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Force Measurement in a Ludwieg Tube Tunnel

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An investigation of the force measurement in a Ludwieg tube tunnel with a test period duration of 100 ms is presented. A classical strain-gauged, six-component balance is used. It is shown that acceleration compensation is unnecessary, by verifying that the natural frequency of the model-balance-sting system and the frequencies of the tunnel vibration remain outside the critical range of interest. It is demonstrated that it is possible to obtain force measurements at least up to the fourth test period that ends at 600 ms from the flow initiation. Good agreement is obtained between existing wind tunnel data for a tangent-ogive cylinder and data obtained in this study.

Nomenclature

A^*	=	throat area
A_{tube}	=	charge tube cross-sectional area
Cn	=	normal force coefficient
Cx	=	axial force coefficient
D	=	model diameter
g	=	gravity acceleration
l_{cyl}	=	model cylinder length
l_{ogive}	=	model ogive length
M	=	Mach number
α	=	model angle of attack

I. Introduction

LUDWIEG tube wind tunnels operate at Mach number regimes ranging from subsonic to hypersonic flows. At DLR, hypersonic flow facilities based on the Ludwieg tube concept have been in use since the sixties. Two decades later, the cryogenic transonic tunnel (KRG tunnel) was inaugurated as a high Reynolds number facility [1]. Because of the nature of the high quality of flow produced by the Ludwieg tube, Schneider et al. [2] had extended the Ludwieg tube tunnels to include facilities that produce "quiet flow"; two facilities were built, one running at Mach 4.0 and the other is a hypersonic tunnel running at Mach 6.0 [3].

Despite the existence of a number of Ludwieg tube tunnels, insufficient data is available in the literature on the use of classical strain-gauged, six-component balance force measurement in Ludwieg tube facilities. Six-component force measurements were performed in the high Reynolds number facility at NASA Marshall Space Flight Center with running times as high as 550 ms [4]. One study [5] claims to evaluate forces and moments using a six-component balance without acceleration compensation. However, only drag measurements at zero angle of attack were shown. The data were averaged over the useful run time after filtering at 20 Hz.

In an investigation of the Ludwieg tube tunnel suitability for transonic flow testing, Starr and Schueler [6] measured forces on a cone at Mach 0.735 for a duration of 120 ms. Eremenko et al. [7] carried out a study to measure pressure drag on a blunt cone in a supersonic Ludwieg tube tunnel that supplied steady flow for 80 ms. However, only one force component (axial) was measured using a load cell.

Ludwieg tube tunnels are short test-time duration tunnels. The test times range from a few milliseconds to several seconds. A subtype of the short-duration tunnel is the impulse-type tunnel in which the run time is less than a few milliseconds. The short test time in such facilities represents an obstacle in force measurements using conventional strain-gauged, six-component balances. The dynamics of the model and the response of the balance demand a duration that could easily exceed the tunnel testing time. Force measurements in short duration have been a subject for research since the advent of hypersonic testing using impulse facilities that are derivatives of shock tubes. An extensive survey has been presented by Bernstein [8] for the development of forced measurement techniques in short-duration tunnels. Bernstein classified the force balances as stiffness-dominated or inertia-dominated. In stiff-dominated balances, the model, the balance, the sting, and the support structure are considered to be a rigid system that is, ideally, unaffected by transient loads during the wind-on conditions of the tunnel and also unaltered by the motion or vibration of the tunnel structures. In reality, the balance cannot be rigid, because we infer forces from measurements of strains that, in turn, require some degree of flexibility of the balance. In addition, model support structure is usually an integral part of the tunnel that transmits tunnel vibrations to the balance. During the tunnel startup, an opening of a diaphragm, or a quick-opening valve, initiates the flow by releasing the high-pressure gas into the test section. During the wind-on conditions, the model, its support structure, and the internal parts of the tunnel experience transient loads that induce stress waves that are measured by the balance. Therefore, the balance measures a combination of quasi-static loads (the loads of interest), vibration loads, and model inertial loads. To ensure that the forces obtained from the balance are only the quasi-static loads of interest, steps must be undertaken to either eliminate or at least to obtain the order of magnitude of the other loads. A critical range of frequencies is defined to have "an upper limit of the reciprocal of the minimum time of interest to resolve the fastest transient and a lower limit down to the reciprocal of the test time (or zero if static calibration are to be used)" [8]. In an attempt to meet the requirement, the balance must be stiff and the model light enough so that the lowest natural frequency of the model and balance does not fall within the critical range. However, this requirement is very difficult, if not impossible, to meet. One way to overcome this difficulty is to make the test time long enough such that several natural frequency cycles occur during the test time. If that is not possible, one must apply acceleration compensation.

