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RESEARCH INTO THE EFFECTS OF ASTRONAUT MOTION ON THE SPACECRAFT: A REVIEW

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Abstract—The paper reviews the research that has been undertaken to understand and quantify the disturbance effects of the astronaut's motion inside and outside the spacecraft on the vehicle's attitude and acceleratory environment. In early investigations, the dynamic interaction of astronauts, modeled as point masses, and the spacecraft, modelled as a rigid body, was analyzed. Through ground-based experiments and the modeling of astronaut-induced forces and moments as stochastic processes, it became possible to estimate the magnitude and energy content of the loads produced by the astronaut. The first experiment in space to measure the astronaut-induced disturbances was conducted on the *Skylab* orbital station. Loads generated while performing routine operations were measured on board the Space Shuttle in 1994 and on the space station *Mir* in 1996–1997. © 2001 Elsevier Science Ltd. All rights reserved

1. INTRODUCTION

External disturbances to a spacecraft in orbit such as aerodynamic drag or solar pressure can be described in simple analytical form and estimated well from vehicle and environmental parameters. Similarly, disturbances inside the spacecraft due to the operation of mechanical equipment such as pumps, fans, and valves can be foreseen and computed. Predicting astronaut-induced disturbances represents a far more challenging task due to the inherent randomness.

This paper reviews much of the research that has been undertaken since the 1960s to understand and quantify the effects of astronaut motion on the spacecraft and presents new results from the dynamic load sensors (DLS) spaceflight experiment flown aboard the Space Shuttle and the enhanced dynamic load sensors (EDLS) experiment flown aboard the Russian space station *Mir*.

NASA's initial concern was that the magnitude of the forces and moments exerted by the astronauts in the cabin would be the largest disturbance source to the vehicle's attitude control system and thus represent the design driver for the system. The early models of spacecraft–astronaut interaction were *deterministic* in nature. The effect of the astronaut motion was uniquely determined by a mathematical expression describing the behavior of point masses (the astronauts) interacting with a rigid body (the spacecraft). Break-through analysis of astronaut-induced disturbances resulted from ground-based experiments and modeling of the astronauts' forces and moments as *stochastic processes*. Together with the experience from human spaceflight and the development of larger spacecraft, it became evident that astronaut-induced disturbances do not represent the major challenge for the control system. By the late 1960s/early 1970s, the prevalent concern was that astronaut-induced disturbances would not permit high-precision pointing of a spacecraft or space station for astronomical observations. An experiment on the *Skylab* station provided the first data collected in space on astronaut-induced disturbances and verified that astronauts can produce significant disturbance forces and moments if they so desire.

In the 1980s, with the advent of the Space Shuttle and the *Mir* space station, microgravity research became a primary motivation for spaceflight. While astronomical observations with precise pointing requirements can be conducted best from unmanned craft, much of the current microgravity research, such as materials processing, benefits greatly from the presence of astronauts. The International Space Station (ISS) is the first space vehicle designed with

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microgravity requirements demanding a recurring 30-day quiescent period (the so-called "microgravity mode") in which disturbances to the acceleratory environment must be minimized or eliminated when possible. As a result, there is a great need to describe, quantify, and predict astronaut motions.

2. DETERMINISTIC MODELING EFFORTS

Early research efforts into the effect of astronaut motions on the spacecraft consisted of modeling astronauts as point masses and the spacecraft as a rigid body with a simple shape such as a cylinder and analyzing the dynamic interaction.

2.1. Spacecraft attitude dynamics with a point mass astronaut

The first person to explicitly raise the issue of astronauts as a disturbance source to the spacecraft was Roberson. Hitherto the crew was regarded as a force and moment generator much like a mechanical component. In his 1962 technical note *Comments on the Incorporation of Man into the Attitude Dynamics of Spacecraft* [1], Roberson wrote that the crew's motion inside the vehicle will result in "a disturbing torque, perhaps the major one". He considered the case of a single astronaut moving in an otherwise quiescent vehicle and derived an expression for the attitude dynamics, which is summarized next.

The mass of the vehicle is denoted by m_v, $\mathbf{r}(t)$, denotes the position vector of the vehicle frame in an inertial reference frame and $\mathbf{g}_\mathrm{v}$ represents the position vector of the vehicle's center of mass in the vehicle frame. The vector quantity $\mathbf{F}_\mathrm{v}$ is an external force and $\mathbf{T}_\mathrm{v}$ an external torque on the vehicle with respect to the vehicle frame. Further, the disturbing forces and torques exerted by the astronaut are denoted by $\mathbf{F}_\mathrm{d}$ and $\mathbf{T}_\mathrm{d}$. If the vector $\mathbf{H}_\mathrm{v}$ is the vehicle's total angular momentum with respect to the inertial frame, then the equations of motion for the vehicle are given by

$$m_\mathrm{v}\frac{\mathrm{d}^2}{\mathrm{d}t^2}(\mathbf{r}+\mathbf{g}_\mathrm{v}) = \mathbf{F}_\mathrm{v}+\mathbf{F}_\mathrm{d} \tag{1}$$

and

$$\frac{\mathrm{d}\mathbf{H}_\mathrm{v}}{\mathrm{d}t} = \mathbf{T}_\mathrm{v}+\mathbf{T}_\mathrm{d} - m_\mathrm{v}\mathbf{g}_\mathrm{v}\times\ddot{\mathbf{r}}. \tag{2}$$

