ICAS-84-4.4.4

DESIGN PROCEDURE OF AN ACTIVE LOAD ALLEVIATION SYSTEM (L A S) FOR A MODERN TRANSPORT AIRPLANE

Authors: Dipl.-Phys. H. G. Gießeler
Dipl.-Ing. G. Beuck

MESSERSCHMITT-BÖLKOW-BLOHM GMBH, Hamburg, dept. TE2403

Summary

MBB-UT has within the scope of government sponsored programs worked out the technological fundamentals for the development of an aircraft with a Load Alleviation System (LAS).

The design and realization procedure, a possible sensor and actuating concept, the way how the control law was derived and a possible operational concept are explained. Taking a modern transport aircraft as an example results of theoretical simulations are shown.

Some graphs from tests to identify the unsteady aerodynamics of control surfaces are depicted.

A windtunnel demonstration of the LAS on a TORNADO-model confirms the design assumptions.

Contents

1. Introduction

MBB-UT has within the scope of government sponsored programs worked out the technological fundaments for the development of an aircraft with a Load Alleviation System (LAS).

Theoretical design work, windtunnel tests and ground simulations indicate the feasibility of the new function of the movables.

The objective of this function is the reduction of wing structural loads due to longitudinal maneuvers and vertical gusts.

So structural weight can be saved and the Direct Operating Costs decrease.

2. Design and Realization Procedure

Fig. 1 shows the main development tasks up to the verification of an a/c with a LAS.

All starts with the assembling of performance criteria and structural design criteria for control system, loads, flutter and flying qualities.

Another basic activity is the data acquisition for geometry, aerodynamics, stiffness, mass,operational limits / mission and control system.

As well the design load cases and the attainable weight reduction have to be fixed. Finally the active control concept has to be chosen.

A set of mathematical models and software systems has to be developed. A LAS synthesis software needed to perform the specified function has to be established.

Within a flight simulation program the control laws have to be exercised in an analytic representation to obtain a performance confirmation.

The control laws are fed back into the maneuver loads, gust loads and flutter analysis programs. These programs reflect flight tests, ground vibration and wind tunnel results.

Then a breadbord hardware system is defined and built. The system includes flightworthy components and all interface to complete the installation on the flight test airplane.

Next the ground test program has to be defined. Some objectives are the development of component hardware, the evaluation of system performance, the verification of compatibility with other aircarft systems, the evaluation of failure modes.

Now the flight test program follows. It has to be determined the extent to which predicted reductions in maneuver and gust loads can be achieved. The adequacy of mathematical modelling to give accurate transfer functions relating airplane motions to control surface motions has to be checked.

Furtheron loads in maneuvers and in turbulence have to be measured.

3. Sensor and Actuating Concept

Optimization studies resulted in the LAS-concept shown in fig. 2 and 3. The presented system alleviates symmetrical wing loads. Two load alleviation functions are distinguished. The first reduces the longwave (low frequency) loads and the maneuver loads.

The frequency region is well below the first wing bending mode. This function senses a fuselage acceleration, which is gain scheduled and fed into a summation point.

The other function can be called Elastic Mode Suppression. It reduces gust loads in the frequency region of the elastic modes. The two sensors are again accelerometers and are placed at the wing tips, where the modal deflections are large.

Left and right wing tip acceleration are summed to eliminate the antimetric part of the signal. After gain scheduling this signal leads to the summation point. The resulting information mix is transformed by one control law into a symmetric input for the servos/actuators.

A zero signal level input during horizontal flight is provided and a command signal dead-zone function is switched in, if the command signal level is less than a pre-set limit for a period of time.

If the computed command signal exceeds the dead-zone limits, the function is switched out. This device protects against mechanical wear and will decrease the drag.

4. System and Operational Considerations

The control law computation will be digital. So an analog to digital conversion of the sensor signals and a digital to analog conversion of the computer output has to be done.

A low pass filter at the entrance of the computer to prevent aliasing effects and a smoothing filter with low pass characteristics in front of the servos are needed because of digital signal processing.

Triple sensor sets,a dual/dual system having two identical signal processing control channels and two identical computers would provide sufficient safety and reliability.

Fig. 4 gives a possible operational concept of a LAS.

