressure change Δp_t as given by equations (2) or (3). The dynamic relationship between the drag change ΔD in the test chamber and the resulting Mach change ΔM can be described by the block diagram shown in Figure 3.

It should be noted that gain K in the first block of Figure 3 has the unit of psf/lb and assumes different values for different equilibrium conditions of the test chamber. Experimental values of K were found at .0168, .0313, .0617, 0.143 for nominal Mach numbers of .80, .95, 1.05, 1.20, respectively.

4. Summaries and recommendations.

The following characteristics of the test chamber Mach number change ΔM due to disturbance ΔD initiated in the test chamber were observed experimentally:

a. ΔM can be computed from the linearly approximated expression given by equation (2). This implies that ΔM is linearly proportional to the algebraic sum of the static pressure change Δp_s in the test chamber and the stagnation pressure change Δp_t . The establishment of this linearity should simplify the on-line computation requirement and procedure of Mach number change significantly.

b. Δp_s is the dominating factor in determining ΔM . Percentage change of Δp_s was found approximately 6.4 times the percentage change of Δp_t. Since Δp_s occurs rather rapidly, it means that ΔM also changes very rapidly initially when Δp_s is the dominating factor. The last portion of ΔM (about 14% of the total change) is a sluggish process influenced by the large time constant of Δp_t .

The dynamic characteristic of test chamber Mach number change is thus established and is shown in Figure 3.

The following requirements on instrumentation were also observed based on experimental evidence:

a. Together with equation (2) and data in Tables 1 and 2, it is possible to calculate the two pressure changes for small Mach number variations. Table 3 lists these pressure changes for Mach number changes of .002 at different operating conditions. This implies that the stagnation pressure measurement device has to be sensitive to the fraction of one psf in order to control the test chamber Mach number with an accuracy of .002.

b. If the test chamber Mach number is the desirable Mach number to be controlled, then either the probe of the pressure measuring device should be located inside the test chamber or the dynamic enhancement technique developed at IRD or other prediction techniques should be applied to the pressure measurements made outside the test chamber. A trace of the static pressure made by a probe in the plenum obtained on the SEL system is shown in Figure 4. A lag in response is clearly indicated. It is fairly safe to assume that this lag is due to the combination of the dynamics of the plenum filling or emptying process and the dynamics of the manometer.

Table 1. Mach Number Changes.

Nominal Mach Number	Test Number	M_1 (initial)	M_2 (final)	$\Delta M = M_2 - M_1$	ΔMc (using Eq. 2)	$\left\lvert \frac{\Delta M - \Delta Mc}{\Delta M} \right\rvert \times 100\%$
M = .8	2253	.8000	.7854	-.0146	-.0145	.68
	2254	.7852	.8007	.0155	.0155	0
	2255	.8018	.7876	-.0142	-.0141	.70
	2256	.7879	.8018	.0139	.0140	.71
M = .95	1824	.9532	.9191	-.0341	-.0340	+.29
	1825	.9173	.9497	.0324	.0320	1.23*
	1826	.9525	.9187	-.0338	-.0336	.59
	1827	.9151	.9486	.0335	.0328	2.09
M = .95	2145	.9521	.9191	-.0330	-.0332	.61
	2146	.9175	.9495	.0320	+.0318	.63
	2147	.9514	.9190	-.0324	-.0324	.0
	2148	.9178	.9499	.0321	.0318	.93
M = 1.05	1931	1.0530	.9802	-.0728	-.0728	.0
	1932	.9762	1.0439	.0677	.0664	1.92*
	1933	1.0536	.9802	-.0734	-.0733	+.14
	1934	.9759	1.0440	.0681	.0662	2.79*
M = 1.2	2038	1.1966	1.1659	-.0307	-.0308	.33
	2039	1.1652	1.1960	.0308	.0305	.97
	2040	1.1974	1.1658	-.0316	-.0317	.32
	2041	1.1657	1.1959	.0302	.0300	.66

* State 2 has not reached equilibrium.

Table 2. Pressure Changes.