The analogous equations for the astronaut are

$$m_\mathrm{a}\frac{\mathrm{d}^2}{\mathrm{d}t^2}(\mathbf{r}+\mathbf{g}_\mathrm{a}) = \mathbf{F}_\mathrm{a}-\mathbf{F}_\mathrm{d}, \tag{3}$$

$$\frac{\mathrm{d}\mathbf{H}_\mathrm{a}}{\mathrm{d}t} = \mathbf{T}_\mathrm{a}-\mathbf{T}_\mathrm{d} - m_\mathrm{a}\mathbf{g}_\mathrm{a}\times\ddot{\mathbf{r}}, \tag{4}$$

where the subscript "a" for "astronaut" replaces "v" for vehicle where appropriate. Adding Eq. (1) to (3) and adding Eq. (2) to (4) and then eliminating $\ddot{\mathbf{r}}$, which is the acceleration of the vehicle with respect to an inertial frame, to generalize the equation for any point in the orbit, yields the expression

$$\begin{aligned}\frac{\mathrm{d}}{\mathrm{d}t}(\mathbf{H}_\mathrm{v}+\mathbf{H}_\mathrm{a}) &= \mathbf{T}_\mathrm{v}+\mathbf{T}_\mathrm{a}-\mathbf{g}_\mathrm{cm}\\ &\quad\times(\mathbf{F}_\mathrm{v}+\mathbf{F}_\mathrm{a})+(m_\mathrm{v}+m_\mathrm{a})\mathbf{g}_\mathrm{cm}\times\ddot{\mathbf{g}}_\mathrm{cm}\end{aligned} \tag{5}$$

in which $\mathbf{g}_\mathrm{cm}\equiv(m_\mathrm{v}\mathbf{g}_\mathrm{v}+m_\mathrm{a}\mathbf{g}_\mathrm{a})/(m_\mathrm{v}+m_a)$ was used for simplification.

The term $\ddot{\mathbf{g}}_\mathrm{cm}$ can be expressed in terms of the astronaut's velocity, $\mathbf{v}$, and acceleration, $\mathbf{a}$, by the equation

$$\ddot{\mathbf{g}}_\mathrm{cm} = \mathbf{a}+2\omega\times\mathbf{v}+\dot{\omega}\times\mathbf{g}_\mathrm{cm}+\omega\times(\omega\times\mathbf{g}_\mathrm{cm}). \tag{6}$$

where ω is the angular velocity of the vehicle frame with respect to inertial space.

Equations (5) and (6) show how the astronaut's motion enters into the spacecraft attitude dynamics, namely, through the astronaut's instantaneous position $\mathbf{g}_\mathrm{a}$, velocity $\mathbf{v}$, acceleration $\mathbf{a}$, and the angular momentum $\mathbf{H}_\mathrm{a}$. While a determination of the first three quantities is a difficult task by itself, the inclusion of the angular momentum requires modeling the astronaut as a non-rigid body, which makes the approach completely impractical.

Roberson also considered another route, specifically measuring the astronaut-induced disturbance force $\mathbf{F}_\mathrm{d}$, and torque $\mathbf{T}_\mathrm{d}$ directly for typical motions and inserting them into the equation

$$\frac{\mathrm{d}\mathbf{H}_\mathrm{v}}{\mathrm{d}t} = \mathbf{T}_\mathrm{v}+\mathbf{T}_\mathrm{d}-\mathbf{g}_\mathrm{v}\times(\mathbf{F}_\mathrm{v}+\mathbf{F}_\mathrm{d})+m_\mathrm{v}\mathbf{g}_\mathrm{v}\times\ddot{\mathbf{g}}_\mathrm{v}, \tag{7}$$

which was derived by inserting Eq. (1) into Eq. (2). However, the disturbing forces and torques depend not only on the astronaut but also on the simultaneous motion of the vehicle. For example, if an astronaut pulls on a handrail to achieve a certain relative velocity, the force required to achieve the velocity depends on whether the vehicle is moving toward or away from the astronaut. Strictly speaking, the quantities $\mathbf{F}_\mathrm{d}$ and $\mathbf{T}_\mathrm{d}$ are also dependent on the spacecraft motion, which is not completely known until Eq. (7) is solved. If the dependency on the vehicle motion can be assumed to be weak, Roberson suggested building a library of $\mathbf{F}_\mathrm{d}$ and $\mathbf{T}_\mathrm{d}$ functions for various tasks based purely on laboratory measurements. While warning that such a procedure required further studies to be legitimate, he felt that it was an attractive procedure to incorporate astronaut motion into the attitude dynamics of spacecraft.

2.2. *Point mass astronauts moving on spinning spacecraft*

The main objective of the research efforts that followed Roberson's work was to find the consequence of an astronaut's translation from one point to another within or on a spacecraft. In 1965, Thomson and Fung published a paper on their investigation on the effect of astronauts moving on a *large spinning* space station [2]. The authors analyzed the cases in which crew members "walk" periodically back and forth along the radius or circumference of a disc-shaped station whose moment of inertia about the symmetry axis is twice the moment of inertia about the other two axes. Thomson and Fung found that the astronauts can "rock" the station and eventually make it unstable if they have a periodic motion that is in "the neighborhood" of an integral multiple of the half-period of the station's angular velocity. The exact periods of motion causing instability depend on a number of parameters, such as the mass of the astronauts, the type and amplitude of the astronaut motion, as well as the station's geometry and moment of inertia.

In a 1965 engineering note, Harding derived a general vector differential equation describing the effect on the rate of rotation of a rigid spinning spacecraft in which point mass astronauts move inside [3]. Further, he presented the solution to the differential equation for the case where the spacecraft is a symmetric body of revolution and the point masses are constrained to move along the axis of rotation or axis of symmetry. Along the same line, Poli published a paper in 1967 in which he developed a mathematical model for a point mass astronaut moving on a right circular cylindrical spacecraft, similar in dimensions to a Project *Gemini*-size spacecraft (radius of 1.5 m, length of 3 m, mass of 3220 kg), to determine a first order approximation to the attitude perturbation [4]. Poli's ideas are summarized below.