It was not until the rekindled interest in hypersonic flight in the late eighties that a significant development in force measurements in impulse facilities was set by Sanderson and Simmons [9]. A new type of balance called the stress-wave force balance, based on the Hopkinson bar, was introduced. A long (compared with the model length) hollow bar is attached to the base of the model. During the wind-on conditions, a transient drag force sends through the bar a

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stress wave that is accompanied by transient strains. The strains are measured by strain gauges located on the stress bar. The force is obtained by applying a deconvolution technique to the strain-gauge signals. Mee et al. [10] demonstrated the use of the stress-wave force balance to measure three-component forces in a few milliseconds. It will be seen that such a balance will not be necessary to use in the current study, but it is an important development in the field of hypersonic aerodynamic testing that is worthy of mentioning.

Sanderson and Simmons [9] concluded that "for practically sized models, stiffness-dominated balances are only suitable for test times greater than 200 ms. Inertia-dominated accelerometer balances can lower this acceptable test time to only 10 ms". However, Jessen and Grönig [11] have demonstrated the six-component force measurements in 2 ms. A stiff strain-gauged, six-component balance has been developed. The balance has the shape of a cross, the arms of which are deformed by the forces on the model. The stiff construction of the balance allows force measurements without resorting to acceleration compensation. According to Jessen and Grönig, *stiff* indicates that at least five cycles of the lowest natural frequency of the model-balance-sting system appear during the test time.

The use of the classical strain-gauged, six-component balances for test runs of a few milliseconds is limited by its low natural frequencies. Six-component balances can be used to obtain force measurements in test durations of a few tens of milliseconds using force compensation. Carbonaro [12] demonstrated the use of the strain-gauged, six-component balance in a test duration of 10 ms using acceleration compensation. Nakakita and Yamazaki [13] used a six-component balance with acceleration compensation to measure forces in a hypersonic shock tunnel in 30 ms.

In the present study, we attempt to measure forces using the classical strain-gauged, six-component balance at Mach 3.0 using the King Abdulaziz University Advance Tunnel 0 (KAU-AT0) facility. The AT0 tunnel is a Ludwieg tube tunnel [14]. The tunnel provides a testing time of 100 ms, which makes it possible to measure forces without resorting to acceleration compensation. If we follow the definition of stiff as proposed by Jessen and Grönig [11], the model needs to have a minimum natural frequency of 50 Hz, far less demanding than the 1 kHz required in the 5-ms test duration of the facility used by Jessen and Grönig. Although the testing time of the AT0 appears to be sufficient for force measurements using the classical strain-gauged, six-component balance, required testing time can only be determined if the dynamics of the model, balance, and facility are understood. In the current study, we present force data of an axisymmetric body (with available experimental data) up to angles of attack of 6 deg. Data will also be presented for the tunnel's behavior during the test run.

II. Operation of the Ludwieg Tube

The operation concept of a tube tunnel was first suggested by Ludwieg [14] in 1955. The Ludwieg tube wind tunnel is a pulsed-type wind tunnel with a long storage tube referred to as the charge tube. The gas dynamic process is sketched in Fig. 1.

The high-pressure tube is separated from a low-pressure tank by a diaphragm or a quick-opening valve. Ideally, when the quick-opening valve opens, an expansion wave travels upstream into the tube and accelerates the gas to Mach number M_3, determined by the nozzle throat to charge tube area ratio A^*/A_{tube}. The flow parameters behind the wave (region 3 in Fig. 1) are constant as long as viscous effects are negligible. Transients in the nozzle are ignored in this figure.

