УДК 629.7.015.4
DOI: 10.26467/2079-0619-2024-27-2-60-68

# Experimental studies of the impact of fluid sloshing in the tank on the dynamic characteristics of the “wing model – fuel tank” system

**G.B. Vardanyan[1], A.S. Kochetov[1], Y.V. Petrov[1]**
*[1]The Moscow State Technical University of Civil Aviation, Moscow, Russia*

**Abstract:** Flexible response of the airframe structural elements under operational loads are one of the main sources of fatigue damage accumulation. It is known that fuel sloshing in tanks can change the dynamic (frequencies and shapes of natural oscillations) and dissipative properties (oscillation damping decrements) of an elastic system, including partially or completely fuel-filled tanks. It is specified that fuel sloshing in tanks due to the additional oscillation energy dissipation of the elastic system can have a significant impact on both the fatigue and aeroelastic characteristics of aircraft structural elements. Theoretical and experimental studies, applicably to the majority of currently operating transport aircraft, have shown that when modeling dynamic phenomena and solving aeroelasticity problems, fuel can be considered conditionally solidified, which actually does not affect the resultant effect. The advent of modern heavy transport aircraft with a high aspect ratio wing and four engines on pylons under the wing has led to a considerable change in the dynamic picture of the aircraft interaction with the environment. The main feature is that, under this arrangement, the first horizontal bending mode of the wing is embedded in the main flexible modes that determine the dynamic response to external effects. In this case, the model of solidified fuel can have a significant impact on the accuracy of predicting dynamic loads and, as a consequence, on the quantitative characteristics of durability and aeroelasticity. The article presents the results of experimental studies of the impact of fluid sloshing in the tank on the dynamic characteristics (frequencies of natural oscillations and amplitudes of forced oscillations) of the “wing model – fuel tank” system. The design of the experimental installation and the methodology of conducting experiments are described. During the experiment, the tank was partially filled with liquid or full, and horizontal bending modes of the wing model, for which considering liquid sloshing in the tank is the most relevant, were studied. The tank refueling levels are determined at which the maximum effect of the system oscillation damping is achieved due to energy dissipation under liquid sloshing. The effect of various factors (presence of a top cover, internal structural frame, perforation in the structural frame) on the amplitudes and frequencies of forced oscillations is analyzed.

**Key words:** liquid sloshing, dynamic characteristics, oscillatory frequency and amplitude, frequency response.

**For citation:** Vardanjan, G.B., Kochetov, A.S., Petrov, Y.V. (2024). Experimental studies of the impact of fluid sloshing in the tank on the dynamic characteristics of the “wing model – fuel tank” system. Civil Aviation High Technologies, vol. 27, no. 2, pp. 60–68. DOI: 10.26467/2079-0619-2024-27-2-60-68

# Экспериментальные исследования влияния подвижности жидкости в баке на динамические характеристики системы «модель крыла – топливный бак»

**Г.Б. Варданян[1], А.С. Кочетов[1], Ю.В. Петров[1]**
*[1]Московский государственный технический университет гражданской авиации, Москва, Россия*

**Аннотация:** Упругие колебания элементов конструкции планера самолета при действии эксплуатационных нагрузок являются одним из основных источников накопления усталостных повреждений. Известно, что подвижность топлива в баках может изменять динамические (частоты и формы собственных колебаний) и диссипативные (декременты затухания колебаний) свойства упругой системы, включающей баки, частично или полностью заполненные топливом. При этом волновое движение топлива в баках за счет дополнительной диссипации энергии колебаний упругой системы может оказывать существенное влияние как на усталостные, так и на аэроупругие характеристики элементов конструкции воздушного судна. Теоретические и экспериментальные исследования применительно к большинству эксплуатирующихся в настоящее время транспортных самолетов показали, что топливо при моделировании динамических явлений и решении задач аэроупругости можно рассматривать условно затвердевшим, что фактически не влияет на конечный результат. Появление современных тяжелых транспортных самолетов с крылом большого удлинения и четырьмя двигателями на пилонах под крылом привело к существенному изменению динамической картины взаимодействия ЛА с окружающей средой. Основная особенность заключается в том, что при данной компоновке в число основных упругих тонов, определяющих динамическую реакцию на внешние воздействия, входит первый тон горизонтально-изгибных колебаний крыла. В этом случае модель затвердевшего топлива может оказать существенное влияние на точность прогнозирования динамических нагрузок и, как следствие, на количественные показатели долговечности и аэроупругости. В статье приводятся результаты экспериментальных исследований влияния подвижности жидкости в баке на динамические характеристики (частоты собственных колебаний и амплитуды вынужденных колебаний) системы «модель крыла – бак». Описана конструкция экспериментальной установки и методика проведения экспериментов. В процессе эксперимента бак частично или полностью заполнялся жидкостью, исследовались горизонтально-изгибные формы колебаний модели крыла, для которых учет подвижности жидкости в баке наиболее актуален. Определены уровни заправки бака, при которых достигается наибольший эффект демпфирования колебания системы за счет рассеивания энергии при волновом движении жидкости. Проанализировано влияние различных факторов (наличие верхней крышки, внутреннего силового набора, перфорации в силовом наборе) на амплитуды и частоты вынужденных колебаний.