Let the body axes of the spacecraft be aligned with the principal axes of inertia and the motion of the astronaut be restricted to linear paths as shown in Fig. 1. The cylindrical spacecraft is spinning about the x-axis such that $\omega_x = \omega_0$ and $\omega_y = \omega_z = 0$. In the first case, the astronaut is moving on either the front or top end of the vehicle ($x{=}0, y{=}y(t), z{=}z(t)$) and in the second case on the surface parallel to the longitudinal axis ($x = 0, y = b, z = z(t)$). Let the mass of the spacecraft be denoted by M, the mass of the astronaut by m, the position vector of the astronaut (with respect to the body axes) by $\mathbf{r}_0$, and the moment of inertia about the x- and y-axis by I.

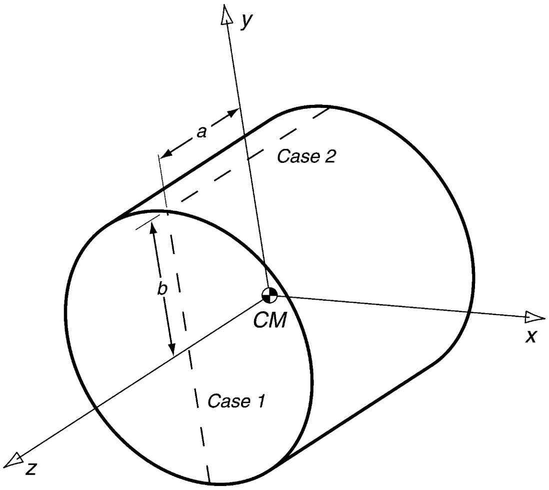

Fig. 1. Corrado Poli investigated in 1967, the effect of an astronaut moving on the surface of a Project *Gemini*-size spacecraft modeled as a circular cylinder. The dashed lines indicate the two paths taken by the astronaut. Adapted from [4].

If the magnitudes of M and m are such that

$$I \gg [Mm/(M + m)]|\mathbf{r}_0|^2 \tag{8}$$

then the motion of the astronaut in the first case does *not change the angular velocity*, ω, of the spacecraft. For Case 2, the angular velocity will change but depends only on the final position of the astronaut and is independent of the astronaut's velocity. Furthermore, an increase or decrease of ω caused by the astronaut walking toward or away from the center of mass of the vehicle is exactly compensated for when the astronaut returns to the original position. Using computer simulations, Poli investigated a number of general paths in all three dimensions that astronauts could take along the cylindrical spacecraft. Unlike the simple linear locomotion cases, the angular velocity does not return to its original value when the astronaut returned to his or her original position since the three governing differential equations are coupled and nonlinear, whereas each of the cases with linear paths produced a single linear differential equation.

3. GROUND-BASED EXPERIMENTS

In 1966, the Douglas Aircraft Company undertook an experimental study for NASA to investigate the disturbance profile of routine astronaut motions in a simulated zero-g environment [5]. The scheme to simulate weightlessness consisted of a counterbalanced pendulous support of the test subject. The subject was suspended perpendicular to a wall with the feet in contact with an instrumented platform. The 90 cm × 180 cm platform simulated an

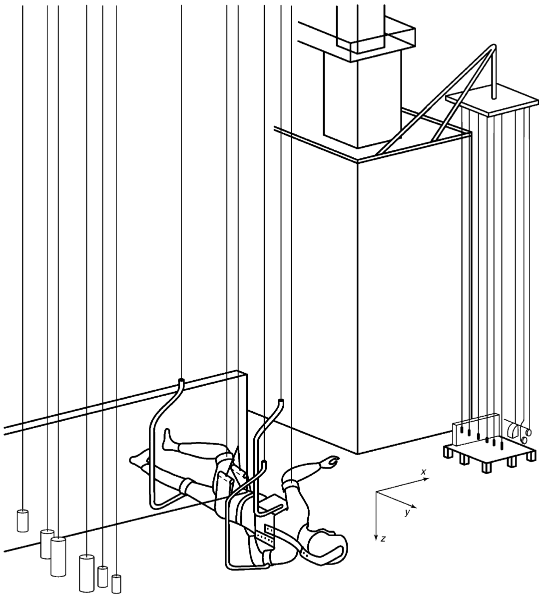

Fig. 2. Test setup of the space cabin simulator. Adapted from [5].

interior surface of a space station and transmitted the applied load to a force balance that recorded the three orthogonal force components and the three orthogonal moment components. The test subject suspension system consisted of six cables with two arm and two leg supports as well as a torso and a pelvic sling as shown in Fig. 2. The tests involved four types of astronaut motion activities: (1) body segment motion, (2) locomotion, (3) console operation, and (4) exercising. Console operation resulted in peak normal forces (i.e., forces in the y-direction) between 13 and 58 N. The peak force during *nominal* soaring was 410 N. During the entire set of soaring trials undertaken forces as low as 130 N and as much as 1560 N were measured. An interesting activity involved walking with special shoes on a velcro surface. For this type of locomotion peak normal forces in the range of 40–220 N were recorded. An error of 6% was observed for the disturbance forces recorded in the local horizontal plane (i.e., parallel to the laboratory's floor and perpendicular to the instrumented platform).

Goodman and Middleton asserted that for long-duration space missions the impulses imparted by the astronauts during their activities inside the spacecraft may in essence cancel each other out, resulting in a very small net perturbation [6]. However, significant attitude errors could accumulate in the short term and would have to be counteracted. To predict the frequency and distance covered in astronaut locomotion to be expected on a space station, measurements were made during a test of a life support system in a space cabin simulator (SCS) by the McDonnell Douglas Astronautics Company. The cylindrical SCS was 3.6 m in diameters, 12.2 m long, and simulated the layout of a space station. The "crew-travel" study recorded the locomotion of four crew members during six separate 24 h periods of a 60 day continuous test in the SCS. A weighted relative disturbance factor was assigned to each type of movement (e.g., going from the command area to the waste management area). The factor was assumed to increase with the length of travel distance inside the station since the longer the distance covered, the more or stronger impulses would be imparted by the astronaut to the station. The result of the study was a travel disturbance histogram showing the relative disturbance due to astronaut motion as a function of time in a day. The largest relative disturbance was recorded between 1 and 2 p.m., which would have resulted in an attitude change of 0.45° for a station with a moment of inertia of 678,000 kg m^2 and typical disturbance impulses of 160 N s.