The test time is the time it takes the wave to travel to the end of the tube and return to the test section. The stagnation conditions (denoted by the subscript t) are different from the charge conditions (denoted by c). If the growth of the boundary layer in the tube remains small, several test periods can be made with constant stagnation conditions. For example, the second period will have the stagnation conditions ahead of the second wave that reflects off the end of the charge tube (region 6 in Fig. 1). Therefore, stagnation conditions for the first period are that of region 3, whereas for the second period it is that of region 6. Ideally, for supersonic flow testing, more test periods can be

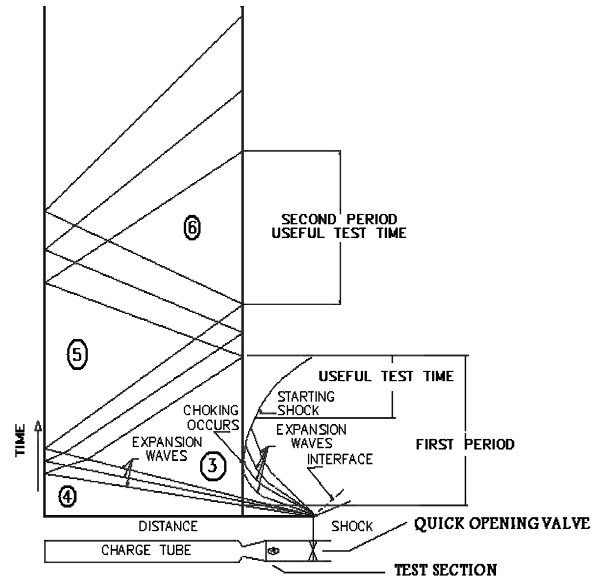

Fig. 1 Sketch of the operation of a Ludwieg tube wind tunnel.

attained until the charge pressure falls below that required to start the tunnel. However, due to the boundary-layer growth, the pressure during the test period does not remain constant, but generally decreases. It will be shown that the AT0 tunnel can provide additional test periods in which useful force data can be attained.

III. Experimental Facility

The KAU-AT0 was inaugurated in 1998. It is described in detail by Al-Dekhiel [15]. The Mach number of the tunnel is 3.0, with an axisymmetric test section diameter of 250 mm. The tunnel has a charge tube diameter of 394 mm and a length of 22 m, which allows a nominal testing time of about 100 ms. The test duration may reduce due to nozzle startup time. The tunnel is started by opening a high-speed quick-opening valve. Located downstream of the test section, the quick-opening valve has the capability to open in 5 ms.

Five pressure transducers have been used to conduct all measurements. Two transducers have been used to measure the static and total pressure at the nozzle entrance, and the other two transducers have been installed at the test section to measure the static pressure at two axial locations with 95 mm between them.

An additional sensor is located at the base of the model. An overview of the measurement setup is shown in Fig. 2.

The transducers, which are used to measure the static pressure, are absolute pressure transducers Kulite XT-190M, XCS-190M, and XCS-062. These pressure transducers have working pressures of 10, $1/3$, and 1 bar, respectively. According to the manufacturer, the transducers XT-190M and XCS-190M have a maximum combined nonlinearity and hysteresis of ± 0.3, with $\pm 0.5\%$ for the transducer XCS-062. The transducers have an infinite resolution and a natural

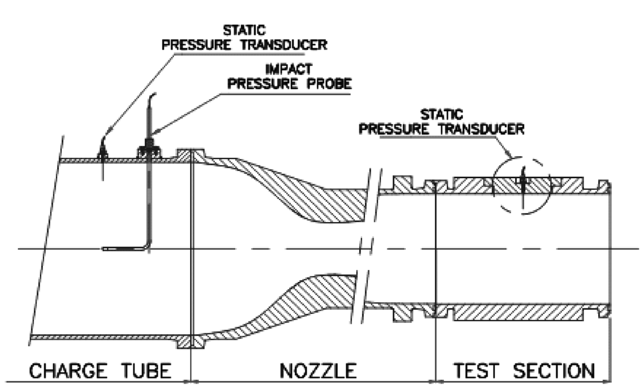

Fig. 2 Measurements setup overview [15].

frequency of 200 kHz. Lower pressure range transducers XCS-190M and XCS-062 were specially ordered from the manufacturer to allow an overpressure of 8 bar. Both XT-190M and XCS-190M transducers measure the static pressure in the test section, whereas the XCS-062 transducer measures the base pressure. The charge tube total pressure is measured by an absolute type Kulite XCQ-062 transducer. It has a maximum working pressure of 10 bar. The manufacturer's specifications indicate its maximum combined nonlinearity and hysteresis to be $\pm 0.5\%$ with infinite resolution and a natural frequency of 100 kHz.