**Ключевые слова:** волновое движение жидкости, динамические характеристики, частота и амплитуда колебаний, амплитудно-частотные характеристики.

**Для цитирования:** Варданян Г.Б., Кочетов А.С., Петров Ю.В. Экспериментальные исследования влияния подвижности жидкости в баке на динамические характеристики системы «модель крыла – топливный бак» // Научный Вестник МГТУ ГА. 2024. Т. 27, № 2. С. 60–68. DOI: 10.26467/2079-0619-2024-27-2-60-68

## Introduction

Elastic modes of the airframe structural elements under operational loads are one of the main sources of fatigue damage accumulation. Some theoretical and experimental studies for tanks of different shape show [1–16], that fluid sloshing in the tank can change frequencies and shapes of free oscillations of technical objects with cavities which are partially or completely filled with liquid. Furthermore, under certain conditions, a level and frequency of loads, acting on the structure due to liquid sloshing, vary substantially, which impacts the magnitude of fatigue damage accumulation in the structural elements. Fuel sloshing in the tanks also impacts aeroelastic characteristics of aircraft structural elements [2, 3].

Numerous theoretical and experimental studies, applicably to majority of operating transport aircraft, showed that while solving dynamic problems, fuel can be considered conditionally solidified which, in fact, does not impact a resulting effect. The advent of modern heavy transport aircraft with a high aspect ratio wing and four engines on pylons under the wing has led to a considerable change in the dynamic picture of the aircraft interaction with the environment. The main feature is that, under this arrangement, the first horizontal bending mode of the wing is embedded in the number of elastic eigentones that determine the dynamic response to external effects. In this case, in conformity with the studies [2, 3], a model of solidified fuel can have a significant effect on the accuracy of predicting dynamic loads and, as a consequence, on the quantitative characteristics of durability.

Known analytical solutions do not make it possible to adequately respond to a variety of key issues: how a level of refueling the fuel tank impacts the dynamic and dissipative characteristics of the “wing – tank” system on the whole; how to evaluate magnitudes of partial logarithmic decrements of fuel sloshing damping in tanks for the use in mathematical modeling; to identify the most rational design schematization of tanks while modeling; to define the extent of upper wing panel impact on fuel sloshing in tanks regarding various levels of refueling.

## Experimental techniques

The experiment is dedicated to the solution of some of the stated issues. The schematic diagram of the experimental installation, designed to investigate the impact of fuel sloshing in the tanks, is given in Figure 1.