In 1971, Hendricks and Johnson published the first statistical description of the disturbing forces and moments resulting from astronaut motion [7]. A mock-up console with a seat, display, and switches was built and placed on a six-degree-of-freedom load-cell array to measure forces and moments a test subject exerts while performing console operation tasks. Since the experiment was performed in a $1g$ environment, the "static" load component was removed *numerically*, leaving "dynamic" forces and moments, when the subject had a velocity relative to the load cell array. It was assumed that only these loads would be present in a weightless environment.

With the approximate zero-g data traces determined, the time functions were transformed into the frequency domain via a fast Fourier transform (FFT) to obtain their power spectral densities (PSDs). The PSD measures the distribution of power in a signal as a function $R(\tau)$ of frequency and is defined as the Fourier transform of the autocorrelation function $R(\tau)$ but can be written more succinctly as

$$P(\omega) = \lim_{T\to\infty} \frac{1}{2T} \left| \int_{-T}^{T} f(t) \mathrm{e}^{-\mathrm{j}\omega t} \, \mathrm{d}t \right|^2 . \qquad (9)$$

The relationship between the PSD of the output $w(t)$ of a linear filter with a transfer function $H(\mathrm{j}\omega)$ and the PSD of the input $v(t)$ is given by

$$P_w(\omega) = P_v(\omega) |H(\mathrm{j}\omega)|^2 . \qquad (10)$$

For white noise input, the power spectral density has a value of unity, thus, the filter output PSD is given by

$$P_w(\omega) = |H(\mathrm{j}\omega)|^2 = H(\mathrm{j}\omega)H(-\mathrm{j}\omega). \quad (11)$$

Depending on the shape of the PSD curve, a particular transfer function for the filter was chosen. Unimodal spectral densities were approximated by a single quadratic in the transfer function, such that

$$H(s) = \frac{\tau s}{s^2 + 2\zeta\omega s + \omega^2}, \quad (12)$$

where τ is the gain, ω the frequency, and ζ the damping ratio. For the approximation of a bimodal PSD curve, a fourth-order polynomial in the denominator of the transfer function was used, so that

$$H(s) = \frac{\tau s}{(s^2 + 2\zeta_1\omega_1 s + \omega_1^2)(s^2 + 2\zeta_2\omega_2 s + \omega_2^2)}. \quad (13)$$

The general form of the spectral density curves was such that it could be expressed by

$$P(\omega^2) = \frac{A_1\omega^2 + A_2\omega^4 + \cdots + A_n\omega^{2n}}{1 + B_1\omega^2 + B_2\omega^4 + \cdots + B_m\omega^{2m}}, \quad (14)$$

where the coefficients A and B are functions of the filter parameters and afterwards adjusted in a least-squares fit to minimize the error of the PSDs from the experimental data. Linear filters driven by white noise for 10 different console activities were developed, and the authors reported that "good approximations" to the PSDs were obtained.

4. FLIGHT EXPERIMENTS

4.1. Skylab crew/vehicle disturbance experiment

The first spaceflight experiment carried out to measure crew disturbances was the *Skylab* crew/vehicle disturbance experiment T-013. Proposed in 1965 [8,9], the objective of the experiment was to "assess the characteristics and effects of astronaut crew-motion disturbances aboard a manned spacecraft, and to investigate the response of the Apollo telescope mount (ATM) pointing control system (PCS) to known disturbance inputs [10]". The primary motivation for the investigation was to aid the designers of stabilization and control systems of future manned spacecraft by verifying the mathematical models that had been developed.

The experiment was performed in the dome area of the *Skylab* Orbital Workshop (OWS) by Commander Alan L. Bean and Pilot Jack L. Lousma during the second manned *Skylab* mission. Almost all data were recorded on August 16, 1973 during a period of less than 80 min. The astronauts had arrived on the station almost three weeks prior to the experiment, and were assumed to have adapted to the microgravity environment.

Two force measuring units, located approximately 3.2 m apart, were installed in the OWS (see Fig. 3) to record the loads applied by test subject Commander Bean while performing a set of *prescribed* tasks. These fell into three categories: (1) gross body motions such as arm and leg movements as well as breathing/coughing exercises, (2) simulated console operations such flipping switches and pushing buttons, and (3) worst-case control system inputs, that is, soaring across the module from one unit to the other. The primary results of the *Skylab* experiment are shown in Fig. 4. The graph shows the average and maximum recorded force for the activities conducted. The average force level for all activities did not exceed 100 N. Analysis of the force data and an examination of the film recorded, showed that the astronauts were able to achieve velocities during soaring of up to 1.9 m/s (4.3 mph). This motion produced close to 400 N of force and resulted in applied disturbance torques on the order of 1000 N · m which induced a vehicle rate on the order of $0.02^\circ\ \mathrm{s}^{-1}$ as recorded by the *Skylab* attitude control system [11].

Analysis of the data from the *Skylab* T-013 experiment continued after the release of a 1976 NASA technical report on the investigation. The astronaut forces and moments were analyzed for statistical characteristics and frequency content and a handbook [12] for incorporating crew motion effects into the design of a manned spacecraft control system was published in 1979. Two working models of crew motion disturbances were developed—for the preliminary design a simple "first-order" model and for the detailed design a stochastic model. The first-order model is a simple time function that uses the peaks of an event, such as soaring, to characterize the disturbance and has all smaller loads and noise set to zero. Then the forces and moments applied to the force measuring unit are transformed from the local measuring unit coordinate frame to the vehicle's coordinate system with its origin at the center of mass.