Pressure data presented in this study does not rely on the calibration of the manufacturer, but on the repeated calibrations made by the authors. The calibration before each run using a secondary pressure standard (Keller, Mano Cali) indicated that the transducers' accuracy is within ± 10 mbar. A calibration check was also carried out while pressurizing the tunnel from atmospheric pressure to testing pressure before each run, and from subatmospheric to atmospheric pressure after the end of the run.

The force is measured using a classical strained-gauged, six-component balance (Rollab I6B414). The balance has a diameter of 14 mm and can measure normal forces up to 600 N and axial forces up to 100 N. The balance was statically calibrated at the time of purchase in 1996. The calibration indicates that the errors for the range of forces of interest in the current study (within 2σ) are less than $+/-0.5$ N. The angle of attack is measured with an accurate digital inclinometer with a range of ± 30 deg and an accuracy of ± 0.005 deg, and the inclinometer is fixed to the traverse mechanism.

The pressure transducers are connected to a data acquisition system (B&K Pulse) with 8 channels and a maximum scan rate of 25 kHz (12.5 kHz is commonly used for testing). All pressure sensors are calibrated before each set of tests. The balance is attached to a data acquisition card (National Instruments AT-MIO-16-XE-50, 16 channels) with a scan rate of 2000 samples per second (2 ksps).

To determine the models' natural frequency, an impact hammer (Endevco 2303-10) and an accelerometer (B&K 4507B) were used. The wind tunnel vibration was measured using a three-axis accelerometer (Kistler 8692B50) with a natural frequency of 22 kHz. The accelerometer was fixed to the external wall of the model traverse section of the tunnel. No measures were taken to isolate the model support system from the wind-tunnel wall. Therefore, the vibration of the model traverse section is, in principle, the vibration of the model support.

Two axisymmetric models are presented in this study, a blunt-nosed short model and an ogive-cylinder model [16]. The models are described in Fig. 3. The blunt-nosed bodies have a nose diameter equal to that of the aft cylinder. The short model has a $l_{cyl}/D = 4.4$, and weighs 104 g. The ogival body has a tangent-ogive nose with an $l_{ogive}/D = 3.5$, an aft cylindrical body of $l_{cyl}/D = 6.0$, and weighs 200 g. The models are made out of aluminum. A reduction in the models' weights is beneficial, because it reduces their inertia and increases the response time of the model-balance-sting system. However, the natural frequency of the model-balance-sting system proved to be high enough for the test duration. Therefore, no attempts were made to reduce the models' weights.

The main objective of this paper is to demonstrate that it is possible to make measurements during a period of 100 ms, including testing at different test periods. The results of such measurements can only be justified if the behavior of the model-balance-sting system and its interaction with the environment of the tunnel are known.

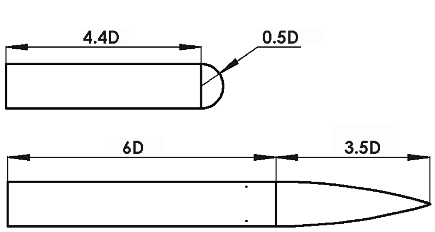

Fig. 3 Schematic showing the models tested.

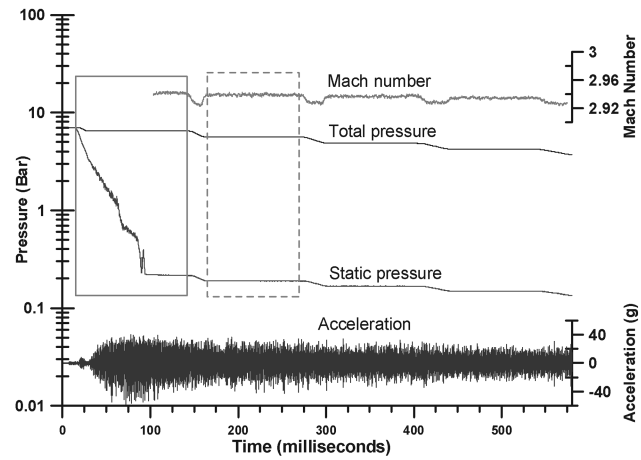

Fig. 4 Typical summary of raw data from a single run showing the pressure data, the calculated Mach number, and acceleration.