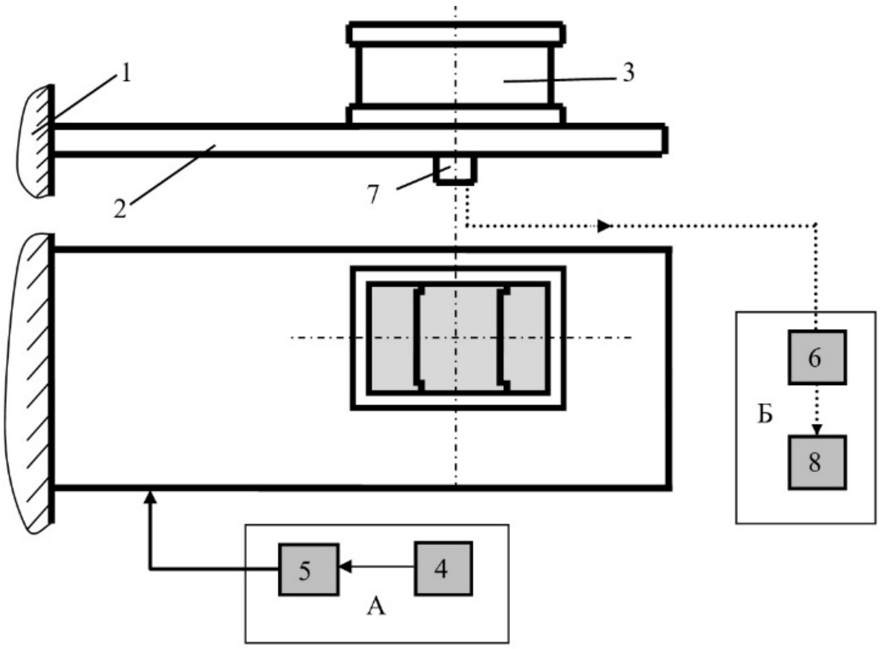


**Fig. 1.** Schematic diagram of the experimental installation

A beam 2, modeling the aircraft wing which inertia-mass and rigidity parameters are known, is tightly fixed on the massive basis 1. A tank 3, manufactured from duralumin plates with the upper organic plastic cap, is installed on the beam. The tank presents a geometrically alike fragment of an integral fuel tank of a heavy transport aircraft. An integral fuel tank is schematized by a rectangular parallelepiped. A capability to install up to five additional ribs (partitions) inside the tank is provided. A rib set comprises complete walls as well as perforated walls of different aggregate area. The tank was filled with water.

A unit of excitation A (fig. 1) energizes a generator of signals 4 and an electric dynamic vibration exciter 5. Forced harmonic beam vibrations in the horizontal plane within a frequency range of $f_B$ = 2.5...4.5 hz, inside which there is free frequency of the first horizontal bending mode of the beam with an empty tank, were excited by the unit A. A recorder unit B activates sensors of vibratory displacement 7, an amplifier of signal 6 and a recording device 8. Processing of measurement outputs was conducted in compliance with GOST P 8.736-2011.

The methodology of conducting the experiment was as follows.

In the first phase, dynamic and dissipative characteristics of a beam with an empty tank were identified, amplitude-frequency response diagrams were built. Thereupon, liquid (water) was poured into a tank, and new amplitude-frequency response systems, containing a cavity partially water-filled which generates wave sloshing, were built. Parameters of an equivalent mechanical analog, which were used to form equations of the disturbed motion for the system "wing model – tank with liquid" and to perform theoretical calculations, are computed under the certain geometrical tank sizes and the assigned level of refueling according to the familiar methodology [2, 17, 18]. The parameters of the mechanical analog were also identified experimentally in accordance with the resonant method. A pitch of the refueling level variation amounted to $\Delta\bar{G}_T = \frac{\Delta G_T}{G_{T0}} = 0.1$, where $\Delta G_T$ – weight of additionally poured water into the tank, $G_{T0}$ – water weight in the full tank. The system characteristics were additionally investigated while using a model of solidified fuel.

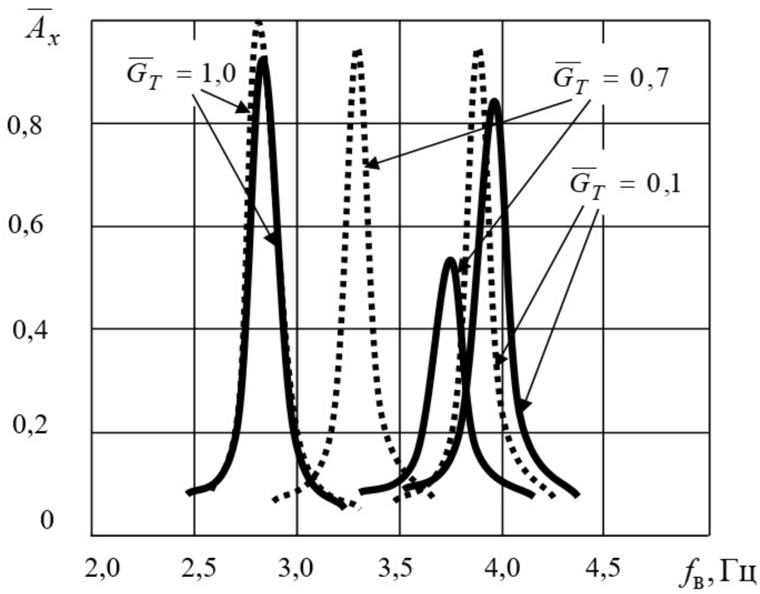


**Fig. 2.** Normalized amplitude-frequency responses of horizontal beam oscillations at the location of the vibration displacement sensor installation (solid line – sloshing liquid, dashed line – conditionally solidified liquid)

In this case, cargo, weighing $G_{T0}$, was put into the tank.

