REPORT OF THE PANEL ON DYNAMICS AND AEROELASTICITY

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INTRODUCTION

Flutter is a dynamic phenomenon which involves the interaction of elastic, inertial, aerodynamic, and temperature-induced forces. (See fig. 1.) At speeds below the flutter point, these forces are interrelated in such a way that any induced excitation of the lifting-surface structure will rapidly damp; at speeds above the flutter point, induced excitations will grow in amplitude (unless restricted by nonlinear effects) and will lead to destruction of the structure.

In view of these possible catastrophic effects, all commercial and military aircraft must be shown to be flutter free by a combination of analysis and experiment. The experimental investigation usually involves the proof testing of complex models which may cost as much as one-half million dollars. To provide an adequate proof test, properly scaled models and specialized wind tunnels are required.

Model scaling will first be reviewed; this review is followed by a brief description of the characteristics of the Langley transonic dynamics tunnel (TDT), a tunnel which was specifically designed for flutter testing. The unique characteristics of the National Transonic Facility (NTF) will be reviewed in the light of dynamic testing. Overlap considerations will be mentioned and will be followed by several recommended test programs.

MODEL SCALING

The model-scaling laws may be obtained by examination of the equations of motion. The scaling parameters are

Mass ratio:

$$\frac{m_m}{\pi\rho_m b_m^2} = \frac{m_A}{\pi\rho_A b_A^2} \tag{1}$$

Mach number:

$$\frac{V_m}{a_m} = \frac{V_A}{a_A} \tag{2}$$

Reduced frequency:

$$\frac{\omega_m b_m}{V_m} = \frac{\omega_A b_A}{V_A} \tag{3}$$

Froude Number:

$$\frac{g_m b_m}{V_m^2} = \frac{g_A b_A}{V_A^2} \tag{4}$$

where

- m structural mass per unit length
- ρ fluid density
- b half-chord
- V velocity
- a speed of sound
- ω frequency
- g gravity

Subscripts:

- m designated model
- A full-scale airplane

Another parameter which has essentially been neglected in flutter work is Reynolds number (R):

$$R = \frac{\rho_m V_m b_m}{\mu_m} = \frac{\rho_A V_A b_A}{\mu_A} \tag{5}$$

when μ is the kinematic viscosity.

For the noncryogenic tunnel, scaling parameters (eqs. (1), (2) and (3)) have been found to be adequate for dynamic model testing of high-speed aircraft. The Froude number (gravity ratio, eq. (4)) is used when static deflections are important. With the advent of the NTF, then it is possible for a dynamic model to be scaled according to the scaling parameters of equations (1), (2) and (3), and to maintain a full-scale Reynolds number capability. As an example of possible model scaling, the following table contrasts a fighter-type model at $M = 1$ (where the model span has been selected as 0.6 of the test section width) where the model was scaled for both the TDT (in freon) and the NTF.

Model/Full-scale values:	TDT	NTF
Length	0.2	0.1
Velocity	0.46	0.56
Temperature	1.1	0.31
Dynamic pressure	0.19	4.2
Density	0.9	13.2
Reynolds Number	0.11	1.0
Model Weight, kg (lb)	130 (287)	244 (538)
Model frequency, Hz	16	38
Wing density, $kg/m^3 (lb/in^3)$	305 (.011)	4430 (0.16)
Stress ratio	1	3

The wing density for the NTF model is about one-half that of steel, and thus it appears possible to construct the wing of steel. The high dynamic pressure experienced by the model in NTF is about 22 times that experienced by the model in the TDT, which could pose a serious static loads problem. For the example noted, however, the NTF test Reynolds number is an order of magnitude greater than that for the TDT.

An important characteristic of a cryogenic tunnel on model construction is related to the ability of the tunnel temperature to be changed independently of Mach number. As pointed out in reference 1, a single model could be tested near 273 K (32°F) with a temperature variation of only ±40 K (± 72°F) and meet the scaling requirement for M = 0.6 to M = 1.3 and maintain the proper mass ratio for each flight altitude. At these conditions, however, the Reynolds number would not be satisfied.

CHARACTERISTICS OF THE LANGLEY TRANSONIC DYNAMICS TUNNEL

The Langley transonic dynamics tunnel is an example of a tunnel which was designed specifically for dynamics testing, and it is thought to be appropriate to review some of the characteristics of the tunnel which should be considered early in the design of the NTF if it is to be used as an adjunct to the TDT. Figure 2 illustrates the slotted test-section including a cable-mounted model.

