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Status of Duct Liner Technology for Application to Aircraft Engine Nacelles

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ABSTRACT

Grazing flows and high acoustic intensities impose unusual design requirements on acoustic liner treatments used in aircraft engine nacelles. Increased sound absorption efficiency (requiring increased accuracy of liner impedance specification) is particularly critical in the face of ever decreasing nacelle wall area available for liner treatments in modern, high-bypass ratio engines. This paper reviews the strategy developed at Langley Research Center for achieving a robust measurement technology that is crucial for validating impedance models for aircraft liners. Specifically, the paper describes the current status of computational and data acquisition technologies for educing impedance in a flow duct. Comparisons of educed impedances for a "validation liner" using 1980's and 2000's measurement technology are consistent, but show significant deviations (up to 0.5 ρc exclusive of liner anti-resonance region) from a first principles impedance prediction model as grazing flow centerline Mach numbers increase up to 0.5. The deviations, in part, are believed related to uncertainty in the choice of grazing flow parameters (e.g. cross-section averaged, core-flow averaged, or centerline Mach number?). Also, there may be an issue with incorporating the impedance discontinuities corresponding to the hard wall to liner interface (i.e. leading and trailing edge of test liner) within the discretized finite element model.

1. INTRODUCTION

The remarkable ability of acoustically treated nacelle inlets and fan exhaust ducts to attenuate turbofan engine tonal noise was demonstrated at the beginning of the turbofan era, some four decades ago.[1] The design goal for acoustic treatments is to create an acoustic boundary condition on the nacelle duct walls such that noise emission spectra are altered in the most propitious manner to minimize community noise impact. To achieve higher thrusts, the turbofan engine was invented in the 1960's with a bypass ratio (BPR) of about 1.4. The BPR has increased to about 9 with the most recent engines. This continued increase in BPR (with consequent decrease in nacelle length-to-diameter, L/D, ratios), along with further innovations in jet-mixing noise reduction, has maintained a constant incentive for passive liner treatments to at least maintain the status quo of some 40 years ago in terms of liner effectiveness. This paper addresses one aspect of this continuing challenge, i.e. the measurement technologies that define the limits of achievable accuracy for the liner impedance as it pertains to aircraft engine nacelle treatment applications.

2. BACKGROUND

Nacelle duct liner treatments are acoustically resonant systems. In their simplest form, they consist of a honeycomb core bonded between a porous faceplate and an impervious back-plate to form a sandwich structure. These load carrying, robust structures retain their mechanical integrity in harsh aero-acoustic environments and require little, if any, maintenance. Single layer liner absorption (or noise suppression) frequency bandwidth tends to be relatively narrow, but the bandwidth can be increased with multiple layers. However, additional layers increase the weight and volume and complicate the design and manufacturing process. Such complications notwithstanding, ongoing design refinements have enabled these absorbing structures to meet the demands for suppressing tonal noise. The critical design feature has always been the acoustic resistance elements. Conventional perforated plate type resistance elements are greatly affected by grazing flows and high incident sound pressures. Because of the resonant character of these liners, depth constraint can be an obstacle to achieving low frequency suppression. However, low frequency suppression was not a pressing issue during the low bypass ratio (BPR) era for turbofan engines (e.g. the JT3D-3 with a BPR of 1.4 and a thrust of 80 kN).[1]

The need for greater engine thrust, while minimizing fan exhaust velocity (and thus jet-mixing noise), has led to higher bypass ratio engines, (e.g. the GE-90 with a BPR of 9 and a thrust of 512 kN). Consequently, for high BPR/higher thrust engines, nacelle diameters have become larger relative to their lengths. Other design changes include decreased fan rotation speeds and fan blade counts. These changes have led to increased blade chord lengths with the end result being a shift of the tonal spectrum to lower frequencies and increased broadband noise. Also, the introduction of fan blade sweep to help alleviate blade wake interaction noise, which together with the fact that the fundamental blade passage frequency is now less than the lowest order circumferential mode order cut-on frequency, has further decreased the tonal noise contribution. The greater role of broadband noise in the emission spectrum and decreased liner treatment length relative to the lined duct diameter (i.e. treatment length to duct diameter ratio, L/D) have tended to make liner treatments less effective over time. Thus, while increased BPR has restrained jet-mixing noise increases, the liner treatment design challenge continues. These trends have motivated the on-going need to seek ways to improve liner suppression bandwidth and efficiency.