Nominal Mach Number	Test Number	p_s, static pressure, psf				p_t, stagnation pressure, psf				Pressure Ratio λ
		p_{s_1} (initial)	p_{s_2} (final)	$\Delta p_s \equiv p_{s_2} - p_{s_1}$	$\left\lvert\frac{\Delta p_s}{p_{s_1}}\right\rvert \times 100\%$	p_{t_1} (initial)	p_{t_2} (final)	$\Delta p_t \equiv p_{t_2} - p_{t_1}$	$\left\lvert\frac{\Delta p_t}{p_{t_1}}\right\rvert \times 100\%$	
M = .80	2253	1391.2	1409.0	17.8	1.28	2120.8	2117.3	-3.5	+.17	-7.5
	2254	1409.8	1391.8	-18.0	+1.28	2117.9	2122.9	5.0	.24	-5.3
	2255	1391.3	1408.1	16.8	1.21	2124.2	2120.0	-4.2	.20	-6.1
	2256	1408.0	1391.9	-16.1	+1.14	2126.8	2125.7	4.9	.23	-5.0
M = .95	1824	1183.5	1222.7	39.2	3.31	2122.5	2111.4	-11.1	+.52	-6.4
	1825	1225.5	1188.9	-36.6	2.99	2112.2	2123.5	11.3	.53	-5.6
	1826	1183.7	1222.5	38.8	3.28	2121.5	2110.6	-10.9	.51	-6.4
	1827	1223.8	1186.2	-37.6	3.07	2105.7	2116.8	11.1	.53	-5.8
M = .95	2145	1183.2	1222.0	38.8	3.28	2120.7	2110.9	-9.8	+.46	-7.1
	2146	1224.9	1189.1	-35.8	+2.92	2111.8	2123.8	12.0	.57	-5.1
	2147	1184.1	1222.5	38.4	3.24	2120.0	2111.3	-8.7	.41	-7.9
	2148	1226.4	1190.7	-35.7	+2.91	2114.7	2127.2	12.5	.59	-4.9
M = 1.05	1931	1051.1	1132.3	81.2	7.73	2118.6	2096.0	-22.6	+1.07	-7.2
	1932	1138.6	1064.9	-73.7	+6.47	2096.7	2120.7	24.0	1.14	-5.7
	1933	1051.2	1132.6	81.4	7.74	2120.3	2096.9	-23.4	+1.10	-7.0
	1934	1138.8	1064.8	-74.0	+6.50	2096.6	2119.7	23.1	1.10	-5.9
M = 1.20	2038	877.6	906.1	28.5	3.25	2118.5	2102.2	-16.3	.77	-4.2
	2039	902.3	869.0	-33.3	+3.69	2091.3	2097.5	6.2	.30	-12.3
	2040	876.4	908.4	32.0	3.65	2117.7	2107.5	-10.2	.48	-7.6
	2041	908.8	878.5	-30.3	3.33	2108.1	2118.9	10.8	.51	-6.5

Table 3. Pressure variations for Mach number variations of .002.

Nominal Mach Number	p_s, static pressure		p_t, stagnation pressure	
	$\lvert \Delta p_s \rvert$	$\left\lvert \frac{\Delta p_s}{p_{s_1}} \right\rvert \times 100\%$	$\lvert \Delta p_t \rvert$	$\left\lvert \frac{\Delta p_t}{p_{t_1}} \right\rvert \times 100\%$
M = .80	2.37	.17	.60	.028
M = .95	2.30	.19	.67	.032
M = 1.05	2.21	.20	.66	.031
M = 1.20	2.01	.23	.71	.034

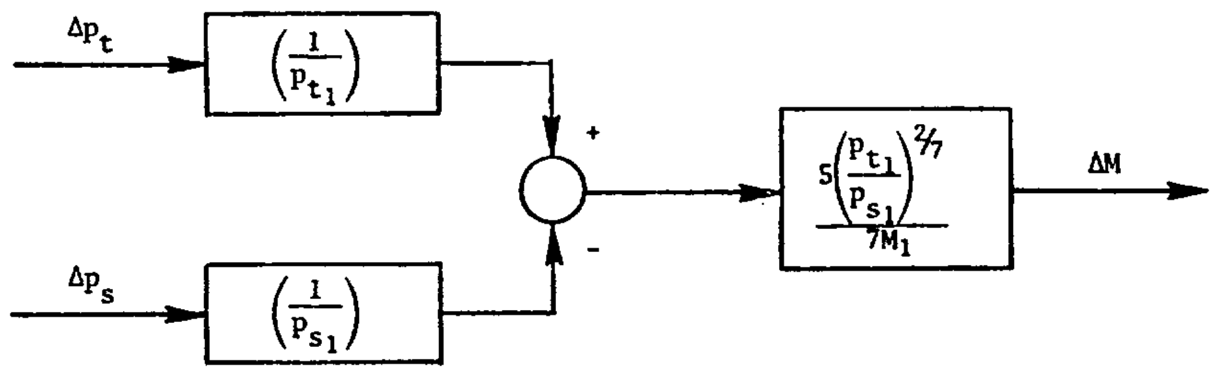

Figure 1. Linear (static) Relationship between Mach Number Change and Pressure Changes.