Transonic Capability

The tunnel operates from low subsonic speeds to M = 1.2. The critical flutter region is from moderate subsonic speeds through the transonic speed to low supersonic speeds. A typical flutter boundary is shown in figure 3, where the dynamic pressure is plotted against Mach number. Note the typical dip in the flutter boundary as the transonic region is approached. The TDT performance capability is also given in the figure. The radial lines emanating from the origin are constant total pressure lines. (The tunnel may be operated from a low pressure to atmospheric.) A typical test would be conducted along a radial line (constant pressure) until the flutter condition was found. The pressure in the tunnel is then changed so that an intersection would be determined at a different Mach number, and thus the flutter boundary is traced.

Test Medium

The TDT utilizes either air or freon as a testing medium. The use of freon has two advantages: (1) Its density is four times that of air: thus the construction of dynamic models is made much easier since one of the primary nondimensional flutter parameters is $m/\pi\rho b^2$ where m is the structural mass per unit length, ρ is the density of the test medium, and b is the half-chord. (2) Its low speed of sound (one-half that of air) not only reduces the power required for tunnel operation for a given Mach number but also reduces the model scaled frequencies leading to simplified model construction (e.g. lower frequency requirements on model control surface actuators and instrumentation).

Test-Section Size

In order to simulate structural details, large models are generally required. The 4.88m (16-foot) test-section size of the TDT has been very adequate for this purpose.

Rapid Tunnel Shutdown

Some of the flutter models tested in TDT have cost about one-half million dollars, and during an extensive series of flutter tests, it is mandatory that the model be saved from destructive flutter. To obtain the capability of reducing the dynamic pressure quickly, a valve was installed in the tunnel which reduces the dynamic pressure by 1.91 kN/m^2 (40 psf) within a few seconds.

Model Visibility

The TDT has a very large plenum chamber. In order to allow the operators of flutter tests to observe the model directly during tests, a control room, accessible to the outside, was constructed inside the plenum chamber so that observation windows could be installed in the tunnel wall. Thus, during a test, an operator can directly view the model and can operate the valve which quickly reduces the tunnel dynamic pressure if flutter occurs.

Tunnel Protection

The possibility always exists that a flutter model will be destroyed and the debris carried around the tunnel to the fan. The TDT has specially designed screens to protect the machinery.

Model Support

Models in TDT are supported by three methods: (1) wall mount, (2) sting mount, and (3) cable support. The cable-support system was devised so that free-flight motions could be ascertained in flutter model tests.

Data Acquisition and Instrumentation

Instrumentation for dynamic studies includes the use of pressure cells for measurement of unsteady pressures, strain gages and accelerometers to measure frequencies, and transducers to measure wing and control surface positions. The use of these transducers in a cryogenic environment must be investigated, and the Langley 0.3-m transonic cryogenic tunnel (TCT) should be used in this development.

The presently proposed data system for NTF should be examined to determine whether the frequency response is suitable for dynamic testing. It should be pointed out that the TDT has recently acquired a $2.7 million dynamic data system. This system is proving to be exceedingly valuable, particularly in reducing the tunnel test time in that a complete test can be programed and run, the data being automatically recorded, analyzed, and plotted. In some cases, the data system is used during the test to analyze a record of random model motion at speeds below the flutter velocity and extract the system damping. During the test the engineer can decide whether to proceed to a higher tunnel speed or extrapolate to the flutter point without actually encountering flutter.

Model Construction and Checkout

The models used in TDT are constructed from a variety of materials including balsa wood, composites, aluminum, titanium, and steel. The question arises as to the construction techniques which may be necessary for a model to withstand the cryogenic temperature as well as the high dynamic pressures in the NTF. Normally, a flutter model is designed on the basis of the flutter scaling parameters and is tested at near zero angle of attack because the load-carrying ability is very low. This is necessary so that the model will flutter within the operating range of the tunnel. In order to utilize the potential of the NTF, namely, high Reynolds number, a high pressure which results in very high dynamic pressures is required. This raises the question of whether a flutter model can be constructed to withstand the severe environment and still provide an adequate flutter test. Therefore, it is suggested that a flutter model be designed for the purpose of determining the practicability of constructing a model to be used in NTF. The model materials must be adequate to withstand the possibility of thermal shock as well as fatigue.

Flutter models are exhaustively tested before entering the tunnel. For instance, the model is vibrated to insure that both frequency and mode shape are within the range desired to simulate a full-scale airplane. Thus, a separate "cold room" facility may be required for NTF in which models would be remotely tested under the anticipated conditions of the test.

Many of the models will require actuators to oscillate the complete wing or control surfaces. Miniaturized hydraulic and/or electrical actuators will be required. The effect of cryogenic temperatures and high dynamic pressures on their operation must be investigated.