IV. Experimental Results

A. Tunnel Operation

The tunnel operation starts by loading the charge tube with typical pressures ranging from 1 to 8 bar. Because the valve is located downstream of the test section, the nozzle, the test section, and the model traverse section are also loaded with the same pressure. The dump tank, located downstream of the valve, is evacuated. The valve is then opened in several milliseconds. Figure 4 shows a typical run at a charge pressure of 7 bar. The charge pressure was measured near the nozzle inlet, and the test section pressure was measured near the nozzle exit. The time duration that is shown in Fig. 4 starts from a time before starting of the test and spans four test periods. The first period is indicated by a rectangular box with a solid border line, and the second test period is indicated by a dotted lined rectangular box. Initially, the pressures in the test section and the charge tube have the same value. As the valve opens, a series of expansion waves travel upstream, passing the test section and the nozzle, then enter the charge tube. The initial sequence of events can be followed by noting that the pressure in the test section drops a few milliseconds (~ 5 ms) earlier than the pressure in the charge tube. The drop of the pressure in the test section continues toward the expected value, eventually stabilizing after 60 ms. The delay is a result of the nozzle starting process, which consumes part of the testing time in the first test period. Once the flow is established in the nozzle, the pressure remains constant within 0.2% until the arrival of the first reflected expansion wave indicated by the pressure drop at about 150 ms. The pressure then continues to be constant for the second test period until the arrival of the second reflected wave. The pattern continues until the pressure drops below that required to start the tunnel. The pressures for each period remain nearly constant even up to the fifth test period [17]. Unexpectedly, the figure reveals that the Mach number remains constant within 0.2% and is independent of the test period. The Mach number is calculated from the static to total pressure ratio using an isentropic relationship. It was expected that, due to viscous affects, run duration of more than 500 ms would fill the tube with a boundary layer. If the tube is filled with a boundary layer, isentropic relationships will not be valid.

The Mach number during the passage of the expansion wave is only fictitious due to the presence of the expansion wave between the nozzle exit and the nozzle inlet.

The nozzle startup time with the presence of the model and/or the traverse mechanism section consumes nearly half of the test time of the first period. At certain conditions, depending on the model used and its angle of attack, the nozzle startup duration can be more than 100 ms. In other words, it is at times not possible to make force measurements using the conditions of the first test period or even the second test period. The inability to make measurements during the first period may be considered as a setback. Throughout our investigation of the Ludwieg tube wind tunnel testing, we have not encountered studies that operate experimentation at successive test periods, with the exception of [2,3]. It is typically accepted that the viscous effects within the charge tube displayed by the boundary-layer buildup would be significant by the end of the first test period. The boundary-layer buildup within the charge tube will be significant if the charge tube Mach number is high. With the exception of the Ludwieg tube tunnels in [2,3], the charge tube Mach number of the existing Ludwieg tube facilities is usually around 0.2, whereas in our facility it is 0.06. The low charge tube Mach number (along with the test time) reduces the viscous effects, which, in turn, extends the usefulness of the successive test periods [17]. This has already been shown in [2,3] with charge tube Mach numbers of 0.014 and 0.006, respectively.

B. Model-Balance-Sting System

As discussed previously, several cycles of the natural frequency of the model must occur during the short test duration to eliminate acceleration compensation. If Jessen and Grönig's [11] criterion is used (five cycles of the model natural frequency), then for the test duration of 100 ms, the model-balance-sting system must have a minimum natural frequency of 50 Hz. The model-balance-sting system natural frequency was obtained just before closing the tunnel for startup. An accelerometer was fixed to the model to measure its response to an excitation by an impact hammer. The measurements of the acceleration from the accelerometer and excitation force from the impact hammer were used to determine the model-balance-sting system frequency response. The test was repeated in all three principal directions (axial, pitch, and yaw). As expected, the lowest natural frequency was obtained when using the ogival body, which is longer and heavier than the short blunt-nosed body. Figure 5 shows the spectra frequency response of the model-balance-sting system during an impact test in the normal direction when the ogival body was installed. The minimum required value of 50 Hz is indicated by an extra grid on the x axis. The figure indicates that the model-balance-sting system had a minimum natural frequency of 70 Hz in the normal direction. The model and force balance is stiffest in the axial direction and so it was expected that the system would have a higher natural frequency than that in the least-stiff direction of the normal force. The minimum natural frequency in the axial direction was determined to be 120 Hz.