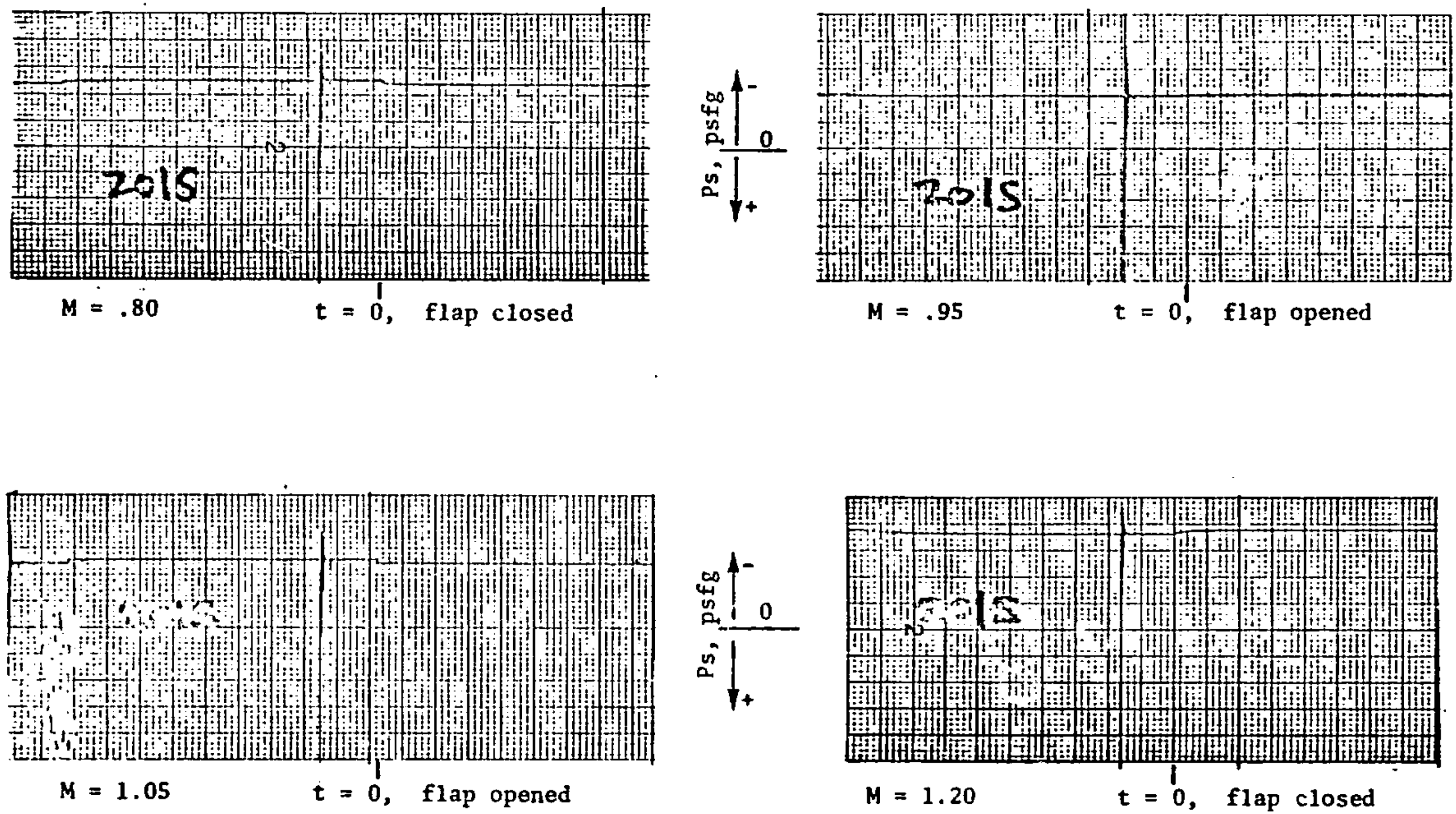

Figure 2. Test Chamber Static Pressures.