## Experimental findings

Main experimental findings are given in Figures 2…5. Figure 2 shows normalized amplitude-frequency responses at the location of the vibration displacement sensor installation of the dynamic system under consideration in the area of the first horizontal bending mode under different refueling levels $\overline{G}_T = \frac{G_T}{G_{T0}}$, where $G_T$ – weight of the filled-tank water.

An analysis of results show that fluid sloshing has a more significant impact on the dynamic (eigen frequencies) and dissipative (response amplitude) parameters of the elastic system under average refueling $(\overline{G}_T = 0.7)$. Under low tank refueling $(\overline{G}_T = 0.1)$ and for full tanks $(\overline{G}_T = 1.0)$, the impact of liquid sloshing can be initially not considered and can be regarded as conditionally solidified.

The variation of the beam eigen frequency with a tank by the first horizontal bending mode $\overline{\Omega}_{ГИ} = \frac{\Omega_i}{\Omega_0}$ ($\Omega_i$ – eigen frequency at the interim fueling level, $\Omega_0$ – the beam eigen frequency with an empty tank) from the refueling level $\overline{G}_T$ is illustrated in Figure 3. The analysis of findings proves satisfactory convergence of the calculation and the experiment.

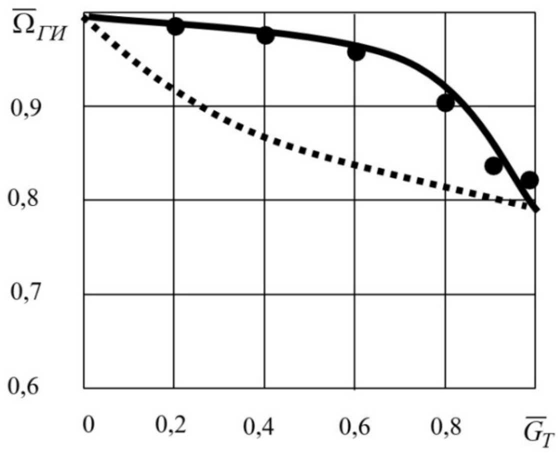


**Fig. 3.** Dependence of the relative beam eigen frequency with the tank $\overline{\Omega}_{ГИ}$ on the level of tank refueling $\overline{G}_T$ (solid line – the calculation considering liquid sloshing; dashed line – the calculation with solidified liquid; dots – experimental data)

The impact of the inner set (ribs) on the dynamic characteristics of the "wing model – fuel tank" system and the parameters of the mechanical analog was evaluated in the course of the experiment as well. In particular, Figure 4 shows the function graphs $\Omega_{ГИ} = f(\overline{G}_T)$, where $\Omega_{ГИ}$ – eigen frequency of the first-mode horizontal bending beam oscillations with a tank; $\overline{G}_T$ – the refueling level. In conformity with the function graphs, while schematizing a real tank structure, a series of its compartments (2…5) can be combined into groups for which the impact of inner ribs can be disregarded.

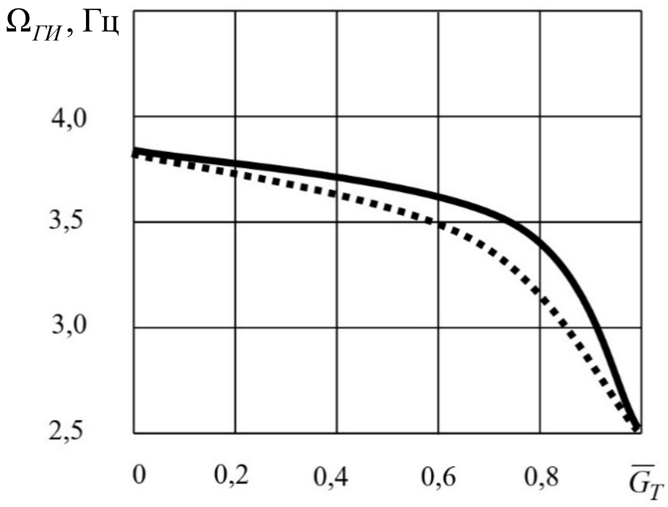


**Fig. 4.** Dependence of the beam eigen frequency with the tank $\Omega_{ГИ}$ on the level of refueling the tank $\overline{G}_T$ (solid line – a tank without ribs; dashed line – a tank with five ribs)