3. METHODOLOGIES FOR EDUCING IMPEDANCE

A. Problem scope: The goal of a comprehensive turbofan noise prediction program is to provide a suite of codes ranging from those for simple optimal liner design to highly elaborate numerical prediction codes for full scale, turbofan/nacelle system noise. These system noise codes provide acoustic spectra distributions on an observer sphere centered on the nacelle. Prediction accuracy is dependent upon a duct propagation model that includes source/duct coupling and radiation effects. The liner impedance is only one of several input parameters required. The scope of this paper is restricted to describing measurement technology for determining liner impedance in a laboratory environment that simulates nacelle duct aero-acoustic conditions.

Improvement in liner design technology, over the past 30 years, has been sought by exploiting increasingly more sophisticated experimental techniques and computational methodologies. These improvements are the basis for impedance prediction models with greater accuracy and less empiricism. Recent improvements have focused on test hardware, data acquisition systems and computational methodologies.

B. Issues with impedance: There are problematic issues with employing the impedance concept as a design tool for liners in aero-acoustic environments. Impedance is a mathematical construct. It is defined at a point, on an imagined surface of interest, as the ratio of frequency domain transforms of acoustic pressure and the normal component of acoustic particle velocity.[2] Should the surface of interest coincide with a liner surface, it may be considered a property of the liner. An impedance spectrum is a unique property of the absorbing liner only when it (the liner surface impedance) is locally-reacting, responds linearly to the acoustic field, and is insensitive to grazing flow. In reality, conventional perforate-over-honeycomb liners, as employed in engine nacelles, are acoustically nonlinear and are generally affected by the local flow field. Thus, the liner impedance boundary condition becomes a joint characterization of the liner structure and the adjacent, local aero-acoustic field. The liner nonlinearity arises from the interaction of the acoustically driven oscillatory local fluid motion with the perforate holes. Conventional perforate faceplates are non-homogeneous on the hole-spacing scale. Thus, point impedance is replaced by "smeared" impedance of a representative area. These complications notwithstanding, liner design technologists continue to "make do" with the impedance concept by constructing semi-empirical impedance prediction models (although highly restrictive) from laboratory test data.

Accurate estimates of impedance from direct measurements of co-located pressure and particle velocity, on even a homogeneous liner surface, are not currently feasible. Even if feasible, such measurements would be inadvisable on a perforate for the reasons alluded to above. Instead, a surface-averaged acoustic particle velocity must be educed by means of an acoustic field model deemed to be applicable in the vicinity of the local absorbing area of interest. The fidelity of this field model is crucial to not only achieving a desired accuracy of the impedance in a laboratory facility, but also to translating its application to a full-scale engine. To emphasize the critical role played by acoustic field models, the term "impedance eduction" is used to succinctly denote the field model contingency of the impedance estimation process by means of laboratory measurements.

C. Methodology features of note: It is noteworthy that within the aero-acoustics community, both noninvasive and invasive methodologies have been employed for educing impedance. Noninvasive methods leave the test specimen intact, whereas invasive methods require embedding at least one microphone into the liner cavity and faceplate. Non-invasive methods are attractive in that they give a global result, whereas invasive methods give a local result. Noninvasive methods tend to require less hands-on, high-precision experimental setup than do invasive methods. The greatest disadvantage of non-invasive methods (as applied in a wave-guide) is that a more detailed field model is required. The accuracy of the noninvasive methodology is therefore more subject to field model fidelity issues than is the invasive methodology. Conversely, the greatest advantage of the invasive method (as exemplified by the in-situ, or Dean[3] method) is the replacement of the duct field model by a simpler, one-dimensional, (analytical) field model inside the honeycomb cell. Over the history of the NASA Advanced Subsonic Technology (AST) and Quiet Aircraft Technology (QAT) programs, industry/academia has pursued both the noninvasive and invasive methodologies, but at Langley, noninvasive methods have been pursued almost exclusively. These two approaches are viewed as complementary because they provide two radically different methods to get what should be the same result for identical test liners in identical aero-acoustic environments.