The lowest natural frequency of 70 Hz exceeds the minimum of 50 Hz derived from the criterion suggested by Jessen and Grönig [11]. It follows that the testing time of 100 ms is greater than the time required to obtain useful force data for this model. Because the blunt-nosed body model displayed a higher natural frequency (not shown in the figure) than the ogival-body model, it is concluded that the testing time is also sufficient for a blunt-nosed body. In other words, the minimum required test time for all models used in this study is 70 ms.

C. Wind-Tunnel Environment

To determine how the tunnel vibration and the action of the quick-opening valve influence the force reading, a three-axis accelerometer, fixed to the external wall of the tunnel model traverse section, measures the vibration of the model-balance-sting system. The accelerometer is aligned to measure the vibration of the tunnel in the direction of the flow and in the directions normal and transverse to the flow (pitch and yaw directions of the model at zero angle of attack). The accelerometer output is presented, along with the pressure data of the tunnel, in Fig. 4. The transients of the quick-opening valve are visible (starting at about 20 ms) in the vibration signature. They appear as a lower-frequency signal (900 Hz) that dampens in about 7 ms. Similar outcomes were obtained with varying running conditions. The results verify that the quick-opening valve induced vibrations disappear much earlier (within a few milliseconds) than the nozzle startup (tens of milliseconds) and therefore do not influence the force measurements.

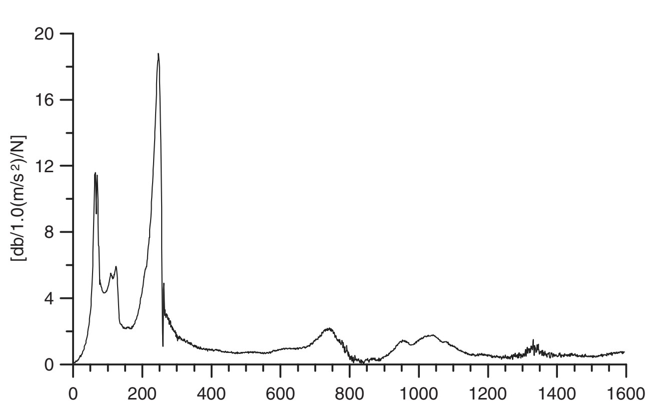

Fig. 5 Frequency response of the model-balance-sting system during an impact test in the normal direction of the ogival body.

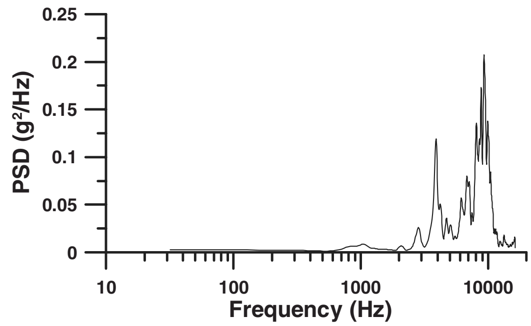

Fig. 6 Tunnel frequency response.

If the tunnel vibration frequencies fall within the critical range, it will interfere with force data. It was found that after the flow is established, the tunnel wall vibrations are in kilohertz. A typical plot of the power spectral density of the tunnel vibration during a test period in the normal direction is shown in Fig. 6. The spectra are flat for frequencies below 700 Hz, which is an order of magnitude higher than that of the lowest natural frequency of the model-balance-sting system. Therefore, the tunnel vibration will not interfere with force measurement.

D. Force Measurements

In this section, we will show a sample of the force measurements made of the blunt-nosed body and the ogival-body models using a classical strain-gauged, six-component balance. Admittedly, the six-component balance used in this study has not been recalibrated since its original calibration ten years ago. A simple rig was constructed to make just a quick check on a few values. However, the purpose in this study is to demonstrate that it is possible to make force measurements rather than to obtain accurate force value.