The stochastic model for the T-013 data used the same approach that Hendricks and Johnson employed. The power spectral density curves were computed for nine types of activities (console operations, respiratory exercises, deep breathing, arm motions, leg motion, bowing, arm flapping, crouch and push-off, crouch and straighten, and soaring). Again, unimodal spectral densities were approximated by a single quadratic in the transfer function

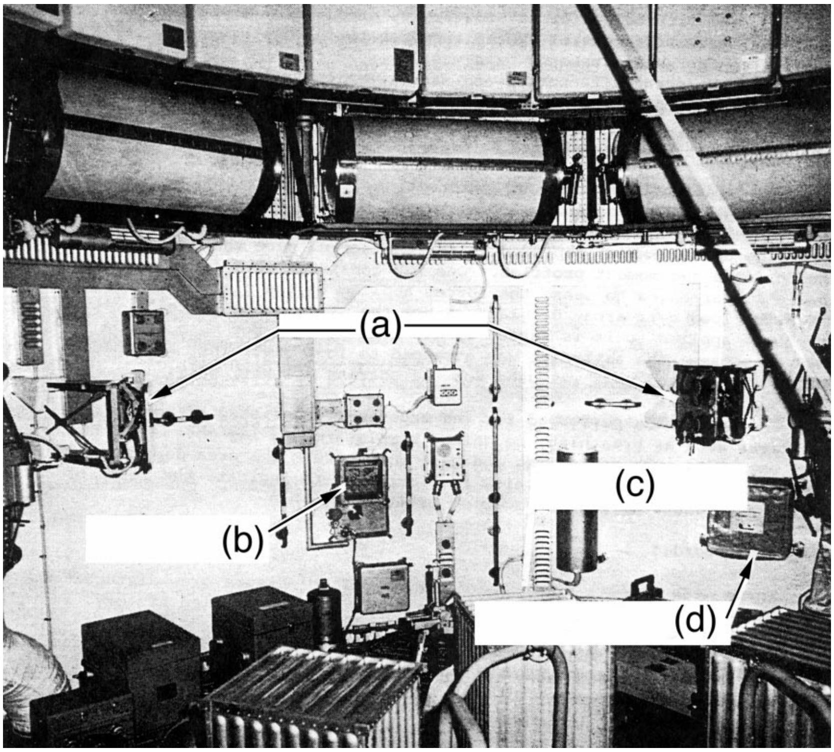

Fig. 3. Experimental setup of the *Skylab* crew/vehicle disturbance experiment in the dome area of the *Skylab* Orbital Workshop [11]. (a) Force-measuring units; (b) Anti-solar (-Z) scientific airlock; (c) Experiment data system (Hidden from view); (d) Storage container for limb motion sensors.

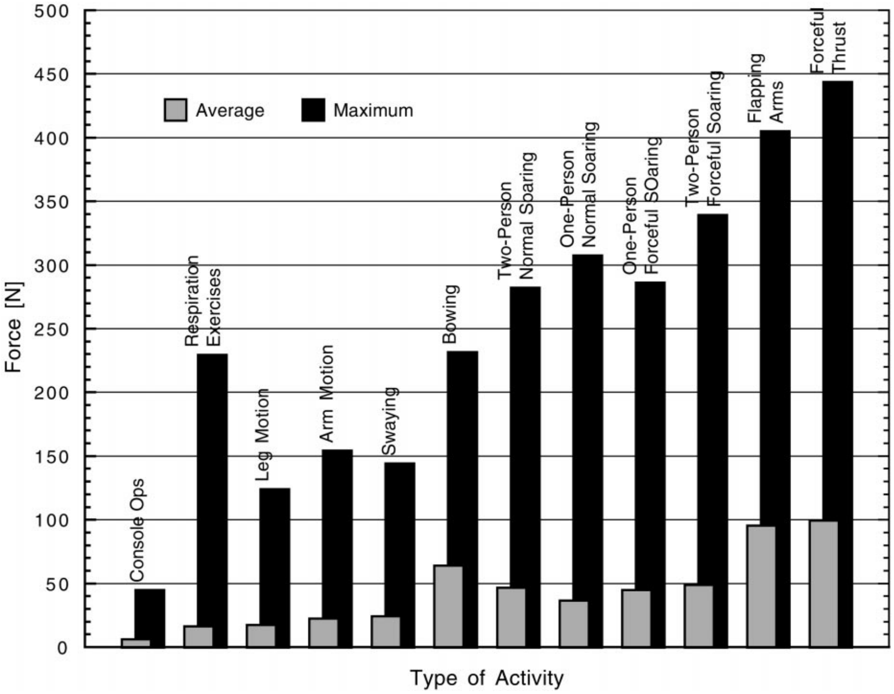

Fig. 4. Average and maximum forces measured during the *Skylab* crew/vehicle disturbance experiment in 1973. Adapted from [12].

and bimodal PSD curves by a fourth-order polynomial in the denominator of the transfer function. While many PSD curves of the spaceflight data contained more than one peak, the quadratic transfer function gave satisfactory results according to the authors of the handbook. The parameters τ, ω, and ζ were tabulated in the report and plots of the original and simulated PSD curves shown.

4.2. Study of astronaut-induced forces conducted on the KC-135A reduced gravity simulation aircraft

In June 1991, a pilot study was undertaken by Glenn Klute to quantify the forces produced by astronauts during push-offs and landings in a simulated zero-*g* environment [13]. The experiment was flown on NASA's KC-135A Reduced Gravity Simulation Aircraft, which performs a series of parabolic flight maneuvers to create approximately 20–25 s of weightlessness during each parabola. The load measurements were taken with a six-degree-of-freedom force plate on the aircraft floor. The force plate had a size of 40 cm × 60 cm and used piezoelectric load cells. The load data for each event was sampled over a period of 15 s with a frequency of 250 Hz.

The test protocol involved four astronaut motions, two using feet and two using hands, as illustrated in Fig. 5. In each case the primary load path was in the vertical or z-direction. In the "foot push-off", the subject pushed off with both feet from the force plate and translated vertically towards the cabin ceiling. In the analogous landing, the subject used his or her hands to push off from the aircraft ceiling, translate vertically down, and land with both feet on the force plate. In the "hand push-off", the subject laid down on the floor and placed both hands on the force plate near the hips and pushed off to translate toward the ceiling. A vertical hand landing involved pushing off the aircraft cabin ceiling and catching the elevated force plate with both hands.