At Langley, the 1980's noninvasive impedance eduction methodologies were developed with the aid of the Grazing Incidence Tube (GIT) as sketched in Figure 1 and described in detail elsewhere.[4,5,6] This facility provides a controlled aero-acoustic environment at two test window locations as shown. The GIT-TB test window, equipped with its axially traversing microphone, allows single mode propagation constants to be measured, when such can be identified apart from spurious contaminations. This methodology allowed impedance eduction by means of a closed form solution to an infinite waveguide field model (i.e. no reflections assumed), both for no-flow and assumed uniform flow profiles, designated as SMM-NF/UF. Also, a finite element (FE) counterpart of the closed form solutions was implemented which served as a starting point for further finite element modeling development; thus the designation, FE-1D-NF/UF. As they have been implemented at Langley, all impedance-educing methodologies are, in principle, deterministic, in that a single valued functional relation exists between a 2-tuple field property descriptor and a single impedance value (e.g. standing wave ratio and null location for the classical standing wave method (SWM), a complex transfer function between two locations in the standing wave field for the modern two-microphone method (TMM), and a complex propagation constant for the SMM). Except for the TMM, all these methodologies require sequential, single frequency tests to generate an impedance spectrum. In practice, over-determined datasets are used to improve accuracy of the impedance eduction process. For example, in the SWM, up to three null locations and corresponding standing wave ratios were measured for each frequency, for the TMM method, signal averaging is employed in the transfer function estimation, and in the SMM, amplitude and phase rates are determined from mean square fits to pressure and phase data obtained from the axially traversing microphone. It should be noted that in all these cases, the over-determined datasets are reduced to a 2-tuple field property which is then entered into an explicit, deterministic calculation of impedance.

The laborious data acquisition required by these methodologies, along with the restrictive assumptions on the field model, prompted further enhancements of both the facility and the finite element modeling. This effort led to a new test window with the traversing microphone replaced by a 95 fixed microphones as shown in the sketch of Figure 1.[4,5,6] Also, FE codes were embedded in an iteration algorithm that minimized an objective function constructed on systematic, sequential guesses of the impedance and the 95 complex pressure measurements. Thus, this methodology incorporates over-determined datasets directly into the eduction process and thus is deemed to be more robust, and hopefully more accurate, than the 1980's methodologies that employed over-determined datasets in an ancillary manner.

4. METHODOLOGY IMPROVEMENTS

A. Methodology evolution at Langley: At Langley, FE based models for educing impedance in grazing flows began in the 1980's with the so-called infinite waveguide method to relate a single mode propagation constant to test liner impedance, as per the upper sketch of Figure 1[4,5,6] Helmholtz-equation solutions were generated for uniform flow, one-dimensional (1-D) shear flow, and two-dimensional (2-D) shear flow. In circumstances where unambiguous, single mode propagation can be identified (i.e. effectively infinite length test liner), these solutions provide a unique impedance corresponding to a measured propagation constant. In the 2000's, FE methodology is being enhanced to account for multiple mode propagation and more realistic inflow and exit boundary conditions (i.e. finite length liner effects). The GIT was also improved by adding a new test window equipped with an array of 95 fixed microphones along with a new high speed, data acquisition system. Some of the microphones were located in the hard wall portions of the test section (before and aft of test liner – see lower sketch of Figure 1) to allow improved quantification of source plane and exit plane acoustic pressure distributions. A non-reflecting exit boundary condition (for all modes) was also added at the exit plane to more nearly match presumed behavior of the flow duct termination.[8] The intention of these enhancements is to improve the overall robustness of the impedance eduction process and to extend the frequency to 7.0 kHz.

B. Methodology performance comparisons: 1980's versus 2000's

1. **Validation test liner**

Educed impedances using both 1980's and 2000's technology are compared using a validation liner (CT57), so-named because of its established acoustic linearity and, arguably, insensitivity to grazing flows as described elsewhere.[4,5,6] This impedance behavior results from an internal structure consisting of densely spaced, tubular channels running normal to the surface of a ceramic matrix to produce a nominal surface porosity of 57%, thus the name, CT57. This structure is amenable to an impedance prediction model based on wave propagation in capillary tubes due to Zwikker and Kosten.[7] The prediction model has been extensively validated in normal incidence impedance tests. For the CT57 validation liner (consisting of about 1400 parallel channels per square inch), the relevant parameters for predicting impedance are: channel diameter, channel length, surface porosity, ambient pressure, temperature, and thermodynamic constants. At the channel anti-resonance frequency, there can be up to 0.2 ρc impedance variability in the educed impedance at different locations over the axial span of the liner. This is likely due to variability in the geometric parameters. Also, effective channel length may not be exactly equal to geometric length. To bring the Zwikker-Kosten model (ZKM) results into better agreement with impedances educed from normal incidence measurements, the geometric parameters were adjusted slightly, but within what is believed to be measurement uncertainty.