Now that the flow conditions in the test section are known, the natural frequency of the model-balance-sting system is higher than the minimum value indicated by the Jessen and Grönig [11] criterion, and the noninfluence of the quick-opening valve or the tunnel vibration on the model-balance-sting system has been demonstrated, we can then proceed to make force measurements.

Figure 7 shows the normal and axial forces of the blunt-nosed body model described in Fig. 3. The Mach number is 2.94, the charge pressure is 6.27 bar, and the angle of attack is 5 deg. The figure also includes the nozzle exit pressure and the model base pressure. Initial base pressure data (from 0 to 87 ms) are not available, because the pressure transducers have an upper limit of 380 mbar, which is lower than the initial starting value of the tunnel. The pressure data is gathered at a sampling rate of 8000 samples per second, whereas the force data is sampled at 2000 samples per second. In the figure, a moving average of 41 points was applied. An insignificant change was observed to the pressure data when a moving average of 21 points was used. However, the force data was slightly influenced by the 60-Hz (electric power) frequency. An effort is in progress to insulate the balance signal wires, which would result in a better signal-to-noise ratio.

The tunnel startup time is shown in Fig. 7 using a dotted boundary box. The tunnel startup lasts for more than 100 ms. During the

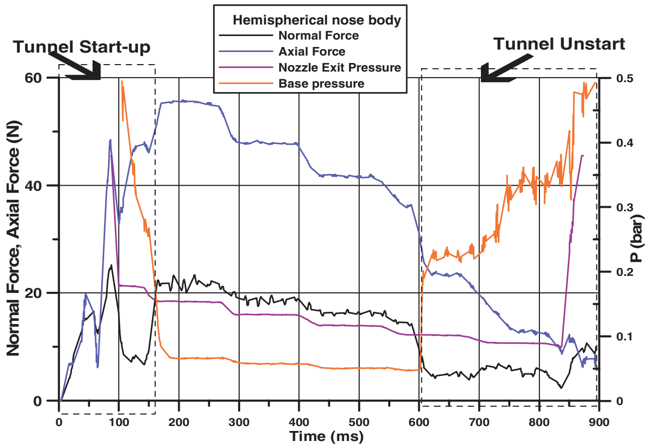

Fig. 7 Time history of the force and pressure data.

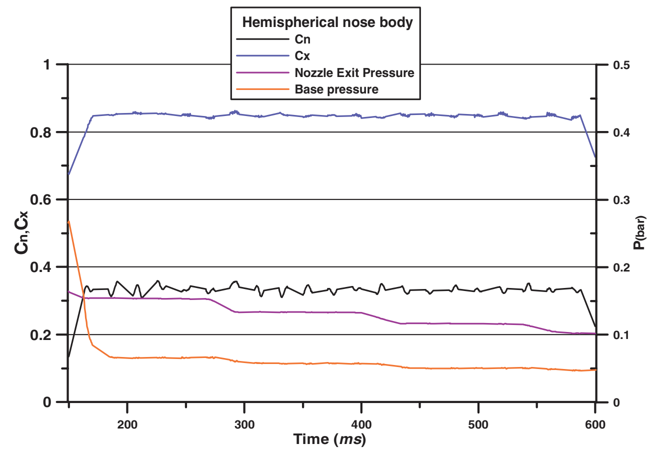

Fig. 8 Time history of the force coefficients and pressure data in the useful periods.

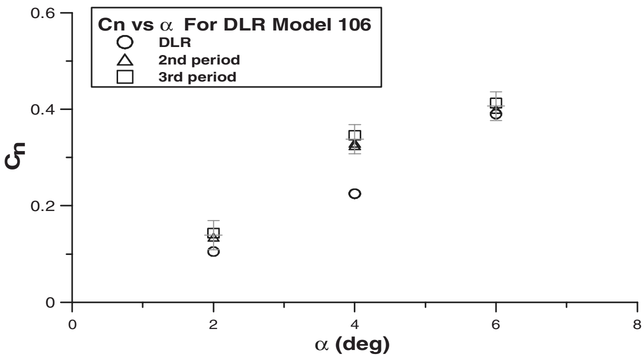

Fig. 9 *Cn* vs α; note the good agreement with DLR results, except at $\alpha = 4.0$ deg.

startup, the nozzle exit pressure becomes constant near the middle of the first test period (at 100 ms), yet the model base pressure is still at a higher pressure than the nozzle exit pressure. This is an indication that the starting shock is near the base of the model and causing a larger pressure value than that of nozzle exit. The first period ends at 140 ms and the second period starts at 163 ms and ends at 270 ms. Because the Mach number remains unchanged during each test period, the drop in nozzle exit pressure is accompanied by a drop in total pressure, such that the ratio of static-to-total pressure remains fixed.