5. Theoretical Simulations

Taking a modern transport aircraft as an example results of theoretical simulations are shown.

Fig. 5 shows the premises for the simulation. Fig. 6 explains the different steps during control law derivation. Fig. 7 to 10 give the attainable load reductions dependant on spoiler and outboard aileron deflection rate and deflection.

For a 12,5 $\bar{c}$ 1-cos gust and a max. deflection rate of 100 ^{o}/s the outboard aileron reaches 13 % and the spoilers 18 % of wing root bending alleviation.

The same values for Continuous Turbulence are 22 % and 31 %. These values are based on equal rigid rolling moment coefficients of ailerons and spoilers (0.321 rad^{-1} for one side). Actually the ailerons only have got about half the efficiency and the mentioned values have to be divided by two. The influence of elasticity and aerodynamic distribution is seen very clearly.

6. Identification of Unsteady Aerodynamics

As a part of a Memorandum of Understanding (signed by ONERA, AS and MBB) MBB and ONERA conducted windtunnel tests with a large A310-halfmodel equipped with rapidly moving spoilers, flaperon and outboard aileron. 3 D-unsteady pressure distributions due to harmonic motion of control surfaces around some mean deflection were recorded and processed by the aerodynamics department to obtain spanwise lift- and moment-distributions.

To use the data for design of a LAS the pointwise given frequency response function is approximated by a rational function in the complex variable s:

$$F_{K,l}(s) = \frac{\sum_{i=0}^{k} a_i s^i}{\sum_{i=0}^{l} b_i s^i} \equiv (k,l)\text{-Approx.}$$

We actually used the combinations (k,l) = (1,1), (1,2), (2,2). Further on b_l = 1 and the constraint $a_o = b_o$ in order to match the steady state behaviour.

Out of this we get the step response function. For k = 1 we expect a Wagner effect, i. e. the step response function has got some nonzero value at the beginning.

This value is determined by the extrapolated behaviour of the frequency response function as the reduced frequency k approaches infinity and thus may be treated with caution, because it depends on the order of approximation.

The k = 1 approximation is believed appropriate for cuts on the wing in the vicinity of the control surfaces. We used k < 1 for the remaining cuts to account for a delay effect due to the spread of disturbance.

For all the spoilers a typical step response (M = 0,83, mean deflection = 5^{o}) of the total lift is shown in fig. 19 for different values of k and l.

Approximation of the local lift response for small times are more sensitive to a variation of the order of the polynominal as mentioned above.

7. Windtunnel Test of an LAS

Within the GARTEUR Action Group on Active Control Applications MBB-UT tested a LAS as described in the previous sections on a Tornado-model in the 3 m - windtunnel of the DFVLR in Göttingen.

Fig. 11 gives an idea of the used model

Fig. 12 lists the test objectives

Fig. 13 to 15 show the frequency response of fuselage and wing tip acceleration and of wing bending moment. They were approximated by rational polynomials and used for the control law synthesis.

Fig. 16 depicts a comparison of measured and approximated wing bending moment. The quality of the approximation was improved by approximating simultaneously several transfer functions with the constraint of a common denominator.

Fig. 17 demonstrates the gust load alleviation by plotting on the same graph the power spectrum density for system on and off due to a sine -gust in the frequency region of the first wing bending mode.

Fig. 18 is a Nyquist-diagram of the LAS. It is obvious that the stability margins are sufficient.

8. Outlook

A lfight test campaign on the A 310 provided a further validation of our design assumptions. Even more can be gained from this modern technology, if the optimizataion of an a/c includes a LAS from the beginning.

9. References

1. Schwarz: Mehrfachregelungen (Springer Verlag)

2. O'Connel: Design,Development and Implementation of an Active Control System for Load Alleviation for a Commercial Transport Airplane. 49th meeting of AGARD Structures and Materials Panel, Köln, 09.10.1979

3. Beuck: Entwurf und Auslegung eines aktiven Lastminderungssystems am Beispiel eines modernen Transportflugzeuges. Jahrestagung DGLR, Stuttgart 05.-07.10.1982