Normal incidence impedances were educed using the standing wave method (SWM) for the 1980's dataset and the two-microphone method (TMM) for the 2000's dataset. The CT57 liner impedance has been demonstrated experimentally to be acoustically linear up to at least 140 dB and there is no evidence to support any impedance change due to grazing flows up to free-stream Mach numbers of at least 0.5.

2. 1980's technology

The 1980's technology employed measurements of single mode propagation constant (SMM) in a rectangular waveguide as depicted in the upper sketch of Figure 1 and discussed previously. At test frequencies where trailing edge (TE) reflections were minimal, an unambiguous, single mode propagation constant could be measured. A finite element model (FEM) of the test section aero-acoustic field then allowed the liner impedance to be educed, deterministically. For isolated instances when TE reflections were significant, a least squares fit of the "standing wave profile" over the liner was employed. Flow speeds were tagged by centerline Mach numbers at the reference point, located 1.87 meters upstream from the liner leading edge (LE). Area-averaged Mach numbers at the mid-point between the LE and TE were used as part of the FEM input. In Figure 2, flow centerline Mach numbers are indicated in the figure legend (i.e. 0.0, 0.1, 0.3 and 0.5) at the reference location. The flow profile was assumed invariant along the test liner length. Cross-sectioned averaged Mach numbers were calculated at the mid-point between LE and TE from a total pressure survey with a multi-probe total pressure rake. Static pressure was maintained constant at the test section axial mid-span and equal to ambient atmospheric pressure. Educed impedance sensitivity to the area-averaged Mach number was found to be substantial.

3. 2000's technology

The 2000's technology employed a 95 microphone array to measure complex pressure distributions along the solid-wall portion of the GIT test section centered on the test liner as described previously in the expanded sketch in the lower part of Figure 1. This technology handles multi-mode propagation and is thus not limited to an upper frequency of 3.0 kHz. It does, however, require a more elaborate input data set that includes source plane pressure distribution, exit plane impedance, and details of the flow profile over the test liner, depending on whether a 1-D shear or 2-D shear flow model is desired. The FEM codes have advanced to shear flow in both the vertical (liner to opposite wall) and transverse directions. Source and exit boundary conditions have been better defined, and test liner to hard wall transitions are currently being investigated. For this paper, only uniform flow results will be presented to illustrate issues that have arisen in the application of this technology.

4. Discussion of comparisons

The left- and right-hand graphics of Figure 2 show comparisons of 1980's and 2000's technology for educed grazing incidence impedance (single tone excitation) for the GIT-TB and GIT-95M test sections, respectively. The flow profiles were assumed invariant along the test liner length. The same CT57 validation test liner was used in the 2000's test as in 1980's test but remounted in a different test fixture that required a channel length reduction of about 3%. This channel length change was included in the ZKM impedance prediction.

Figure 2 shows normalized resistances and reactances. Data are shown at 0.5 kHz increments from 0.5 to 3.0 kHz. The continuous curves are the predicted normal incidence impedance for the CT57 validation liner, and from previous arguments, are claimed to hold for all grazing incidence/flow tests. For all graphics, the symbols are keyed to centerline Mach numbers obtained at reference planes located 1.87 meters upstream of the LE for the GIT-TB and at the mid-point between LE and TE planes for the GIT-95M test section.

Generally, the agreement, between educed impedances for both 1980's and 2000's technologies, is in reasonable agreement (to within about 0.5 ρc for the most part) with the ZKM prediction model. Outliers are noted in the 1980's dataset at 1.0 kHz and at a centerline Mach number o 0.5, for both resistance and reactance. These are believed due to incorrect flow Mach number inputs used in the processing of this particular computation as it is not present in the corresponding dataset for sound propagation upstream in the flow duct (see Table II(b) of reference 6). Deviations greater than 1 ρc are also noted, for both technologies, at, or near, the CT57 channel anti-resonance frequency of 2.0 kHz. These deviations are attributed to extreme sensitivity of the educed impedance to measured input parameters and have traditionally been an issue for all impedance eduction methodologies, including the classical standing wave method.