The five test subjects represented an astronaut population ranging from a 5th percentile Japanese female to a 95th percentile American male, as defined in NASA's Man–Systems Integration Standards [14]. Four of the subjects were experienced flyers with over 400 parabolas prior to the study, while one subject had no previous experience in weightlessness. The results of the experiment are summarized in Table 1. The environment aboard the KC-135A aircraft has significant vibrations, therefore, baseline conditions with no subject activity were recorded and are also shown in the table. The accuracy level of the force plate and associated electronics was estimated to be ±13 N. The study recorded forces in the z-direction between 36 and 534 N and showed that the ability to perform specific motions was dependent on the subject's prior experience in weightlessness. The test subject with no prior experience in the KC-135A aircraft produced some of the largest forces during the activities. While experience on the reduced gravity aircraft is helpful, it is not comparable to an actual space flight experience. During an ingress test for a proposed Assured Crew Return Vehicle for the space station on the KC-135A, the performance of astronauts from Space Shuttle mission STS-40 was compared with that of experienced KC-135A fliers. The former were observed qualitatively to move about much more easily in weightlessness than the latter [13].

4.3. Dynamic load sensors (DLS) experiment on STS-62

Exclusive use of the data recorded on *Skylab* to assess crew-induced disturbances was considered questionable since it involved a set of prescribed activities and did not reflect nominal crew motion. In addition, almost the entire data set was recorded on a single day in a single session and comprised only one test subject. As a result a more comprehensive spaceflight experiment was undertaken by the Massachusetts Institute of Technology on the Space Shuttle. During mission STS-62 (March 4–18, 1994) an investigation was conducted to quantify the forces and moments exerted by the astronauts on the Orbiter middeck as they are going about their *normal* on-orbit activities [15]. The key hardware of the study, known as the dynamic load sensors (DLS) experiment, was a set of three load sensors—consisting of a touchpad, a foot restraint, and a handhold. These sensors provided the same functionality as the mobility and restraint aids built into the Orbiter. They incorporated strain-gauge flexure units in each sensor to measure the applied forces and moments in three axes (x-, y- and z-direction) [16]. The sensors were installed in the Orbiter middeck (see Fig. 6) to capitalize on frequent astronaut activity.

Astronaut-induced load data were taken on Flight Day (FD) 7, 8, and 11 of the 14 day mission. From over 67 h of DLS force/moment data recording, 301 distinct astronaut motions were identified using a supplemental video recording of crew activities in the middeck. Figure 7 shows a histogram of the peak force magnitudes (i.e., the vectorial sum of the three force components) of the 301 events. The average force level was 53 N

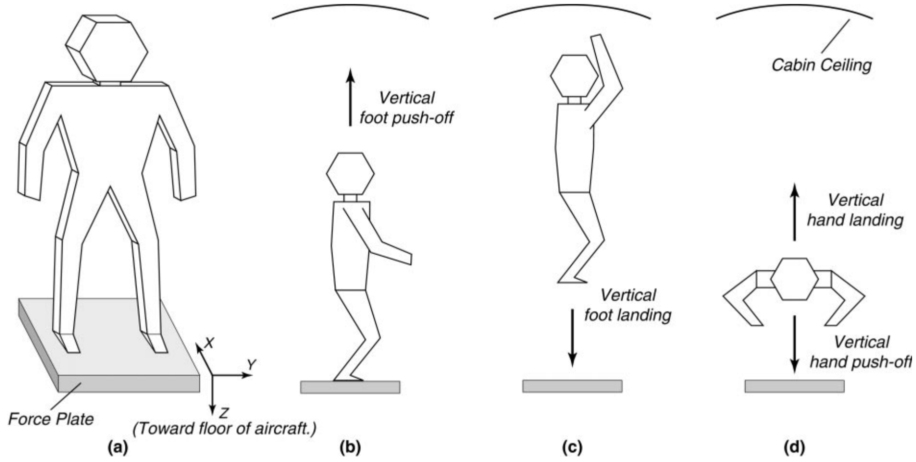

Fig. 5. (a) The axes of the force plate used in the KC-135A pilot study. (b) The vertical foot push-off from the force plate towards the ceiling. (c) The vertical foot landing on the force plate. (d) The vertical hand push-off and landing. Adapted from [13].

Table 1. Crew-induced forces in a KC-135A zero-g aircraft pilot study

		Force in x-axis (N)			Force in y-axis (N)			Force in z-axis (N)		
Crew activity	No. of events	Min.	Avg.	Max.	Min.	Avg.	Max.	Min.	Avg.	Max.
Foot push-off	5	22	71	169	22	40	67	111	311	534
Foot landing	1		67			31			200	
Hand push-off	4	∼ 0	49	111	∼ 0	44	133	67	151	267
Hand landing	3	22	31	44	31	36	44	36	102	178
“Baseline”	2	±9	±9	±9	±9	±11	±13	±13	±16	±18