The experimental definition of logarithmic decrements of liquid sloshing damping under its wave motion in the tank is of paramount importance, as all the existing analytical methods are merely applicable for specific tank shapes with smooth walls. In the experiment, the logarithmic decrements of oscillation damping of the "wing model – tank with liquid" system were identified. The partial logarithmic decrement of the main mode liquid sloshing damping was calculated analytically using experimental data. For this purpose, a two-mass calculation model of the system was used: a single mass beam model with the reduced mass to the center of tank gravity as well as a single mass pendulum model of wave liquid motion. To be based on processing the experimental oscillograph charts of free mode of the system, partial frequencies as well as the logarithmic decrements of beam oscillations damping (empty tank) of the eigentone and the whole system under different levels of tank refueling were obtained. The design model allows us to compute the partial decrement of the pendular oscillator vibration damping. As a result, an array of data was derived: a level of tank refueling $\overline{G}_T$ – the partial logarithmic decrement of the pendular oscillator vibration damping $\delta_T$, modeling fuel sloshing. In order to obtain an analytical dependence, the method of least-squares was used.

The results, given in Figure 5, are in the form of the dependence of the logarithmic liquid sloshing damping decrement in the tank by the first mode $\delta_T$ of wave motion in the horizontal plane on the refueling level $\overline{G}_T$, where the curve, obtained according to the empirical formula $\delta_T = 0.08 + 0.2\overline{G}_T^3$, is presented by a solid line. Experimental data is shown by dots in the picture. The empiric formula can be used while conducting preliminary evaluation calculations of aeroelastic and strength characteristics of the aircraft with fuel sloshing in tanks.

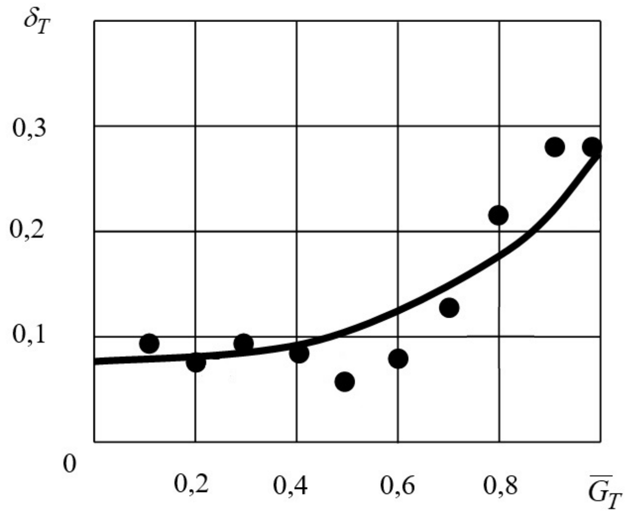


**Fig. 5.** Dependence of the logarithmic oscillation damping decrement $\delta_T$ on the refueling level $\overline{G}_T$

## Conclusion

The findings revealed that considering liquid (fuel)sloshing in the tanks under the horizontal bending mode of the outer wing can significantly specify its dynamic response to the external disturbing effects. The impact of the tank refueling level on both eigen frequencies as well as the dissipative parameters of the system was evaluated. The empirical formula to calculate the partial logarithmic decrement of liquid sloshing damping under horizontal bending wing modes which can be used while preliminary mathematical modeling.

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## Information about the authors

**Georgiy B. Vardanyan,** Candidate of Technical Sciences, Associate Professor of the Technical Mechanics and Engineering Graphics Chair, Moscow State Technical University of Civil Aviation, g.vardanyan@mstuca.aero.

**Aleksander S. Kochetov,** Candidate of Technical Sciences, Associate Professor of the Technical Mechanics and Engineering Graphics Chair, Moscow State Technical University of Civil Aviation, a.kochetov@mstuca.aero.

**Yuriy V. Petrov,** Doctor of Technical Sciences, Professor, The Head of the Technical Mechanics and Engineering Graphics Chair, Moscow State Technical University of Civil Aviation, doctor561@rambler.ru.

## Сведения об авторах

**Варданян Георгий Бенурович,** кандидат технических наук, доцент кафедры технической механики и инженерной графики МГТУ ГА, g.vardanyan@mstuca.aero.

**Кочетов Александр Сергеевич,** кандидат технических наук, доцент кафедры технической механики и инженерной графики МГТУ ГА, a.kochetov@mstuca.aero.

**Петров Юрий Владимирович,** доктор технических наук, профессор, заведующий кафедрой технической механики и инженерной графики МГТУ ГА, doctor561@rambler.ru.

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| Поступила в редакцию | 01.12.2023 | Received | 01.12.2023 |
| Одобрена после рецензирования | 10.01.2024 | Approved after reviewing | 10.01.2024 |
| Принята в печать | 21.03.2024 | Accepted for publication | 21.03.2024 |