It should be noted that these results are typical of a much more extensive dataset that includes both 1D and 2D shear flows.[9] In these more extensive datasets (at 0.1 kHz increments), educed impedance deviations from the ZKM predicted impedance of up to 0.5 ρc were found in the low frequency (0.5 to 1.2 kHz), high Mach number (0.5) data for the 2000's technology. Such high-density data were not acquired for the 1980's technology, and direct comparisons are not available. This disparity is believed to arise mainly from Mach number sensitivity. Mach number sensitivity studies have demonstrated that +/- 5% change in average Mach number can move the anti-resonance by 0.2 to 0.4 kHz. This can cause significant discrepancy in the impedance above anti-resonance. Also, there is some suspicion that the acoustically soft-to-hard discontinuous, boundary-condition jump at the LE and TE may be a significant contributor to the discrepancy at the lower frequencies. It has also been determined that exit impedance effects are a significant factor in variability at 0.5 kHz. All these potential effects may produce a more irregular impedance spectrum than was the case for the more simplistic 1980's technology. Thus, these more data intensive models (FE-1D, 2D, 3D) require more attention to input parameter accuracy, e.g. Mach number, flow profile, source and exit boundary conditions.

5. CONCLUSIONS

Comparisons of 1980's and 2000's impedance eduction methodologies using the same flow duct facility and validation test liner have been completed. The 1980's methodology is inherently deterministic and limited to measurements of identifiable single mode propagation constants and bandwidth limited to about 3 kHz. The 2000's methodology employs enhanced data acquisition systems to increase dataset density and acquisition efficiency. Finite element computational technologies have been employed to improve field model fidelity to realistic flow duct aero-acoustics. Validation of these new technologies has centered on testing a liner whose impedance can be predicted from first principles. Comparisons of the 2000's technology with the simpler 1980's technology are consistent. This consistency provides the confidence to continue more extensive validation tests (beyond 3 kHz) for the current technologies. These tests will include systematic parameter studies to quantify Mach number sensitivity issues.

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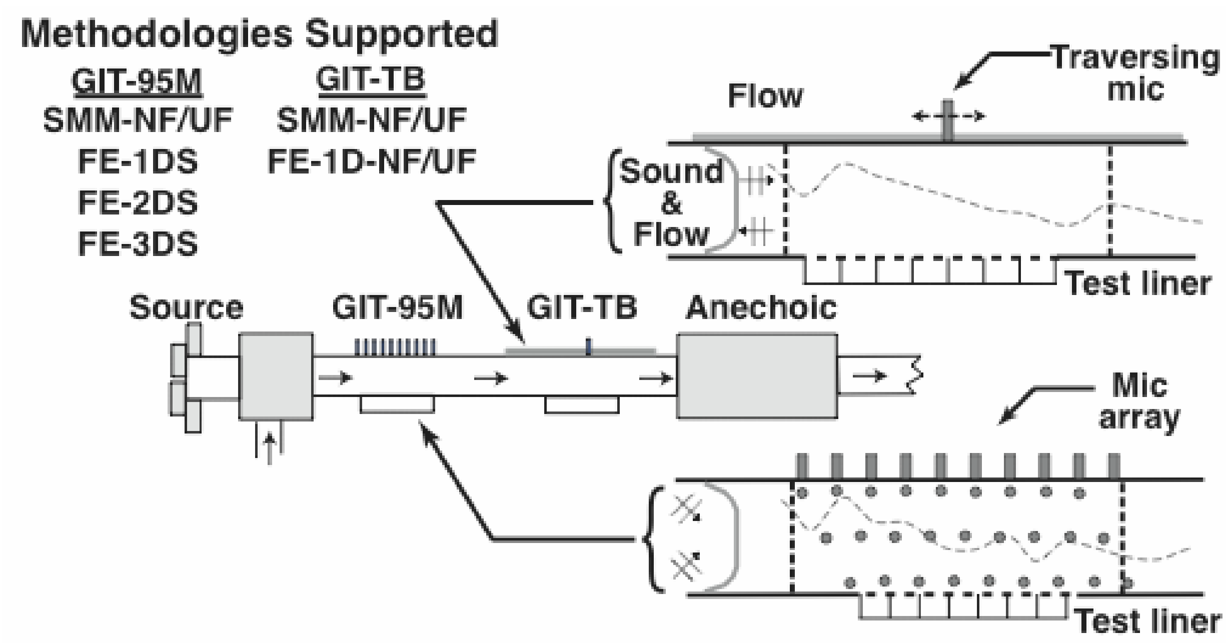