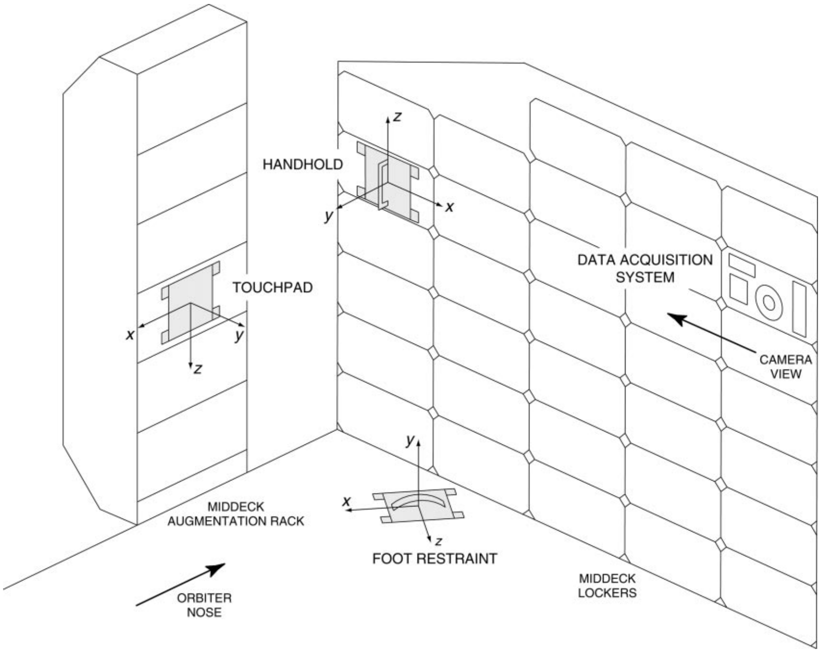

Fig. 6. Location of the DLS sensors in the Space Shuttle Orbiter middeck during mission STS-62.

and the standard deviation 41 N. Two data points, one at 286 N and the other at 466 N, are clearly outliers of the peak force data at, respectively, 6 and 10 standard deviations from the mean. The true source of these loads remains unknown. Considering a Shuttle Orbiter mass of 91,000 kg, an astronaut-induced peak force of 53 N, translates into an acceleration of $6 \times 10^{-4}g$.

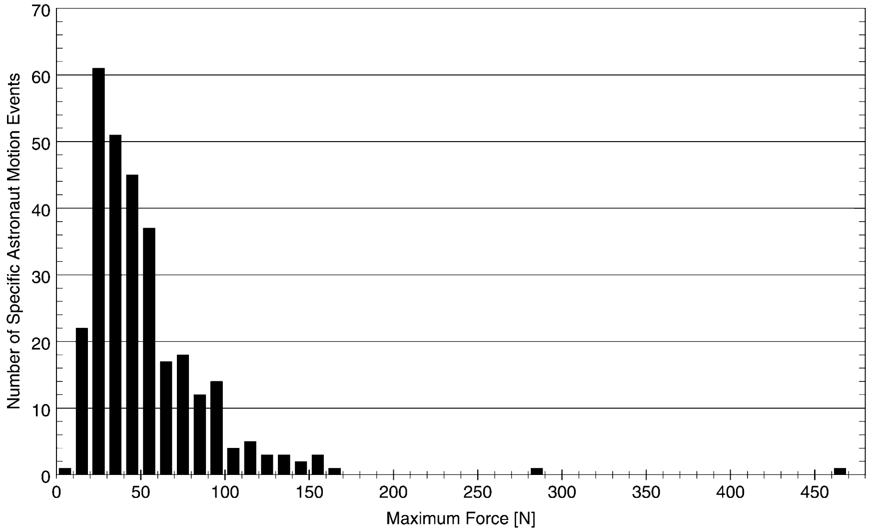

Fig. 7. Maximum forces recorded in 301 astronaut motions in the DLS experiment on the Space Shuttle.

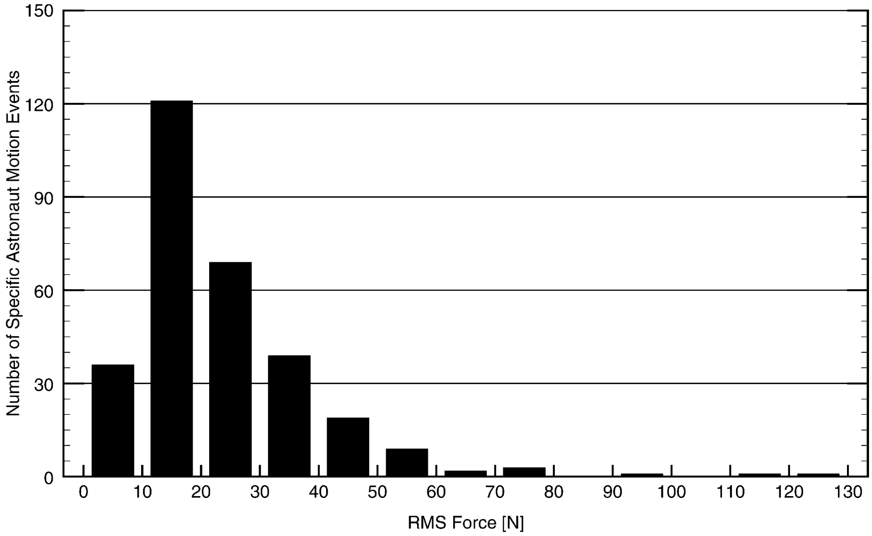

Fig. 8. Root-mean-square forces recorded in 301 astronaut motions in the DLS experiment on the Space Shuttle.

Table 2. Average astronaut-induced forces and moments recorded by the DLS experiment

	Avg. duration (s)	Force (N)		Moment (Nm)	
Type of motion		Avg. peak	Avg. RMS	Avg. peak	Avg. RMS
Flying and landing on a sensor	1.2	59.6	27.4	7.0	3.7
Pushing off a sensor and floating away	1.1	97.4	46.8	5.5	3.1
Vertical re-orienting; usually during posture control	2.1	48.4	25.5	8.9	5.0
Horizontal re-orienting; usually during posture control	0.8	35.7	17.5	3.2	1.7
Flexing a limb while using a sensor	2.3	51.9	23.8	7.6	3.8
While using sensor, extending a limb	2.1	66.2	30.8	6.3	3.3
Using two limbs for support	6.6	43.1	16.6	5.9	2.7
Using one limb for support	4.8	73.4	31.5	9.4	4.3
Twisting body while using a sensor	8.1	40.9	13.8	4.1	1.6
All motions	3.1	52.9	23.8	6.6	3.3