CHARACTERISTICS OF NTF OF SPECIAL IMPORTANCE FOR DYNAMICS AND AEROELASTICITY

There are two major characteristics of the NTF which make it useful for dynamic or flutter testing. First, with the ability to adjust fluid temperature independent of Mach number, the potential exists for flutter testing a given model at different values of the mass ratio $m/\pi\rho b^2$ at a given Mach number. The second unique feature is, of course, the ability to test at full-scale Reynolds number.

Mass Ratio Variation

For flutter test in the TDT, a model is constructed for one particular mass ratio, which corresponds to a specific altitude and Mach number. A test in TDT proceeds along one of the radial lines of constant pressure until it intersects the flutter boundary, and the intersection could correspond to the value of mass ratio for which the model was designed (see fig. 3). If one desires to determine the complete flutter dip near $M = 1$ in the TDT, a different tunnel pressure is selected and the test proceeds in the same manner, and another intersection with the flutter curve is obtained. The mass ratio for this point will not exactly correspond to the altitude-Mach number relationship desired. If the flutter curve is well above the operation curve, the effect may be ignored. On the other hand, one could analytically correct the flutter speed to account for the improper density. Also, for the TDT, it is conceivable that a series of models could be constructed, each having the proper density ratio for a certain Mach number and altitude. This is not usually done.

The use of the NTF could obviate this difficulty since the temperature can be independently controlled and thus the proper density-Mach number relationship can be obtained.

Reynolds Number

The primary justification for the NTF is the ability to obtain full-scale Reynolds number at transonic speeds. For flutter, the effect of Reynolds number has been largely ignored, principally because no facility existed to establish Reynolds number effects over a significant range. With the advent of the NTF, it now appears likely that this assumption may be investigated. Actually, for wing flutter, theory and model experiments have been in rather good accord. The principal discrepancies in flutter speed have occurred in control surface flutter, and it is in this area that it is thought that the greatest contribution can be made. Control surface aerodynamic derivatives have notoriously been in serious error, and it has been usually attributed to flow breakdown and Reynolds number effects.

Accurate control surface aerodynamics are needed not only for flutter but also for the accurate design of optimal control systems for ride quality, stabilization, reduced static margin, etc.

A plot of the Reynolds number capability of the TDT and the NTF is shown in figure 4, and it is apparent that the new tunnel would open up the whole range of Reynolds number. Therefore, it is strongly recommended that the initial tests in the NTF be concerned with the measurement of wing and control surface oscillating aerodynamic derivatives.

Tied in with this concept, an investigation should be made to determine whether the NTF can be used as an adjunct to complete flutter model tests in the TDT. That is, conduct tests on simplified models at full-scale Reynolds numbers and in the NTF, then, by use of this data, design adjusted flexible dynamic models to be flutter tested later in the TDT.

SOME REMARKS CONCERNING CHANGES TO NTF FOR DYNAMIC TESTING

The features of the TDT which make it unique for flutter testing have already been discussed. If the NTF is to be used for flutter testing, some of these TDT features would be highly desirable. These are:

(1) Rapid tunnel shutdown

(2) Ability for operator to observe model during test

(3) Protective screens for fans to contain debris after destructive flutter

(4) Several types of model support systems (namely, provisions for a wall mount and a "soft" model suspension system)

(5) A rapid dynamic data-acquisition system

(6) A room for checkout of the model at cryogenic temperatures.

OVERLAP ASPECTS

Because of the high dynamic pressure in the tunnel, it is very probable that models designed for static investigation may experience undesirable response. Some possible problem areas are

(1) Large unwanted structural distortions which may obscure the Reynolds number effects being investigated

(2) Stresses so high that the model is destroyed

(3) Divergence

(4) Flutter

(5) Buffeting

(6) Dynamic response due to shock interaction

It appears that a complete criteria document should be written that outlines the tunnel conditions, the possible model instabilities, and the depth of analysis required to obviate these potential problems. Possibly, an inhouse group should be organized to provide the necessary guidance and know-how to check any model design before it enters the tunnel.

RECOMMENDED PROGRAM FOR THE NTF

Before embarking on extensive programs in the NTF, it was felt by the panel that a considerable amount of precursor work could be done in the Langley 0.3-m transonic cryogenic (0.3-m TCT) tunnel. For instance, it is entirely possible that some of the proposed programs for NTF could be considerably modified or eliminated if the 0.3-m TCT were used with the viewpoint of assisting in designing the test for the NTF, including the development of instrumentation, test techniques, etc.