4. Giesseler: Gebrochen-rationale Approximation und Extrapolation von Frequenzgängen MBB-Bericht TN-TE2203/1-82

Fig. 1: Main Development Tasks

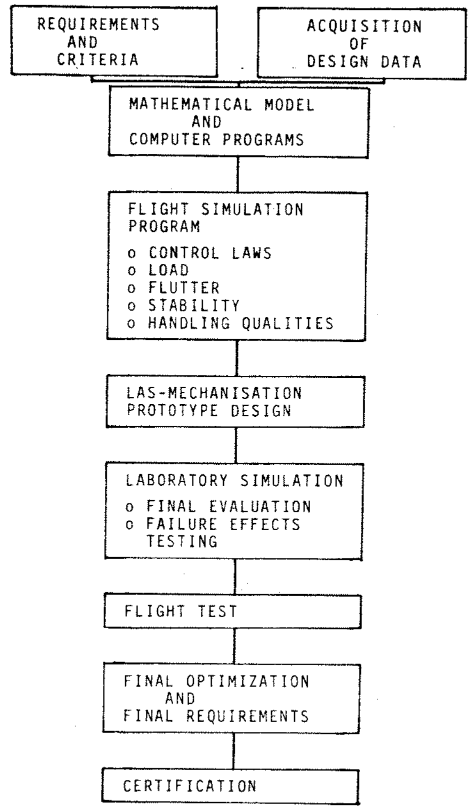

Fig. 2: Functional Block Diagram of the LAS

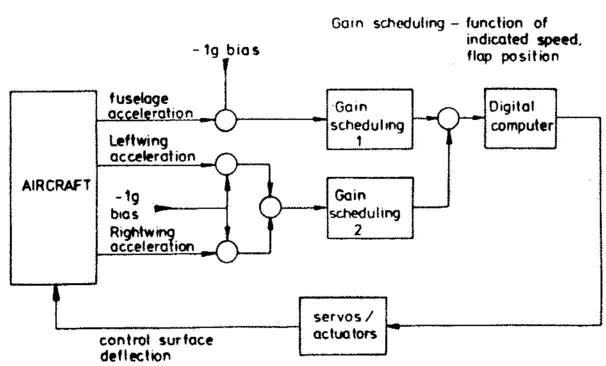

Fig. 3: Location of Principal LAS Components

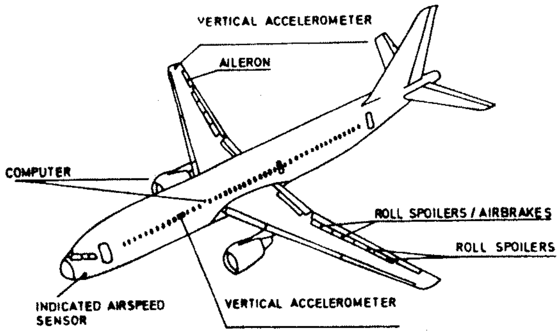

Fig. 4: Possible Operational Concept of a LAS

- A/C IS DESPATCHABLE WITH ONE CHANNEL OF THE LAS INOPERATIVE AND NO OPERATIONAL LIMITATIONS
- A FAILURE OF TWO CHANNELS WILL RESULT IN LAS-SWITCH-OFF
- A SINGLE SENSOR FAULT IS ALLOWED WITH NO OPERATIONAL RESTRICTIONS
- IN CASE OF COMPLETE SYSTEM DISCONNECT THE A/C CAN CONTINUE THE FLIGHT BY USING NORMAL OPERATIONAL PRACTICES (FAIL-OPERATIONAL CAPABILITY)
- CONTINUED OPERATION WITHOUT LAS WITH DEFINED OPERATIONAL RESTRICTIONS
- THE PROBABILITY OF LOSS OF SYSTEM FUNCTION HAS TO BE GREATER THAN 10^{-5} PER FLIGHT HOUR.