The significance of the astronaut loads is more evident from the root-mean-square (rms) forces recorded for the 301 events shown in Fig. 8. The average r.m.s. force was 24 N and the standard deviation 16 N. An examination of the video footage, led to the identification of nine characteristic motions that astronauts perform in the microgravity environment of the Orbiter. Descriptions and char-

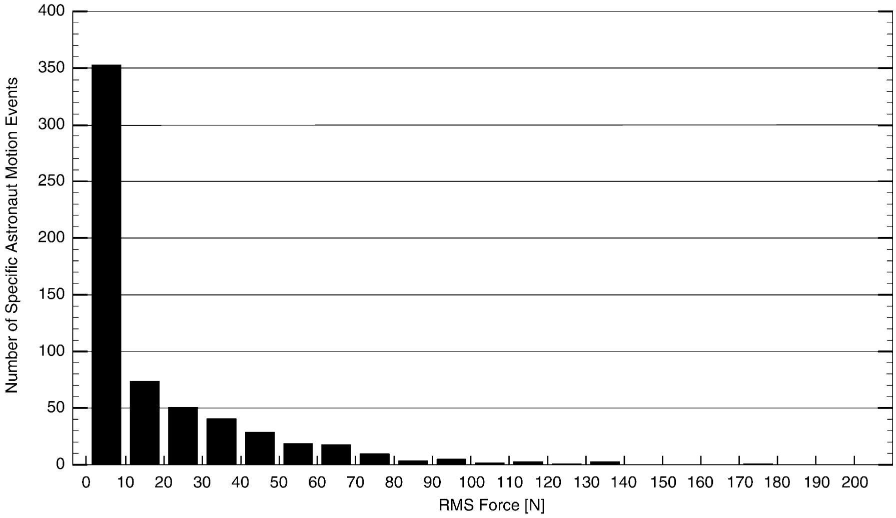

Fig. 9. Root-mean-square forces recorded in 614 astronaut motions in the EDLS experiment on the space station *Mir*.

acteristics of these motions are provided in Table 2. Four types of motions were recorded on all three sensors and five motions involved only two of the sensors—either the handhold or the foot restraint. The maximum forces recorded by each sensor were as follows: 466 N for the foot restraint, 75 N for the handhold, and 153 N for the touchpad. Overall, 95% of the time the maximum force magnitude was below 120 N and 94% of the time the root-mean-square force level was below 50 N. The distribution of the energy in the astronaut-induced disturbances was determined by computing the frequency below which 95% of the power spectral density is contained (the 95% PSD). As is expected for human motion, the energy is contained in the low-frequency regime. Approximately, 86% percent of the astronaut activities had a 95% PSD below 6 Hz.

4.4. Enhanced dynamic load sensors experiment (EDLS) on Mir

The enhanced dynamic load sensors (EDLS) experiment conducted on the Russian space station *Mir* was a follow-on to the DLS research on the Space Shuttle. It was conducted as part of Phase I of the International Space Station (ISS) Program involving US experiments and astronauts on *Mir*.

The EDLS effort was funded by NASA as a so-called risk mitigation experiment for the ISS to expand upon the database acquired with DLS and gather representative data on a space station. The size and layout of the Space Shuttle middeck and the number of astronauts present does not reflect the common situation one would find in a long-duration space flight on a space station. Furthermore, Space Shuttle missions are too short to observe long-term crew adaptation to weightlessness. The presence of general-purpose accelerometers to measure the microgravity conditions on *Mir* provided the opportunity to corollate astronaut-induced forces and moments with the accelerations experienced by the station.

A preliminary analysis of more than 600 specific astronaut motion events collected during the NASA 4 mission to *Mir* (February 25–May 7, 1997), showed that approximately 95% of the time, the r.m.s. force was below 70 N (see Fig. 9). The maximum force magnitude in these events, was about 68% of the time below 100 N and 95% of the time below 325 N. Since *Mir* provided more volume to move in and fewer astronauts in the vicinity of the sensors, it is not surprising that the recorded disturbances are higher than on the Shuttle with the middeck's limited volume.

5. SUMMARY

The paper described the past and present research of astronaut motions and their effects on the spacecraft. Robert E. Roberson was the first to explicitly raise the issue of astronaut disturbances. He showed that one would need to know the instantaneous position, velocity, acceleration, and angular momentum of the astronauts to precisely compute the spacecraft attitude dynamics, which is impractical. A better approach suggested by Roberson would be to conduct experiments to build a database of forces and moments generated during typical astronaut motions. During the mid- and late-1960s, studies were conducted to determine the effect of astronauts "walking" on spinning spacecraft or stations. These investigations were followed by more practical laboratory experiments. The McDonnell Douglas Company simulated weightlessness in a ground-based experiment to estimate the disturbance forces that astronauts generate in orbit. A study in a space cabin simulator led to an assessment of the net impulse on a space station due to astronaut motions over an extended period of time. A description of the astronaut-induced loads as stochastic processes further improved the understanding of the issue. A 1973 experiment aboard the *Skylab* station recorded the forces and moments generated by a test subject during a set of prescribed activities. It was the first measurement of astronaut-induced loads in space. While the force level recorded during "vigorous soaring" exceeded 400 N, the average peak load across all tests was below 100 N. The forces and moments produced by astronauts during nominal on-orbit activities were measured on the Space Shuttle in the so-called DLS experiment and on *Mir* in the EDLS experiment. The data collected in these two investigations allowed to build an extensive database of the typical loads produced by astronauts—as suggested by Roberson. An analysis of the loads recorded on the Shuttle, showed that about 94% of the time, the root-mean-square (rms) force was below 50 N. On *Mir*, where more volume to move about was available, about 95% of the time, the r.m.s. force was below 70 N. Qualitative observations, verified quantitatively to some extent, lead to the conclusion that veteran astronauts exert smaller forces on the spacecraft than unexperienced astronauts or subjects in ground tests. While astronauts can produce high disturbance forces of several hundred Newtons, if they so desire, their nominally induced loads are fairly low.

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