It is felt that it would be highly desirable for the NTF design group and the aeroelastic group to hold meetings in the near future to assure that the items brought out in this report may be discussed in greater depth and thereby provide a greater appreciation of the viewpoints of other scientists.

Some of the dynamic problems which can be studied in the NTF are control-surface buzz, unsteady shocks, effects of boundary layer (steady and unsteady), buffet, stall flutter, basic unsteady aerodynamic derivatives, dynamic stability derivatives, flow over bluff bodies, tests of small, full-scale rockets, and ground wind loads on models of large launch vehicles.

Of these problem areas, the panel selected four specific topics which should be initially programed for tests in the NTF. The programs are presented in order of the priority assigned by the panel:

PROBLEM AREAS

1. Reynolds Number Effects on Control Surface Unsteady Aerodynamics

Objective: Obtain unsteady aerodynamic force, moment, and pressure measurements due to control surface motion at flight Reynolds numbers.

Background/Need/Justification:

Lack of available data on control surface unsteady aerodynamics at flight Reynolds numbers.

Reynolds number effects are important for control surface aerodynamics due to boundary-layer growth on the trailing edge and interaction with shocks.

Needed for:

Design of control-configured vehicles (CCV)

Prevention of "buzz"

Avoidance of control-surface flutter

Preventing control-system instabilities

2. Effect of Reynolds Number on Buffet Onset and Loads

Objective: Establish significance of Reynolds number effects and aeroelastic effects separately on buffet onset and intensity change with Mach number and/or angle of attack.

Background:

Discrepancies between tunnel-predicted and flight-measured buffet loads indicate Reynolds number and/or aeroelastic effects

Uncertainty in predictability has resulted in undesirable buffet characteristics in flight

Late identification of problems result in costly redesign after flight test

Special Considerations:

Flexible model in high dynamic pressure environment

Dynamic pressure transducers to 1000 Hz (approximately 50 required)

Accelerometers (approximately 6 required)

High-response strain gage balance

Flow visualization is desirable

Precursor Work (in-house or joint effort):

Instrumentation development

Preliminary model design

Configuration choice

3. Transonic Unsteady Aerodynamics

Objective: Evaluate effects of Reynolds number, Mach number, and amplitude and frequency on unsteady pressures on oscillating airfoils and wing planforms

Justification:

Same as for steady-state aerodynamics

Present disparity between maximum wind-tunnel capability and flight

Need sufficient data to evaluate and improve results from lower cost wind tunnels

Validate computational methods

Special Considerations:

Provisions for forced oscillation system

Dynamic pressure transducers

Dynamic boundary-layer measurements

Visual model monitoring

Precursor Work:

2-D tests in Langley 0.3-m transonic cryogenic tunnel

4. Flutter

Objective: Evaluate Reynolds number effects on flutter characteristics of wing planforms and airfoils; develop guidelines for improving full-scale test simulation in TDT (e.g., boundary-layer modifiers)

Justification:

Present aircraft designs are strongly influenced by flutter

Full-scale (flight Reynolds numbers) flutter test not feasible

Present Reynolds number uncertainties lead to overconservatism in design

Special Considerations:

Model construction and calibration

Temperature effects on structural characteristics (e.g., damping)

Construction with dissimilar materials

Pre-entry vibration testing at cryogenic conditions

Screens (e.g., model failure)

Fast "q" change or tunnel shutdown

Precursor Work:

Test in Langley 0.3-m Transonic cryogenic tunnel

CONCLUSIONS AND RECOMMENDATIONS

The panel offers the following conclusions and recommendations:

1. The NTF can be a very valuable adjunct to the Langley TDT for aeroelastic studies and flutter studies.

2. Precursor dynamic tests should be made in the Langley 0.3-m transonic cryogenic tunnel to develop instrumentation, strategies for the NTF, and possibly to eliminate some proposed NTF tests.

3. Several overlap considerations should be investigated. When testing at the very high dynamic-pressure conditions in the NTF, all models should have a flutter and aeroelastic clearance performed by a competent group.

4. To utilize the NTF as a dynamics facility, several characteristics of the Langley TDT should be considered, including

(a) Fast tunnel shutdown

(b) Model visibility

(c) Tunnel protection

(d) Dynamic model support systems

(3) Dynamic data-acquisition system

5. A theoretical investigation should be made to determine the feasibility of constructing and testing a flutter model in the NTF.

6. The initial series of tests in the NTF should be concerned with the determination of the effect of Reynolds number on wing- and control-surface derivatives by measuring oscillating pressures on "rigid" models which would be externally oscillated.

7. For flutter models, the potential of utilizing in the NTF one model for a complete altitude range should be investigated.