Fig. 5: Premises for theoretical Simulation

A 320, LAS - DESIGN

- o FULL FLEX. DYNAMIC EFFECTS TAKEN INTO ACCOUNT
  - 2 RIGID BODY MODES (HEAVE, PITCH)
  - 10 FLEXIBLE MODES
- o GUST MODELS
  - DISCRETE GUST (12,5 $\bar{c}$)
  - CONTINUOUS TURBULENCE (V. KARMAN SPECTRUM)
- o LOAD ALLEVIATION ON WING
- o MAX. ATTAINABLE LOAD ALLEVIATION
- o STUDY RESTRICTED TO WING ROOT BENDING DESIGN CONDITION
- o USE OF ANALOG CONTROL LAW
- o LINEAR SYSTEM BEHAVIOUR
- o MAX. DEFLECTION RATE 100 °/SEC.
- o STRIP THEORY FOR ALL LIFTING SURFACES
- o UNSTEADY AERODYNAMICS BY USING APPROXIMATED WAGNER- AND KÜSSNER-FUNCTIONS
- o RESULTS BASED ON EQUAL RIGID ROLLING MOMENT-COEFFICIENT OF AILERONS AND SPOILERS

Fig. 6: Control Law Derivation

- COMPUTATION OF WING ROOT BENDING TRANSFER DUE TO SYMMETRICAL VERTICAL GUSTS OF THE UNCONTROLLED A/C
- CONSTANT PERCENTAGE OF W R B ALLEVIATION AT EACH FREQUENCY
- CONTROL LAW SYNTHESIS AT DISCRETE FREQUENCIES
- APPROXIMATION OF DISCRETE CONTROL LAW BY RATIONAL POLYNOMIALS

$$R(s) = V \cdot \frac{Z(s)}{N(s)}$$

Fig. 7: Attainable Load Alleviation Versus Defl. Rate

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A320 CONTROL SURFACE DEFLECTION RATE / D.C.

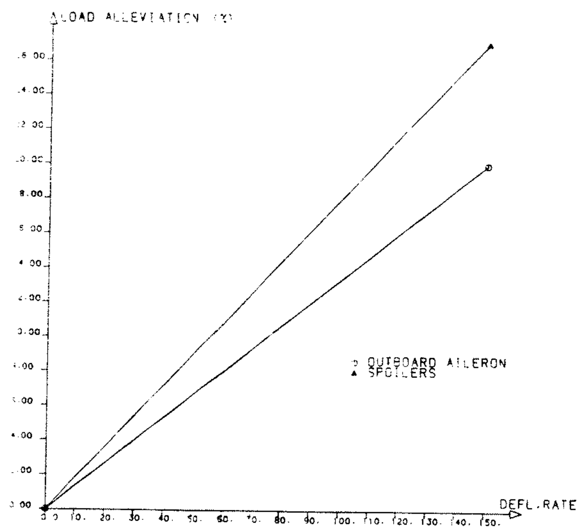

Fig. 8: Attainable Load Alleviation Versus Deflection

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A320 CONTROL SURFACE DEFLECTION / D.C.

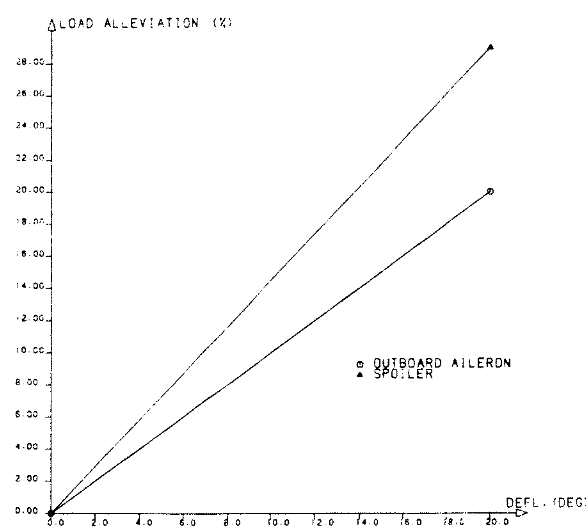

Fig. 9:

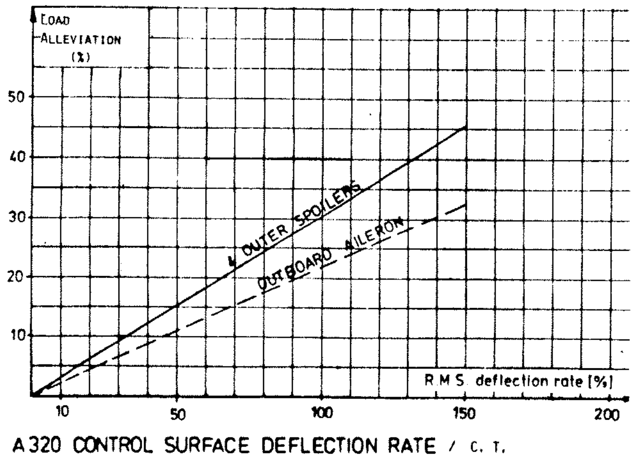

Fig. 10:

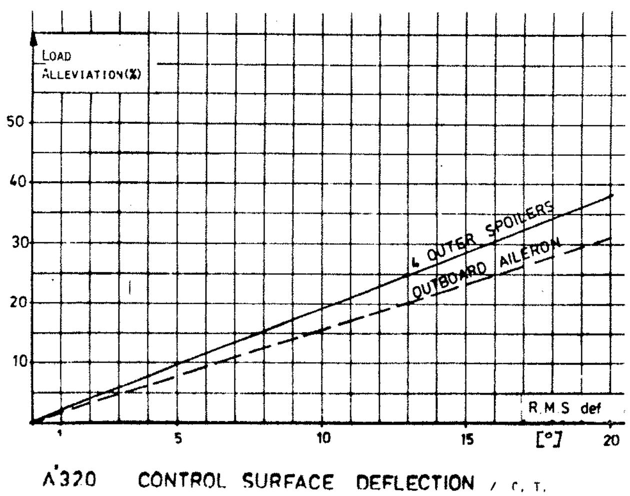

Fig. 11: Wind Tunnel Model

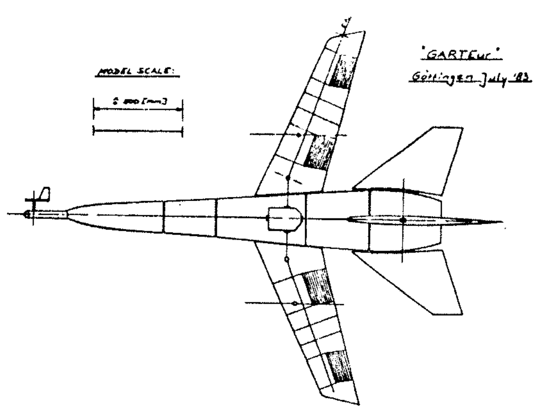

Fig. 12: Objectives for "GARTEUR" Tests of DFVLR Göttingen

TEST OBJECTIVES

- ALLEVIATION OF LONG-WAVE (LOW FREQUENCY) SYMMETRICAL GUSTS (THE FREQUENCY REGION IS WELL BELOW THE FIRST WING BENDING MODE)
- ALLEVIATION OF SYMMETRIC GUST LOADS IN THE FREQUENCY REGION OF THE 1. WING BENDING MODE
- ALLEVIATION OF SINUSOIDAL AND RANDOM GUSTS
- NO CHANGE IN FLUTTER SPEED AND FLUTTER FREQUENCY
- GAIN MARGIN ± 6 DB AND PHASE MARGIN ± 30°
- SUFFICIENT DAMPING OF PITCH AND HEAVE MODE IN TURBULENCE
- TEST OF DIGITAL CONTROL TECHNIQUE