Figure 1. Langley Grazing Flow Impedance Tube (GIT) facility showing 1980's technology test section (GIT-TB) and 2000's technology test section (GIT-95M).

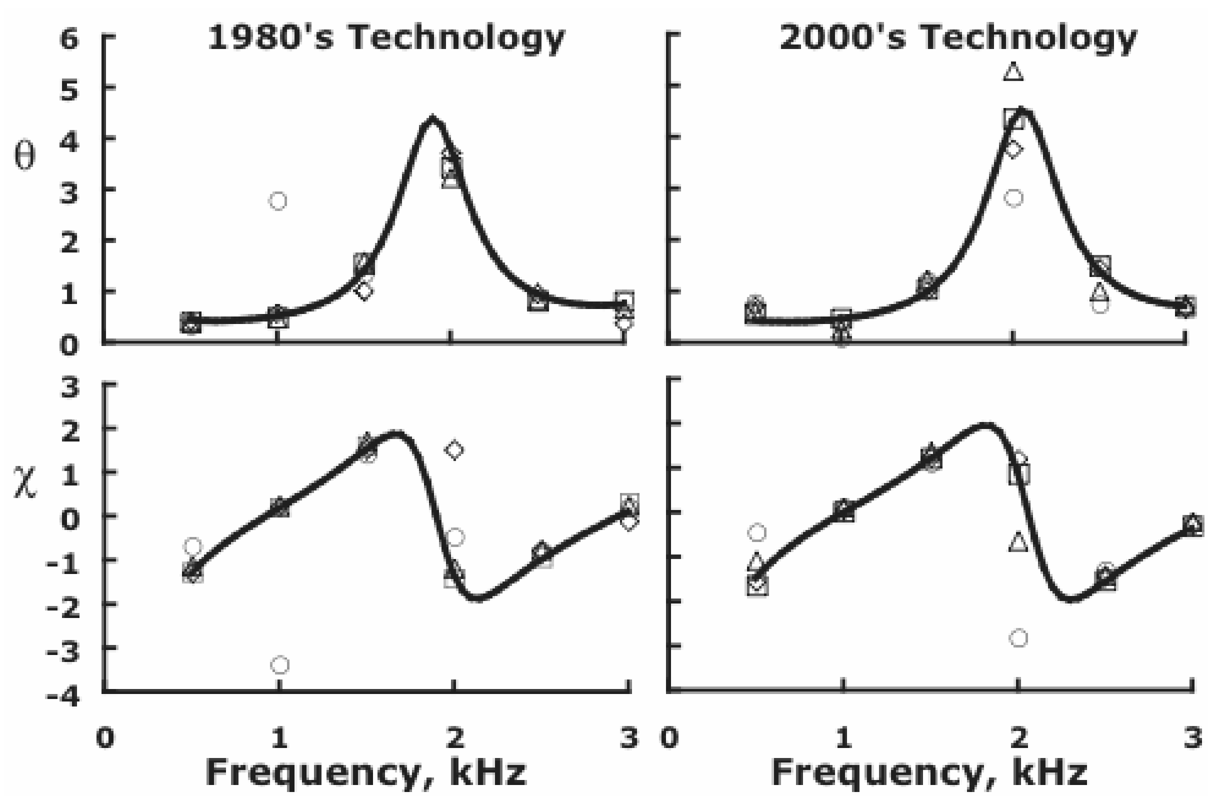

Figure 2. Comparisons of 1980's and 2000's grazing incidence/flow, impedance eduction methodologies for a ceramic tubular (CT57) validation liner: ▬ Zwikker-Kosten prediction model; □ M_{CL} = 0.0, ◇ M_{CL} = 0.1, △ M_{CL} = 0.3, ○ M_{CL} = 0.5.
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