REFERENCES

1. Destuynder, Roger: Feasibility of Dynamically Similar Flutter Models for Pressurized Wind Tunnels, Paper presented to Fluid Dynamics Panel, AGARD, Sep. 14, 1976.

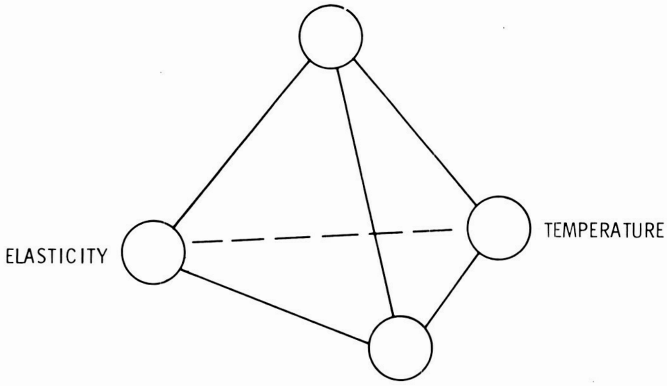

Figure 1.- Aerothermoelasticity.

L-76-6766

Figure 2.- Flutter model installed on cable support system in Langley 16-foot transonic dynamics tunnel.

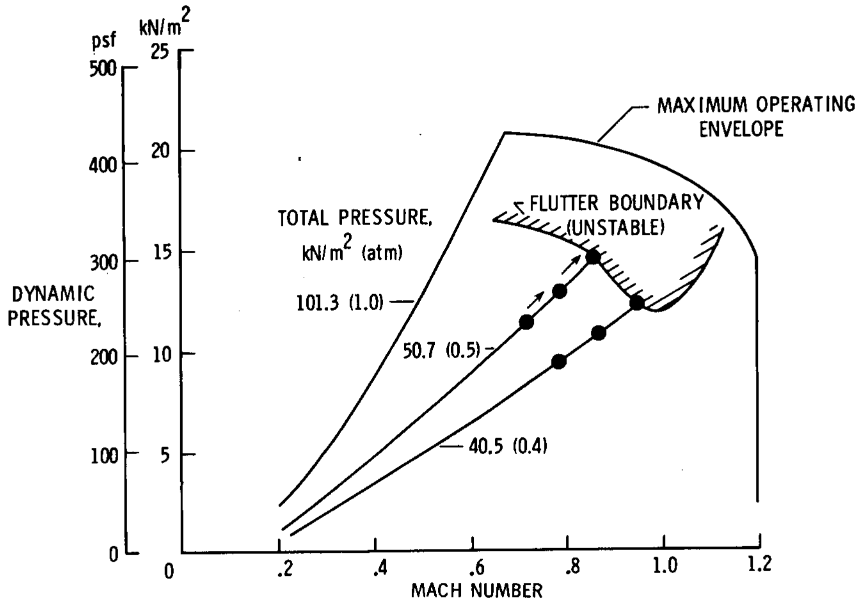

Figure 3.- Flutter testing procedure in Langley transonic dynamics tunnel.

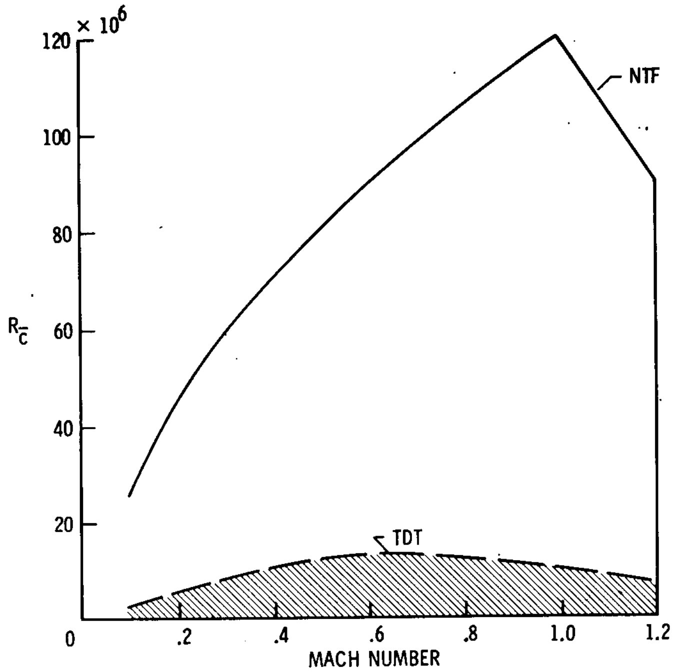

Figure 4.- Operating envelope of National transonic factility (NTF) and transonic dynamics tunnel (TDT).