The normal and axial loads on the model follow the pressure history. Once the base pressure approaches its steady value during the test period, the axial force remains nearly constant at 55.5 N, whereas the normal force remains at an average value of 21.5 N. The higher scatter data in the normal force is due to its lower signal-to-noise ratio when compared with the axial force. As soon as the pressure drops at 270 ms, signaling the end of the second test period, the forces follow the drop intimately, even when the pressure stabilizes at approximately 300 ms, signaling the beginning of the third period. The normal force in the third test period is 18 N and the axial force is 48 N. The behavior of the force response continues for the fourth test period in which forces are also measured.

It is not yet certain that the values obtained up to the fourth test period are acceptable. If the boundary-layer thickness within the charge tube is significant to the extent that the vorticity produced by the boundary layer dominates the flow within the test section, the forces will surely be affected. The fact that the Mach number was shown to be constant for each of the four test periods (Fig. 4) is not sufficient to ensure that the force data is reliable. To address this issue, the force data in Fig. 7 from 200 to 600 ms is plotted again in Fig. 8 as force coefficients. The pressures are also shown to indicate the test-period duration. The figure indicates that the values of Cx and Cn are unaffected by the change in test period conditions up to the fourth test period (i.e., 600 ms after the initiation of the run). Therefore, the forces were not affected by the growing boundary layer within the charge tube. Although the loss of the first test period was an undesirable outcome of the long startup time of the particular tunnel used in this study, the data at successive test periods remain valid. Thus, it is possible to obtain useful force data in Ludwieg tube tunnels in successive test periods.

In separate runs, the invariability of the force coefficients for all four test periods was also demonstrated for the ogival body. Caution has to be taken when the flow is sensitive to the Reynolds number. During the successive testing periods, the Reynolds number variation is small. However, if the Reynolds number changes are large, differences in the result between test periods should be anticipated.

A further demonstration of the force measurements in the Ludwieg tube tunnel is shown in Fig. 9. The figure exhibits the normal force coefficient as a function of angle of attack up to 6 deg for the second and third periods. The vertical error bars represent $\pm 2\sigma$ confidence intervals. The figure reveals that the normal force coefficient for the second and third periods is nearly the same. The figure also contains data obtained by DLR of the same ogival body in a long-duration test time tunnel [16]. With the exception of the data at 4 deg, the data illustrates that good agreement can be obtained using a Ludwieg tube tunnel. Additional tests are in progress to investigate the difference obtained at a 4-deg angle of attack.

V. Conclusions

Force measurements in a Ludwieg tube tunnel were studied using a classical strain-gauged, six-component balance. Because the duration of the tunnel is short (100 ms), several requirements were set forth by this study for acceptable force measurements. Both the natural frequency of the model-balance-sting system and the vibration of the tunnel had to be measured. The test time must be long enough that at least several cycles of the natural frequency of the model-balance-sting system occur within the test period. Five cycles of the natural frequency was chosen as an acceptable criterion, as recommended by Jessen and Grönig [11]. The models used in this study, along with the wind tunnel, were verified to obey the set requirements.

This study presents, for the first time, force measurements in several test periods of the Ludwieg tube tunnel. The balance response was compared with the pressure history and determined to have a good response to variations of tunnel conditions, in particular, during the transient conditions of the nozzle and the transition from one test period to a consecutive one. Through the measurements of forces it also determined that the force coefficients were constant throughout multitest periods (i.e., test duration of 600 ms). The unchanged force coefficient is related to the quality of the flow and the buildup of the boundary layer within the charge tube. It suggested that the charge tube boundary-layer buildup was smaller than expected; this would require further investigation on the nature of the boundary-layer buildup with the charge tube.

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