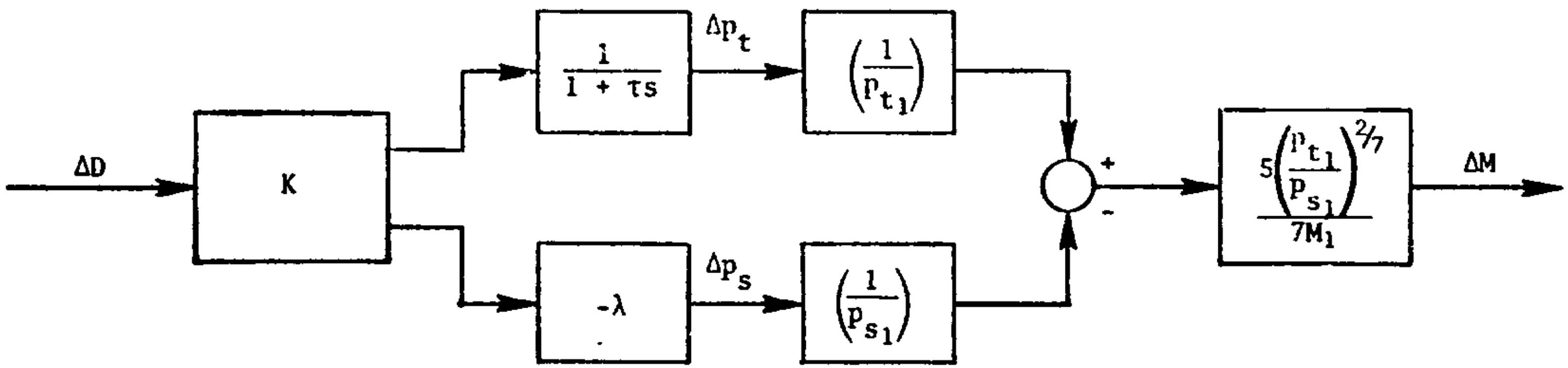

Figure 3. Dynamic Relationship between Mach Number change and Drag change.

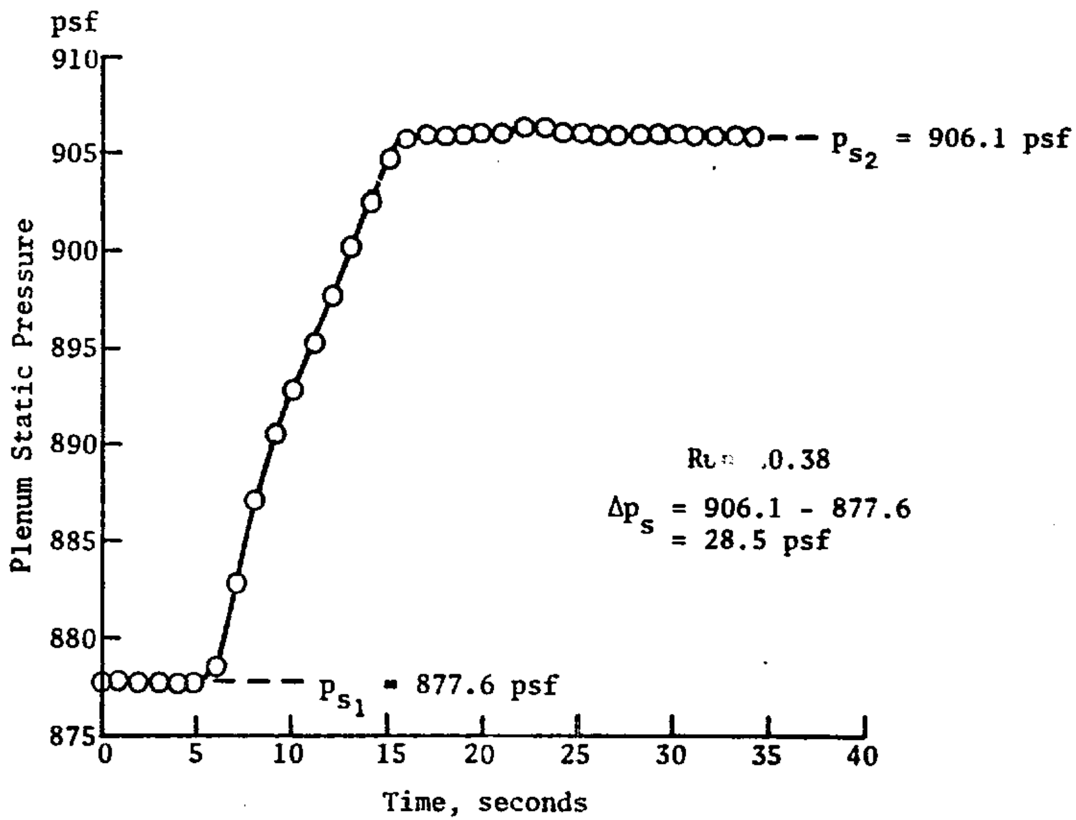

Figure 4. Plenum Static Pressure.

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