Fig. 13: Wing Tip Acceleration V = 30 m/s Outboard Aileron Input

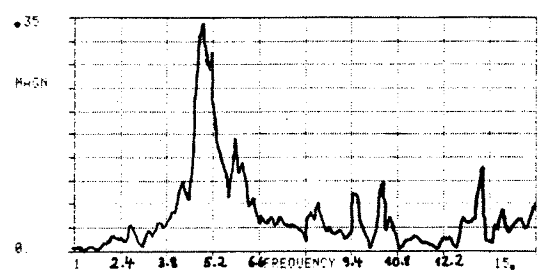

Fig. 14: C.G. Accleration V = 30 m/s Outboard Aileron Input

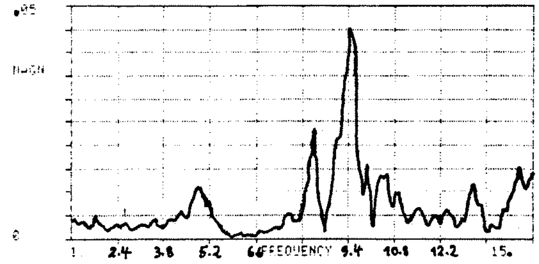

Fig. 15: Wing Root Bending Moment
V = 30 m/s
Ourboard Aileron Input

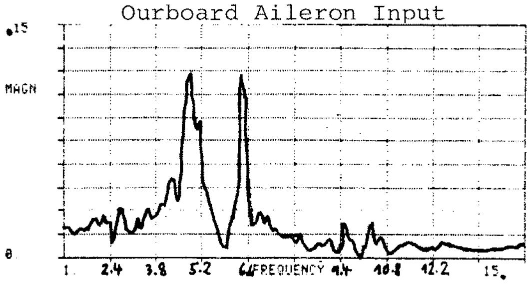

Fig. 16: Approximation of the Frequency Response Function Wing Root Bending/Outboard Aileron

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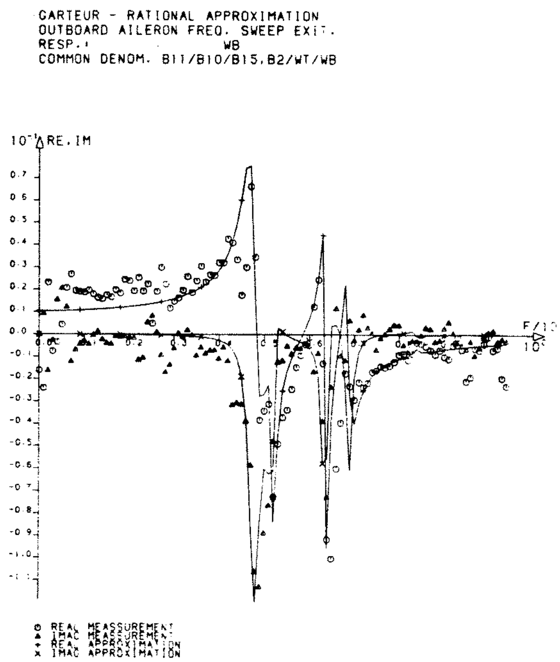

Fig. 17: PSD of Wing Root Bending Moment with LAS ON/OFF

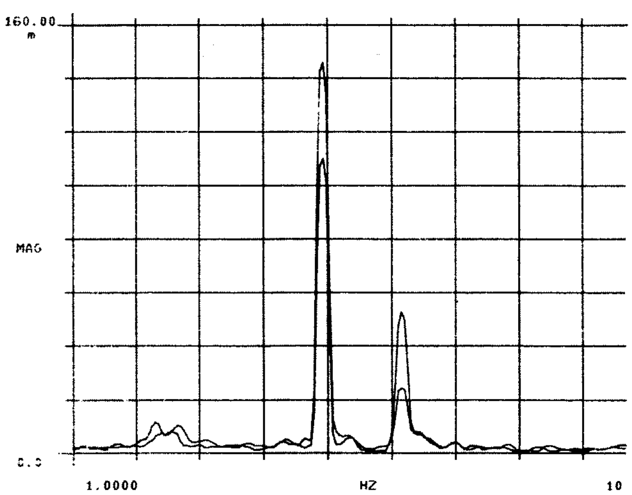

Fig. 18: Nyquist-Diagram for LAS showing Sufficient Stability Margins

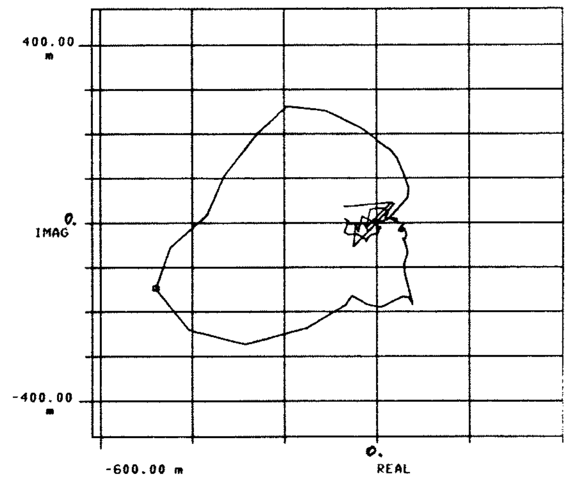

Fig. 19: Normalized Indicial Function, Derived from Harmonic Tests (5^{o} mean defl., 1^{o} Ampl.)

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